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# *Ex Ante* Analysis of Small-Scale Irrigation Interventions in Dangila

Texas A&M University Integrated Decision Support System Team
USAID Feed the Future Innovation Laboratory for Small-Scale Irrigation

Jean-Claude Bizimana, Neville P. Clarke, Yihun T. Dile, Thomas J. Gerik, Jaehak Jeong,
Javier M. Osorio Leyton, James W. Richardson, Raghavan Srinivasan, and Abeyou W. Worqlul

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## Interpretive Summary

This report is part of the product of the USAID Feed the Future Innovation Laboratory for Small Scale Irrigation (ILSSI), and summarizes ILSSI's analysis of proposed small-scale irrigation (SSI) interventions in Dangila woreda, in the Amhara region of Ethiopia. Farm-family livelihoods in the area are derived from cereals produced in the rainy season and irrigated crops grown in the dry season. Groundwater potential and experience in SSI is relatively high; however, decision makers have historically lacked means to assess the effects of increased SSI on crop production, farm-family economics, and environmental services.

In Dangila, ILSSI proposed maximizing SSI of high-value, dry-season crops, using shallow groundwater and one of five alternative water-lifting technologies. ILSSI evaluated the proposed SSI interventions by simulating and comparing two alternative farming systems:

1. a crop rotation of maize and teff grown in alternating wet seasons, applying fertilizer at rates currently used by farmers in the region; and
2. a crop rotation consisting of wet-season grains (maize or teff), fertilized at government-recommended rates, plus an irrigated, dry-season double crop (onion) on all irrigable land (i.e., all areas with slopes less than 8%), using shallow groundwater.

Onion was chosen as representative dry-season crop for purposes of the simulations, based on input from local experts. Additional crops will be modeled in ex post studies that reflect field studies and broader applications.

Simulations indicated that there is a large potential for increased SSI in Dangila. A complete hydrologic analysis of the area's 5150-ha watershed calculated that the average annual volumetric groundwater recharge was over 26 million m$^3$, and simulations indicated that the proposed SSI interventions would use less than 20% of the annual shallow groundwater recharge. Excessive irrigation from shallow groundwater can deplete aquifers that contribute to stream flow, potentially reducing those flows; however, simulations indicated that the proposed SSI interventions would reduce average monthly stream flow by only 8%, and should not compromise downstream flows. This suggests that the proposed SSI interventions can be sustained by the shallow groundwater recharge without affecting long-term groundwater storage, and would not compromise the environmental health of the watershed.

The proposed SSI interventions (especially when combined with increased fertilization rates) increased wet-season grain yields significantly, presumably because crop rotation operations implemented in conjunction with the proposed SSI scenarios resulted in improvements in soil organic matter. As expected, simulations predicted that onion yields would increase with applied irrigation water of up to 391-392 mm (the irrigation depth required to reduce plant stress levels to 0%).

Economic analyses were conducted to estimate the effects of the proposed SSI interventions (in conjunction with the simulated, improved cropping system) on farm-family economics in Dangeshta, a kebele in Dangila. These analyses also compared the costs and benefits of five water-lifting technologies: pulley-and-bucket irrigation, and rope-and-washer pumps operated by hand, animal, gasoline motor, and solar power. Of the alternative technologies examined, none of water lifting technologies met the irrigation water requirements for the proposed SSI interventions (i.e., for all 856 ha of irrigable land in the kebele). Implementation of the proposed SSI interventions using gasoline-motor-powered rope pumps produced by far the highest net present value, net cash farm income, and ending cash reserves of the six scenarios simulated (including the baseline, non-irrigated scenario). In each of the alternative scenarios, the increase in farm revenue was due almost entirely to the sale of surplus irrigated onion. Where a gasoline-motor pump was used, the forecasted sales of irrigated onions contributed, on average, 46% of the total crops receipts and 100% of the net cash (profit) for the five-year planning horizon.

The main barrier to SSI with motor pumps is the initial investment in the technology. The initial investment costs of an animal-powered pump or hand-powered pump are much lower; however, the NPV results strongly suggest that an investment in a gasoline-motor pump would pay large dividends in increased income and wealth. Moreover, individual farmers might benefit by spreading entry costs over more irrigated area, perhaps by having two or three farmers share a motor pump. Accordingly, in Dangila, we would recommend implementing the proposed SSI interventions using a motor pump.

Despite improvements in farm-family economics resulting from the proposed SSI interventions, nutritional deficiencies persisted under the simulated, improved cropping system. We would also, therefore, propose expanding the types of crops irrigated in the dry season to increase family nutrition and net cash income, but only if such crops can be irrigated without causing excessive soil erosion or reduction in environmental benefits. The evaluation and comparison of alternative farming systems, including the types of crops grown, recommended management practices, and associated impacts on soil erosion and environmental benefits, are subjects for proposed future study.

## Introduction

There are three major components of ILSSI: (1) field studies evaluating selected SSI methods; (2) household surveys to assess the evaluate gender, nutrition, and economic consequences of SSI interventions; and (3) the application of a suite of integrated models to quantitatively estimate the impact of SSI on production, environmental, and economic outcomes. An iterative process of engagement is involved in linking the three components of ILSSI to form a final product.

The analyses summarized in this report contribute to the third ILSSI component: estimating the impacts of proposed SSI interventions using the ILSSI's Integrated Decision Support System (IDSS). The IDSS is comprised of a suite of previously validated, interacting, and spatially explicit agroecosystem models: the Soil and Water Assessment Tool (SWAT), Agricultural Policy Environmental Extender (APEX), and Farm Scale Nutrition and Economic Risk Assessment Model (FARMSIM). The IDSS predicts short-term and long-term changes in crop and livestock production, farm economies, and environmental services produced by changing land uses, agricultural technologies and policies, climate, and water resources management, including SSI. The four models (and their sister and antecedent decision tools) have been used successfully for more than 25 years to address complex biophysical and economic issues in the United States and around the world. Designed to use readily available input data from global, national, and local sources, they can provide decision makers with reliable predictions of the production, environmental, and economic impacts of their actions.

The objective of this study was to use the IDSS to evaluate the benefits, environmental effects and economic viability of proposed SSI interventions on farms in Dangila, a Feed-the-Future woreda in the Awi zone of the Amhara region of Ethiopia. Dangeshta, one of the rural kebeles located in Dangila woreda, is located about 80 km southwest of Bahir-Dar, one of the region's main markets. The region's climate is subtropical, and temperatures are ideal for cropping year-round, with a main rainy season from June to September and a dry season from October to January. The dramatic shift in rainfall that occurs between wet and dry seasons restricts rain-fed cropping to the rainy season. For double cropping, irrigation is needed in the dry season.

There are an estimated 1766 ha of cropland in Dangeshta kebele, and about 661 ha of pastureland. The average household practices mixed-subsistence farming, cultivating a main crop of cereals in the rainy season. Some households also produce irrigated vegetable crops in the dry season. The main sources of irrigation water in the area are traditional river diversion and hand-dug wells. Currently, a number of households irrigate using motor pumps, mainly to divert water from rivers.

Rapidly increasing population, economic growth, and the movement of the rural population to cities provide a strong incentive for the Ethiopian government to help farmers increase production and farm-family nutritional and economic well-being. However, as in other parts of the world, farming systems in Ethiopia are complex and can have adverse environmental effects such as soil erosion, loss of plant nutrients, and changes in watershed hydrology. Increased reliance on small-scale irrigated agriculture, which is promoted by the government of Ethiopia, could have both positive effects on food production and negative effects on stream flows and shallow aquifers used for human and livestock water supplies. In addition, depending on equipment costs, labor availability, other crop input costs, and market prices of agricultural commodities, the increased use of SSI, or of specific irrigation technologies, may or may not prove economically beneficial.

Information about Dangila's natural resources, existing cropping systems, farm-family characteristics, and market conditions for agricultural products were obtained from a number of international, national, and local sources. These data were then used as inputs to the IDSS modeling system.

The baseline farming-system scenario simulated with FARMSIM, SWAT and APEX was the typical farming system currently used by farmers in the region. It consisted of traditional grains (maize and teff) grown as monocrops during the main rainy season, using shallow tillage with animal traction, and current fertilizer application rates. The proposed SSI interventions simulated with SWAT and APEX were the increased cultivation of an irrigated, dry-season, double crop (onion) in all irrigable cropland areas (irrigation-appropriate soils with slopes of less than 8%) within the 5150-ha Dangeshta watershed. (As noted above, onion was chosen as representative dry-season crop for purposes of the simulations, based on input from local experts. Additional crops will be modeled in ex post studies that reflect field studies and broader applications.) In addition, APEX was used to simulate seven irrigation amounts, and SWAT was used to simulate application of government-recommended fertilizer rates on maize and teff, with and without the proposed SSI intervention. FARMSIM was used to simulate the effects on farm-scale economics of various water-lifting technologies that could be used to implement the SSI interventions.

Parameterization, calibration, and execution of SWAT, APEX, and FARMSIM were closely coordinated, with input and output data exchanged in an integrated fashion to assure comparability of production, environmental, and economic results.  This report describes the methodology, results, and implications of this study.

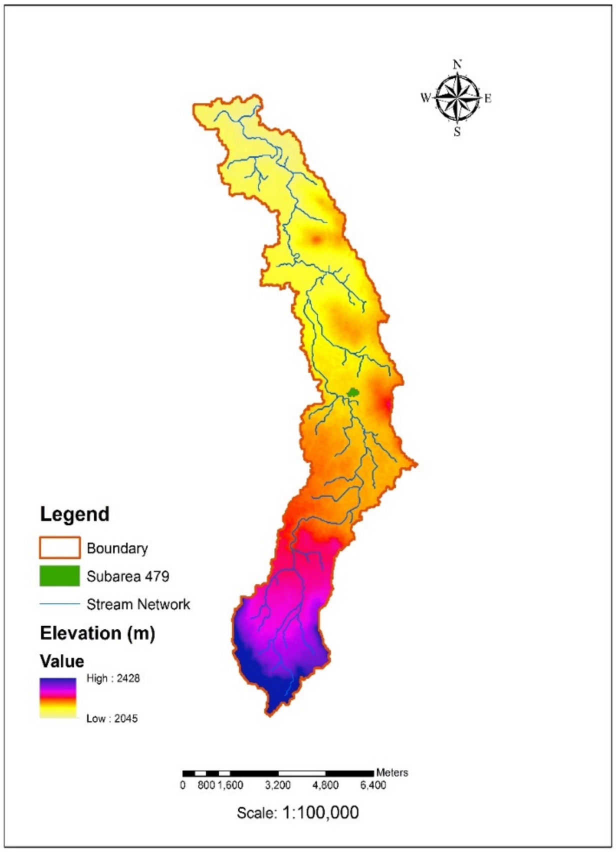


**Figure 1.** Dangeshta watershed boundary, main streams and Subarea 479, simulated with APEX.

## Methods

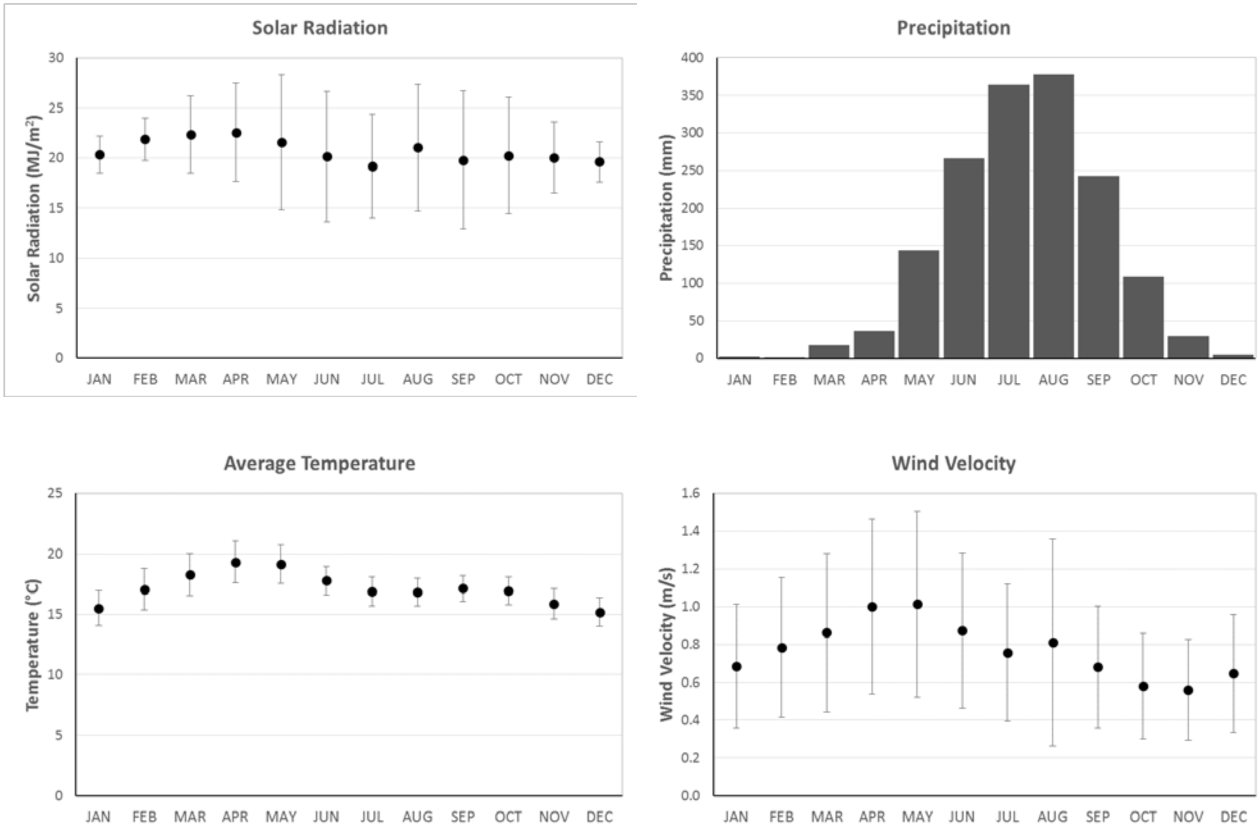
**Model Inputs.** Input data used in this study for SWAT and APEX simulations included:

a) The 30-m resolution Digital Elevation Model (DEM) from SRTM Enhanced Shuttle Land Elevation Data (USGS EarthExplorer). These data were improved to 10-m resolution by re-projection with cubic convolution and using stream network burning to define streams, delineate the watershed, define slopes, and discretize subarea parameters. Five slope classes were defined within the watershed based on their varying suitability for irrigation (Chen et al. 2010; FAO 1997; Kassam et al. 2012; Mati et al. 2007). The slope classes were <2%, 2-8%, 8-12%, 12-20%, and >20%.

b) For SWAT analyses, an existing land use map (MoWE 2012). For APEX simulations, a LANDSAT-8 image from the USGS Global Visualization Viewer, processed with ERDAS IMAGINE 2014, MULTISPEC, and ArcGIS 10.1. This image was classified using cluster analysis, and four major classes were identified: forestland, cropland, bare soil and water. The final land use map has a 30-m resolution (WGS84 UTM 37N).

c) The soils map shape file (MoWE 2012), which classified the entire watershed area as Haplic Luvisols (LVh). Soil parameters used by SWAT and APEX were estimated with the SWAT soil parameter generating tool.

d) Twenty-four years of daily weather data, from 1990 to 2013, obtained from the Dangila Syn weather station (ENMSA 2012). These data included rainfall, temperature (min/max), relative humidity, sunshine hours (solar radiation), and wind speed. Quality control of the data was performed to eliminate erroneous values that were beyond historical extreme records. Missing values were estimated using WXGN weather predictor. SWAT and APEX used the same weather dataset. Figure 2 illustrates monthly means and standard errors for the watershed.



Solar Radiation

Precipitation

Average Temperature

Wind Velocity

**Figure 2.** Monthly weather data from Dangila Syn station (1990 - 2013) (ENMSA 2012).

**Subbasin Delineation.** SWAT divided the 5150-ha Dangeshta watershed into 972 subbasins (referred to as subareas in APEX) with areas ranging from one to ten hectares. The watershed discretization generated for SWAT was used to calibrate APEX to gauge streamflows and sediment yields. The subbasins/subareas were defined with assistance from International Water Management Institute staff.

Subbasin/subarea shape and size were identical for the two models, to guarantee that SWAT and APEX streamflow volumes and sediment yields would be comparable.

As a case study, Subarea 479 (equivalent to SWAT's Subbasin 479) was selected for the simulation with APEX. Subarea 479 is 7.65 ha, characterized as cropland, and entirely composed of LVh clay soil, with a depth of 1.4 m, and a slope of 0.026 m/m. The latitude/longitude of its centroid was: 11.239 by 36.879 degrees, respectively. This area overlaps as well with the sample of households that were used for the farm-level economic and nutritional analysis (FARMSIM).

**Crop Management.** Generally, crop management in Ethiopia varies from farmer to farmer and from year to year, depending on when the rainy season begins. Table 1 provides baseline crop management data for maize and teff, as simulated by SWAT and APEX. The baseline maize and teff crop management schedules and fertilization practices (type and rate) were based on farmer interviews and expert opinion (Personal communications: Y. Dile and P. Nakawuka).

**Table 1.** Crop management data used by APEX for maize and teff in the Dangeshta watershed.

| Date | Maize Practice | Amount |
|---|---|---|
| May-15 | Tillage | |
| Jun-15 | Tillage | |
| Jun-15 | Tillage | |
| Jun-15 | 1st stage urea fertilizer application | 42.5 kg/ha |
| Jun-15 | DAP fertilizer application | 85 kg/ha |
| Jun-15 | Planting | |
| Aug-15 | 2nd stage urea fertilizer application | 42.5 kg/ha |
| Oct-15 | Harvest | |

| Date | Teff Practice | Amount |
|---|---|---|
| May-15 | Tillage | |
| Jun-15 | Tillage | |
| Jul-15 | Tillage | |
| Jul-15 | 1st stage urea fertilizer application | 17.5 kg/ha |
| Jul-15 | DAP fertilizer application | 37.5 kg/ha |
| Jul-15 | Planting | |
| Aug-15 | 2nd stage urea fertilizer application | 17.5 kg/ha |
| Dec-15 | Harvest | |

Onion is the region's most common dry-season vegetable crop, and it is typically irrigated with shallow groundwater or river water. For SWAT simulations, irrigation was implemented in all areas designated for agricultural land use and with slopes of less than 8% (as recommended by FAO). A total area of approximately 856 ha met these criteria. Table 2 presents baseline crop management data for onion used by SWAT and APEX.

**Table 2.** Crop management for onion in the Dangeshta watershed

| Date | Operation | Amount |
|---|---|---|
| Jan 1 | Tillage | |
| Jan 5 | Planting | |
| Jan 5 | UREA fertilizer | 85kg/ha |
| | DAP | 35kg/ha |
| Jan 5 | Auto-irrigation | |
| Feb 20 | UREA fertilizer | 85kg/ha |
| Apr 11 | Harvest and killing | |

The fertilizer rates in sub-Saharan Africa, and Ethiopia in particular, are generally low (IAASTD 2009). In Dangila, fertilizer rates for teff and onion are low, though fertilizer rates for maize tend to approach recommended rates. Accordingly, we also simulated crop yield responses to application of fertilizer at recommended rates (table 3).

**Table 3.** Recommended fertilizer application rates in most parts of Ethiopia (EIAR 2007).

| | *Urea (kg/ha) | DAP (kg/ha) |
|---|---|---|
| Teff | 100 | 100 |
| Maize | 100 | 100 |
| Onion | 150 | 200 |

*The urea is applied in two split applications

**Stream Flow and Crop Yield Calibration.** SWAT was calibrated to actual stream flow data gathered from the Gilgel Abay river gauging station close to Merawi town (MoWE 2012). APEX field-scale runoff values were calibrated to match SWAT predictions using the automatic calibration tool APEX CUTE. Estimates of historical mean yields of maize and teff were obtained from the 2005 Spatial Production Allocation Model (SPAM) dataset (HarvestChoice 2014) for an area including the Dangeshta watershed. In SPAM, teff is included in the “other cereals” category, but it is by far the most important representative of that group in Dangila. (HarvestChoice 2014). Therefore, SPAM yield estimates for “other cereals” were used to calibrate yields of teff. Table 4 gives SPAM grain yields (t/ha, dry weight) for maize and teff for the 2005 cycle (HarvestChoice 2014). Statistical analyses could not be performed for calibration of yields since only four SPAM grid cells covered Dangila. Onion yield estimates used in model calibration were acquired from the Ethiopian Central Statistical Agency (2012).

**Table 4.** SPAM estimates of maize and teff yields for four grid cells associated with the Dangeshta watershed.

| Region | Cell ID | Maize | Teff |
|---|---|---|---|
| Dangila | 4080681 | 2.27 t/ha | 0.92 t/ha |
| Dangila | 4080682 | 3.74 t/ha | 0.88 t/ha |
| Dangila | 4085002 | 3.43 t/ha | 0.87 t/ha |
| Dangila | 4089322 | 3.32 t/ha | 0.90 t/ha |

**Economic Analyses.** FARMSIM was used to provide economic analyses of several promising SSI interventions identified by SWAT and APEX simulations. These included: (1) increased cultivation of an irrigated, dry-season, double crop of onions; and (2) the evaluation of five alternative water-lifting technologies. In all cases, fertilization of teff, maize and onion crops was increased to rates recommended by the Ethiopian government.

The baseline and five alternative scenarios were each defined as follows:

Baseline: no irrigation + current fertilizer

Alt.1: pulley-and-bucket irrigation + recommended fertilizers

Alt.2: hand-operated rope-and-washer pump irrigation + recommended fertilizers

Alt.3: animal-powered rope-and-washer pump irrigation + recommended fertilizers

Alt.4: gasoline motor-powered rope-and-washer pump irrigation + recommended fertilizers

Alt.5: solar-powered rope-and-washer pump irrigation + recommended fertilizers

Though not widely used in Ethiopia, rope-and-washer pumps powered by animals, gasoline motors and solar power are utilized in other parts of Africa, as pictured below, and may be viable options for SSI:

*Pulley-and-bucket system*

*Hand-operated rope-and-washer pump*

*Rope-and-washer pump operated by horse*

*Gasoline-motor-powered rope-and-washer pump*

*Solar-powered rope-and-washer pump*

For the sake of brevity, we will hereinafter refer to hand-operated rope-and-washer pumps, animal-powered rope-and-washer pumps, gasoline motor-powered rope-and-washer pumps, and solar-powered rope-and-washer pumps as "hand-operated pumps", "animal-powered pumps", "motor pumps" and "solar pumps", respectively.

In comparing the five irrigation technologies, we estimated the costs of employing each technology, as well as the amount of land that could be irrigated by each without water stress to the crops. Estimates were based on the costs (operating and capital) of each technology and the capacity of each (as determined by its pumping rate) to irrigate available land. Our analysis assumed the following:

1) Number of active family members (adults) required to carry out the irrigation: 2
2) Number of irrigation hours per family member per irrigation day: 4
3) Number of irrigation days per season, assuming 2 days per week of irrigation during a period of 3.5 months (January through mid-April): 28
4) Total number of hours of irrigation per season: 2*4*28 = 224 hours
5) Pumping rates for the different water-lifting technologies:
    - Pulley and bucket: 8 L/min
    - Hand-operated pump[1]: 20 L/min
    - Animal-powered pump[2]: 60 L/min

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[1] Nederstigt and Van del Wal (2011)/PRATICA Foundation

[2] http://www.ropepumps.org/horse.html/ PRACTICA Foundation

- Motor pump[3]: 170 L/min
- Solar pump[4]: 24 L/min

Crop yields were simulated by APEX for different levels of water stress. The irrigator's equation was used to estimate the total amount of water that can be delivered by a water lifting technology:

Irrigator's equation: $Q*t = d*A$

Q: flow or pumping rate (L/min)
T: time for irrigation (min)
d: depth of irrigation water applied (mm)
A: area covered ($m^2$ or ha)

Based on the total amount of water required to irrigate a crop for the entire dry season, and the total amount of water per hectare delivered by each water-lifting technology (based on pumping rate and irrigation hours), we computed the fraction of water supply provided by each technology. Given the total irrigable land available for an irrigated onion crop and its water requirements, we used the amount of water that could be supplied by each technology to compute the fraction of cropland that could be irrigated with minimal water stress for each water-lifting technology. Based on the above assumptions, results show that none of the technologies are able to provide the required water quantity to onions for a total irrigable onion land of 856 ha. The pulley irrigation system covers only 2.7% of the total irrigable land to meet irrigation water needs; the hand-operated rope pump covers about 7%; and a rope pump operated by animal, solar motor or gasoline motor can irrigate 21%, 41.1%, and 8%, respectively, of the maximum irrigable onion land.

Other simulation assumptions

To show the full potential of adopting new technologies, we assumed that the alternative farming technologies (alternative scenarios) simulated in this study were adopted at 100% by farmers. Also, the markets were assumed to be accessible and function at a competitive level with no distortion where the supply and demand determine the market prices. However, in the five-year economic forecast, market selling price in each of the five years was assumed to equal the average selling price of year 1 for each crop sold.

The FARMSIM model was run 500 times for each of the six scenarios—the baseline scenario and five alternate scenarios—to sample variation in crop yields due to weather and other stochastic variables. To determine which of the six scenarios would be most beneficial to farm families, three types of economic indicators were calculated: Net Present Value (NPV), Net Cash Farm Income (NCFI), and Ending Cash (EC) Reserves. The performance of the six scenarios as estimated by each of the three indicators was displayed graphically as a cumulative distribution function (CDF) and as a "stoplight graph."

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[3] IWMI field studies conducted in 2015 on behalf of ILSSI project
[4] Mzuzu University in Malawi: http://old.solar-aid.org/project_water_pump/

## Results and Discussion.

**Hydrology.** Our results indicated that there is great potential for additional SSI in the Dangeshta watershed. The average annual groundwater recharge simulated by SWAT was 420-547 mm (fig. 3), and the annual generated surface runoff was estimated to be 371-503 mm. For the Dangeshta watershed, with a catchment area of 5150 ha, the average annual volumetric groundwater recharge and surface runoff potentials are over 26 million $m^3$ and 23 million $m^3$, respectively. These results are consistent with the observation that shallow groundwater wells are often used in the watershed to irrigate vegetable crops.

b)

**Figure 3.** Water resources potential in the Dangeshta watershed; a) the average annual groundwater recharge, and b) surface runoff.

For SWAT simulations, irrigation water was derived from shallow groundwater. Therefore, it was necessary to determine whether shallow groundwater recharge could support irrigation water requirements when irrigated, dry-season onions were cultivated. The average annual shallow groundwater recharge under baseline conditions was more than 400 mm across the 5150-ha watershed, and the average annual irrigation was less than 179 mm over the 856 ha of irrigated onion (fig. 4). Since groundwater withdrawals would be less than 20% of average recharge, we can safely conclude that irrigation of onion during the dry season can be sustained by the shallow groundwater recharge without affecting long-term groundwater storage.

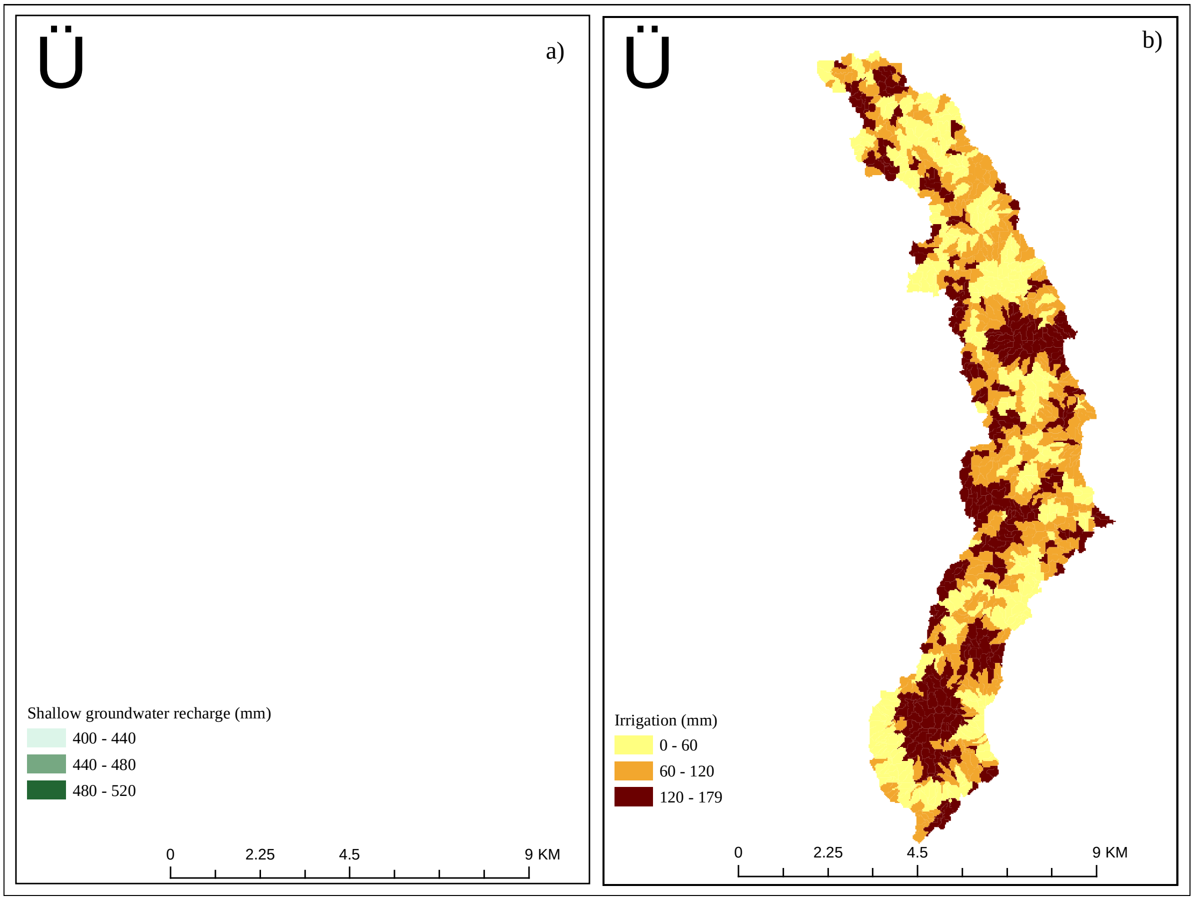

**Figure 4.** a) Average annual shallow groundwater recharge under baseline conditions, and b) average annual irrigation for cultivating onion during the dry season.

Annual water balance components for maize and teff estimated by APEX are illustrated in figure 5. The results indicate that evapotranspiration is slightly greater in maize than in teff, reflecting maize's larger leaf area and more rapid growth rates. As a result, deep percolation is slightly reduced where maize is cultivated.

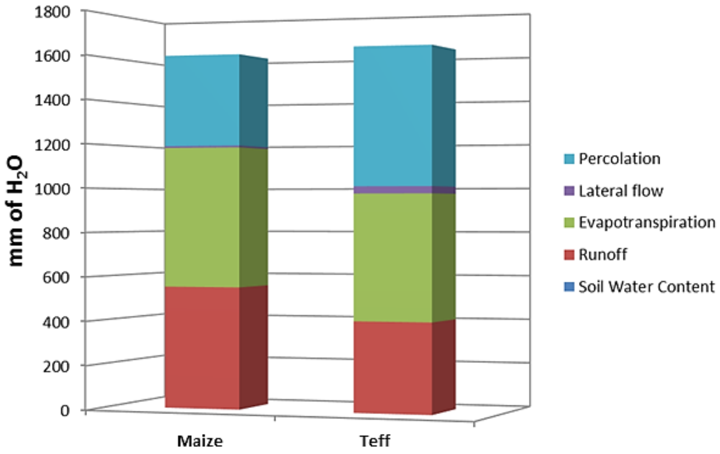

**Figure 5.** Water balance for maize and teff in Dangeshta watershed estimated by APEX.

The average annual rainfall in the watershed for the period 1990 to 2013 was 1628 mm. About 46% of the annual rainfall became stream flow and 41% was evaporated back into the atmosphere (fig. 6). Surface runoff contributed 61% of stream flow and base flow contributed 39%.

Figure 6 illustrates the simulated hydrology of the watershed for the baseline cropping system without irrigated onion, as compared to the same cropping system with irrigated onion. Dry season onion irrigation on all land with less than 8% slope slightly reduced stream flow from 46% to 42% of precipitation because the pumping of groundwater from the aquifer reduced return flow. However, it also caused a small increase in the fraction of stream flow derived from surface runoff, probably because of increased runoff associated with irrigation. Actual evaporation increased to 46% of rainfall when irrigated, dry-season onions were cultivated, but the ratios of percolation to rainfall and deep recharge to rainfall did not change.

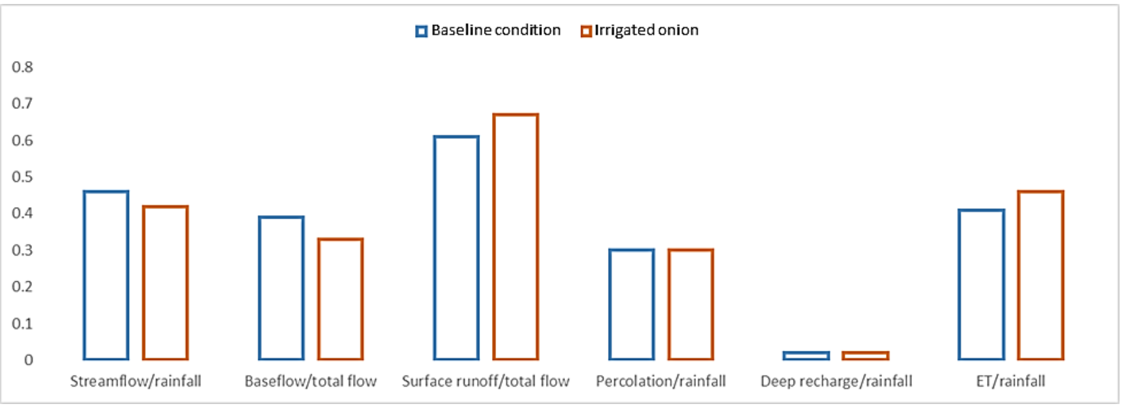

**Figure 6.** Water balance partitioning for the Dangeshta watershed for the baseline cropping system without irrigated onion and for the same cropping system with irrigated onion.

Irrigation of dry-season onion caused a slight reduction in average stream flows simulated by SWAT at the outlet of the watershed. The average monthly stream flow for the non-irrigated baseline scenario from 1995 to 2013 was 1.24 $m^3$/sec. Addition of irrigated onion to the cropping system during this same time period reduced the average monthly stream flow by 8% to 1.14 $m^3$/sec, and also produced minor reductions in peak flows (fig. 7). The increase in fertilization from baseline to recommended rates did not change average monthly stream flow. These results suggest that implementation of SSI on 856 ha of the 5150 ha in the watershed (all cropland with less than 8% slope) to produce high-value, dry-season crops should not compromise downstream flows.

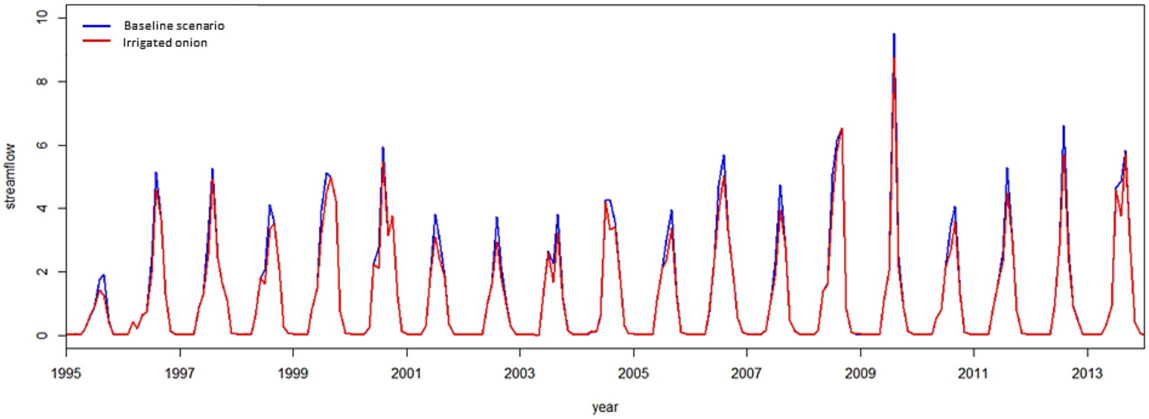

**Figure 7.** Stream flow at the outlet of the Dangeshta watershed for the baseline cropping system and for the same cropping system with irrigated onion.

**Crop yields.** Calibrated APEX cereal yields were similar to those estimated by SPAM (fig. 8). Once APEX crops were calibrated, the crop parameters were transferred to SWAT. Calibrated crop yields for 24-year weather were transferred to FARMSIM for socio-economic analyses.

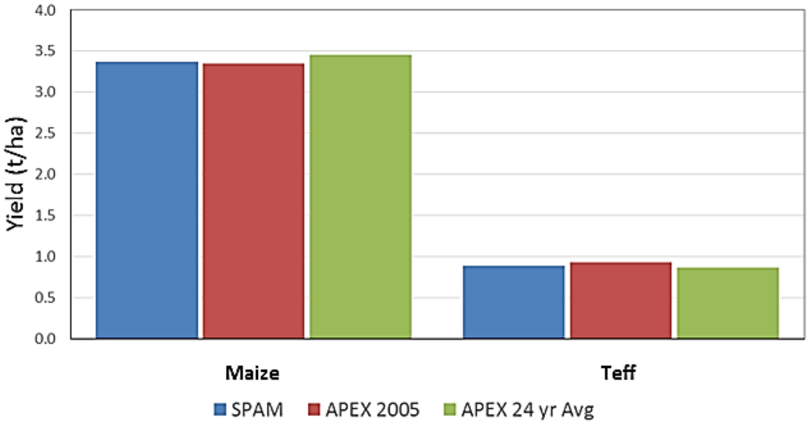

**Figure 8.** Comparison of maize and teff yield from SPAM 2005 with APEX-simulated yields in 2005 and APEX-simulated yields averaged over the 24-year period (t/ha dry weight).

APEX-simulated crop yields of maize were greater but more variable over the 24-year period than those of teff (fig. 9).

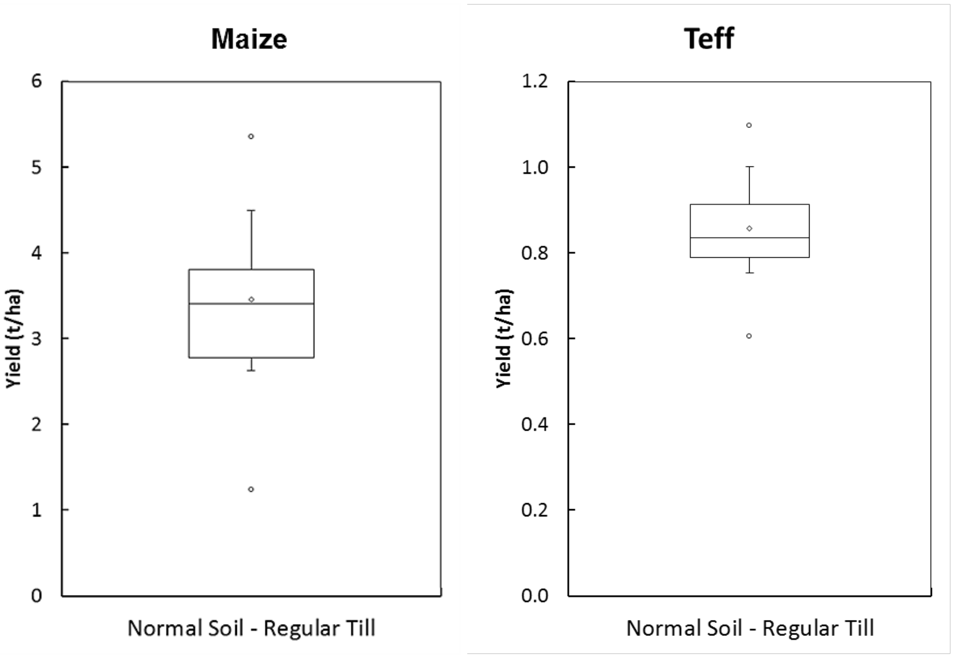

**Figure 9.** APEX-simulated crop yield for normal soil and current tillage practices.

**Runoff and Soil Erosion.** Simulated field-scale runoff and edge-of-field sediment yield were simulated with APEX. Simulated edge-of-field runoff and soil erosion were lower for teff than for maize (fig. 10), reflecting the fact that crops like teff with closely spaced rows are given a smaller curve number than crops like maize that are grown in widely spaced rows. Soil erosion rates were high, suggesting that soil conservation research and extension should be priority activities in this region of Ethiopia.

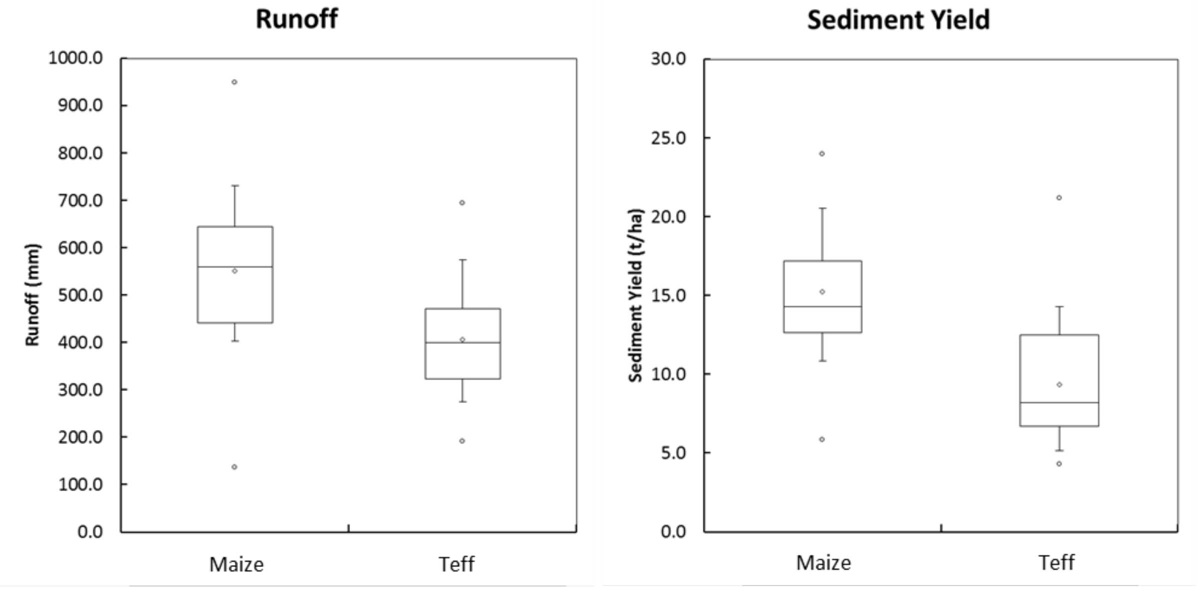

**Figure 10.** Runoff and sediment yield for rain-fed monocrops.

**Irrigation effects.** There is often a strong relationship between the amount of irrigation water supplied to a crop and that crop's yields. However, the relationship is sensitive to crop, land, soil, weather, and management practices (Vaux and Pruitt 1983; de Juan et al. 1996; Brumbelow and Georakakos 2007). Because APEX and SWAT simulate the interacting effects of soil, land, weather and management on the crop, they can be used to simulate complex combinations of natural resource and management variables.

We simulated the production of irrigated onions with the automatic irrigation feature of APEX. We set model parameters to simulate irrigation at several plant stress levels, ranging from near zero (non-stressed) to 85% (highly stressed). Equation 1 and figure 11 describe the simulated relationship between onion yield and the quantity of irrigation water applied.

$$Y = -0.000005x^2 + 0.0028x + 0.657 \ (R^2 = 0.95) \qquad [\text{Eq. 1}]$$

Where: Y is crop yield (t/ha) and x is irrigation water applied (mm)

As expected, onion yields increase with applied water up to 391-392 mm:

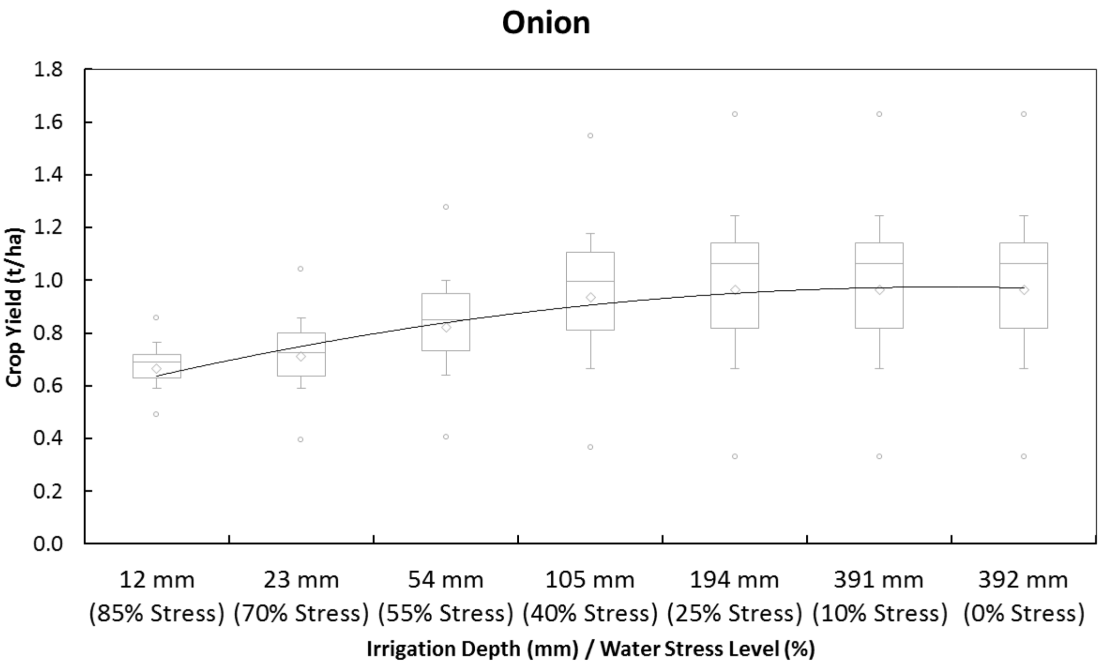

**Figure 11.** Onion yield (t/ha oven-dry weight) in Dangeshta as a function of irrigation water applied.

In Dangila, irrigation from hand-dug, shallow wells is common. Water supply for irrigation from these wells is contingent on well depth, each well's recharge rate, and the capacity of pumps to lift water. The depth and recharge rates of shallow wells are quite variable and they are dependent on the soil and the geologic and surface characteristics of each location.

For the following analysis, we assumed that shallow ground water was 10 m below the surface, and the aquifer was adequate to supply the irrigation water required by the crop. Therefore, irrigation water supply was limited by the capacity of the pumping technology. In Ethiopia, human power, animal traction, and motor pumps are used to pump irrigation water. Using the irrigations requirements for onion estimated with APEX (Equation 1) and pumping rates for a pulley and bucket (0.25 l/s), a hand-powered pump (0.6 l/s) and a motor pump (1.36 kW; 14.0 l/s) (pumping rates taken from Awulachew et. al 2009; Brikke, F. and M. Bredero 2003), we estimated the times required to irrigate 0.25 ha with each method.  For example, to achieve a mean onion yield of approximately 8 t/ha (fresh weight) on 0.25 ha required application of about 50 mm of irrigation water (0.05 Ml /ha). To deliver this quantity of water to the crop over the growing season required 60.2 hours with a pulley and bucket, 25.1 hours with a hand-powered pump and 1.1 hours with a motor pump.

**Economic Analyses.** NPV is an indicator that assesses the feasibility and profitability of an investment or project over a certain period of time. Comparison of the CDFs of the six scenarios indicated that it is worth investing in certain methods of irrigation and recommended fertilizer application (fig. 12a). The use of recommended fertilizers on grain crops, in combination with onion irrigated with animal-powered or motor pumps (Alts. 3 and 4) were by far the most economically profitable alternatives (their CDF values lie far to the right of the other scenarios for all 500 draws of the simulation model). The next-best-performing scenarios involved the application of recommended fertilizers and irrigation with a hand-operated or solar  pump (Alts. 2 and 5), which performed slightly better than the baseline or the pulley-and-bucket system with recommended fertilizers (Baseline and Alt. 1). Note that the pulley-and-bucket system and the baseline scenario (without irrigation) were the lowest performing scenarios, and produced equivalent NPV values.

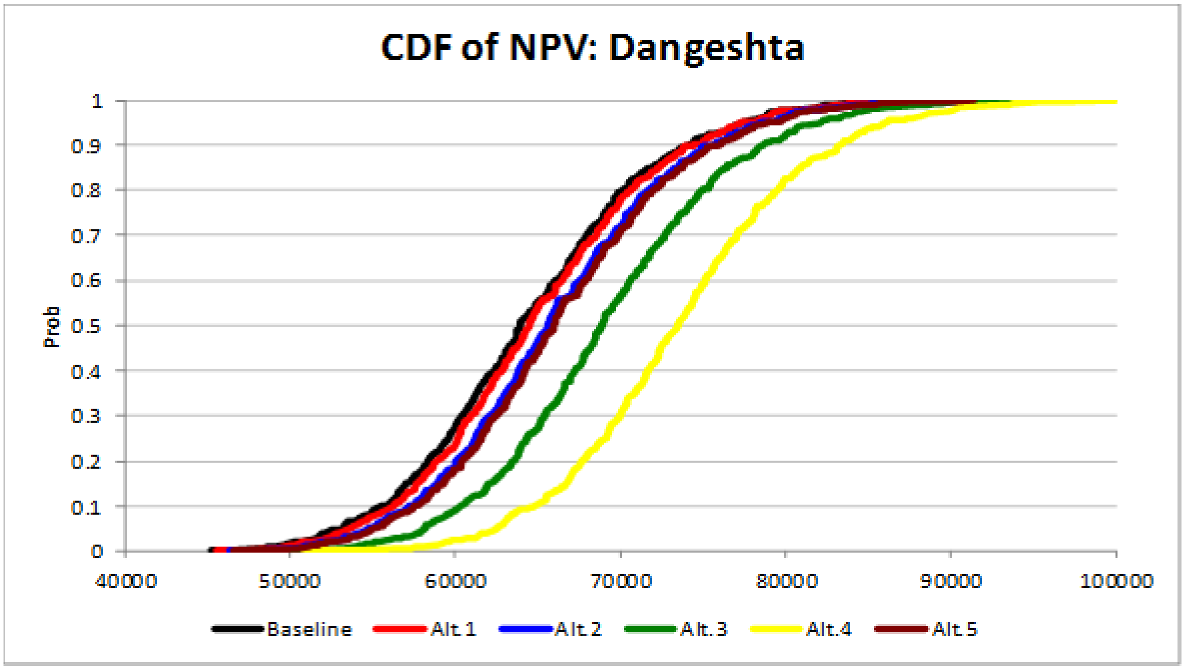

**Figure 12a.** Net present value for the six scenarios

The stoplight chart presents the year-three probabilities of NPVs of less than 64,000 Ethiopian Birr (ETB) (red), greater than 71,000 ETB (green), and between the two target values (yellow) for the six scenarios. The target values are the averages of NPV for the baseline scenario (lower bound) and the best-performing alternatives (Alts. 3 and 4) (upper bound). For a farmer using the baseline scenario, there was a 51% chance that NPV would be less than 64,000 ETB, and only a 17% chance that NPV would exceed 71,000 ETB (fig. 12b). For farmers who implemented animal-powered and motor pump irrigation (Alts. 3 and 4), the probability that NPV would exceed 71,000 ETB was 39% and 64%, respectively. The main barrier for the best-performing scenario (Alt. 4) was the initial investment in the water-lifting technology. The cost of a motor pump (approximately 6,400 ETB) is about twice the cost of an animal-powered (approximately 3,400 EB). Since most farmers already own large animals like bullocks, the initial investment costs of an animal-powered pump are negligible by comparison; however, the NPV results strongly suggest that the investment in motor pumps would pay large dividends in increased income and wealth. Motor pumps seem to be more profitable than solar pumps, given the higher entry costs of the latter; however, the comparatively lower operating, maintenance, and environmental costs of solar technologies may make them more promising in the long-term.

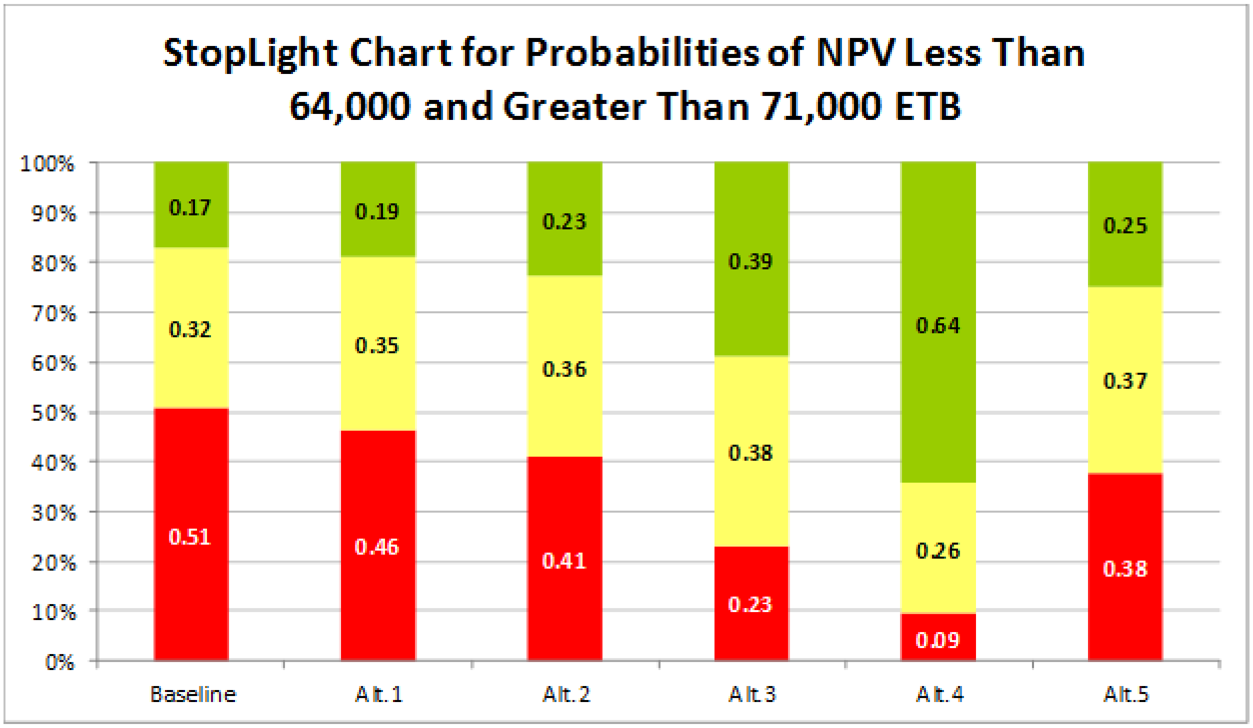

**Figure 12b.** Stoplight chart for the NPV for the six scenarios

The CDF graph for annual net cash farm income (NCFI) shows a clear difference between the two best-performing scenarios—animal-powered and motor pump irrigation (Alt. 3 and 4)—and the rest of the scenarios (fig. 13a). Alternatives 3 and 4 generated higher levels of NCFI at all probability levels, making them the preferred scenarios for decision makers. Irrigation by other water lifting technologies (pulley, hand-powered, solar-powered) and the baseline scenario did not show differences in NCFI. Note that the baseline scenario (without irrigation) performed slightly better than alternative 1, suggesting that investing in the pulley-and-bucket system to cover more irrigable onion land would cost more than growing non-irrigated onions.

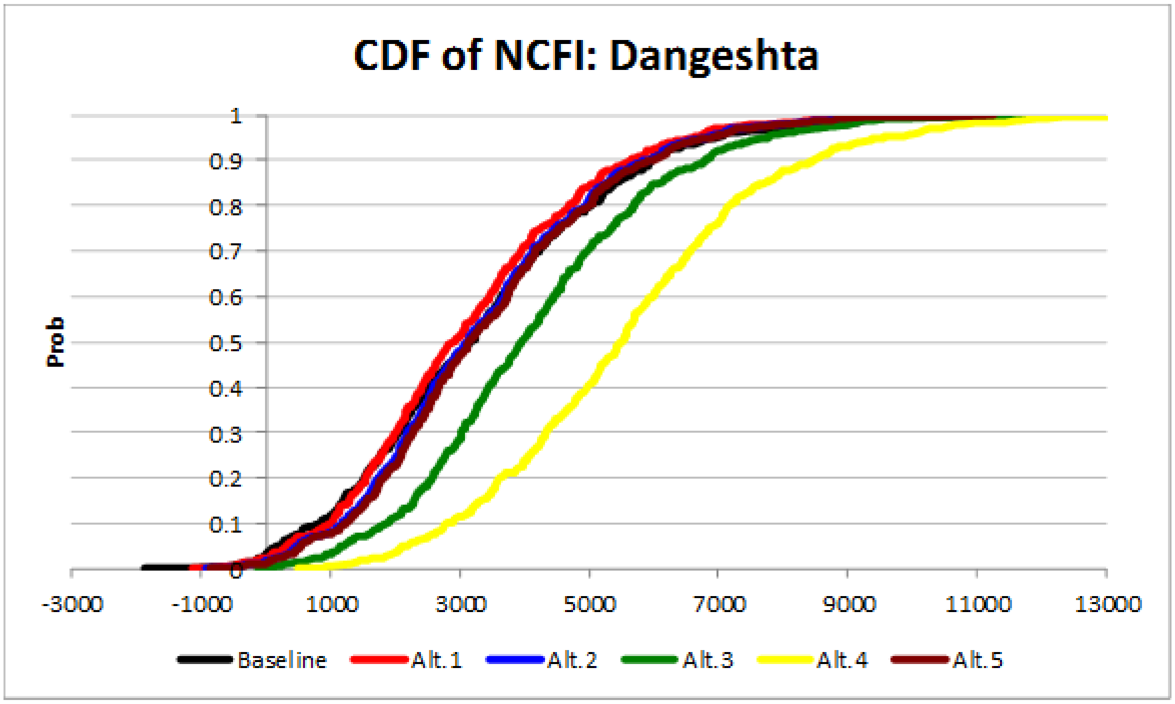

**Figure 13a.** Net cash farm income for the six scenarios

The stoplight chart for NCFI in year three of the planning horizon shows that, in the baseline scenario, there was a 51% probability that a farm would generate NCFI of less than 3,200 ETB, and a 20% chance that NCFI would exceed 5,000 ETB (fig. 13b). A farm that irrigated with a pulley and bucket (Alt. 1) was even more likely to generate NCFI of less than 3,200 ETB (55%) than a farm that did not irrigate, because of the costs involved in using the irrigation system. For a farm that adopted hand-operated pump or solar pump irrigation (Alts. 2 and 5), the likelihood of generating NCFI of less than 3,200 ETB was 52% and 51%, respectively. In contrast, for a farm that adopted animal-powered or motor pump irrigation (Alts. 3 and 4), there was only 34% chance or 14% chance, respectively, that NCFI would be less than 3,200 ETB, and a 29% or 59% chance, respectively, that NCFI would exceed 5,000 ETB.

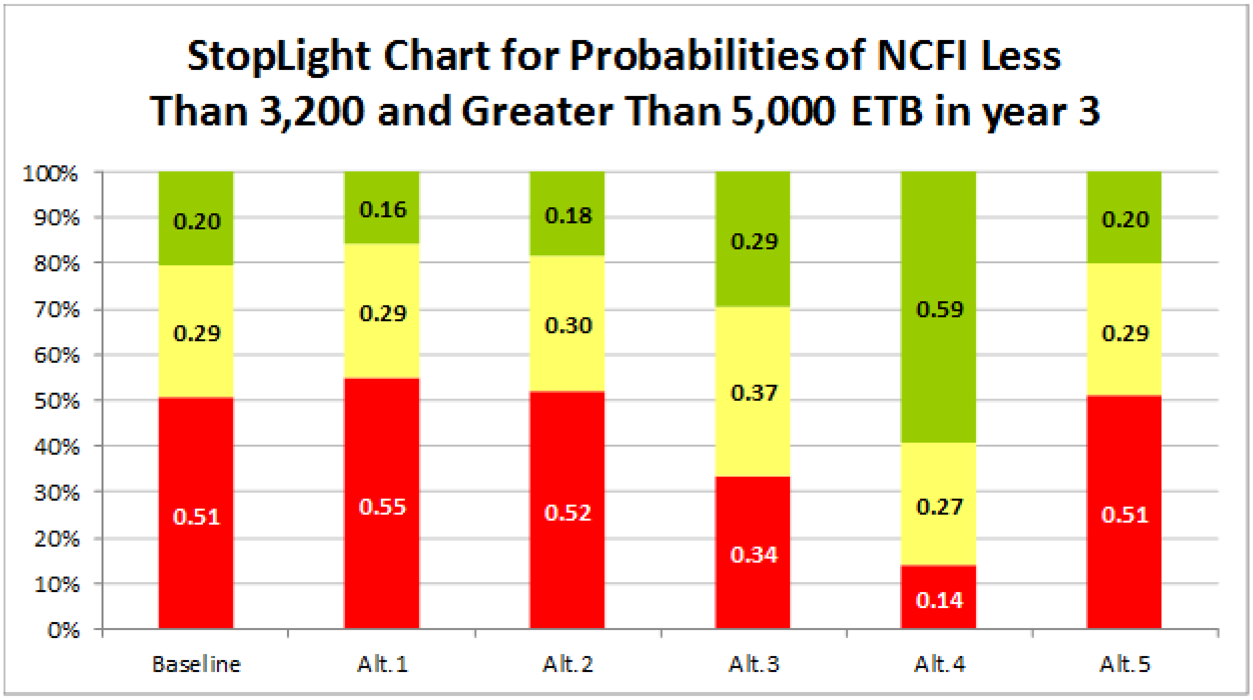

**Figure 13b.** Stoplight chart for NCFI.

The Ending Cash (EC) reserve indicator (fig. 14a) highlighted once again the superior performance of animal-powered and motor pump irrigation (Alts. 3 and 4). The CDF values for alternatives 3 and 4 lie entirely to the right of the baseline and all other scenarios, indicating that a farmer who invested in these technologies was far more likely to have higher cash reserves at the end of the five-year planning horizon. A farmer who irrigated with a hand-operated or -solar pump (Alt. 2 and 5) had slightly higher EC reserves than one who did not irrigate or who irrigated with a pulley and bucket (Baseline and Alt. 1). Note that, again, a farmer who did not irrigate (Baseline) performed as well as or slightly better than one who adopted pulley-and-bucket irrigation.

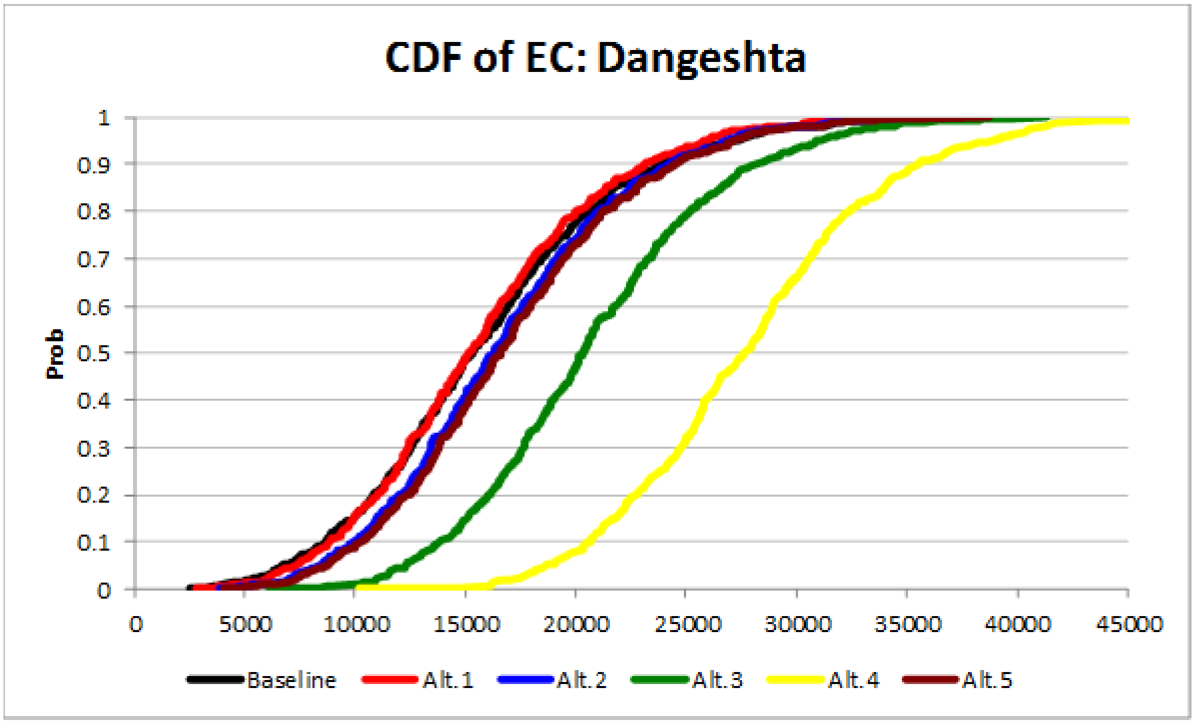

**Figure 14a.** Ending cash reserve (EC) for six scenarios

The stoplight chart for EC reserves (fig. 14b) shows that, in year five, a farmer who did not irrigate (baseline) had a 51% probability of having EC reserves of less than 15,500 ETB (baseline average) and a 10% probability of having EC reserves of more than 24,000 ETB. In contrast, a farmer who irrigated with an animal-powered or a motor pump (Alt. 3and 4) had a 26% or 75% probability, respectively, of having EC reserves of more than 24,000 ETB and a 18% or 0% probability, respectively, of EC reserves under 15,500 ETB. Again, a farmer who irrigated with a pulley and bucket (Alt. 1) was more likely to generate EC reserves under 15,500 ETB than one who did not irrigate at all.

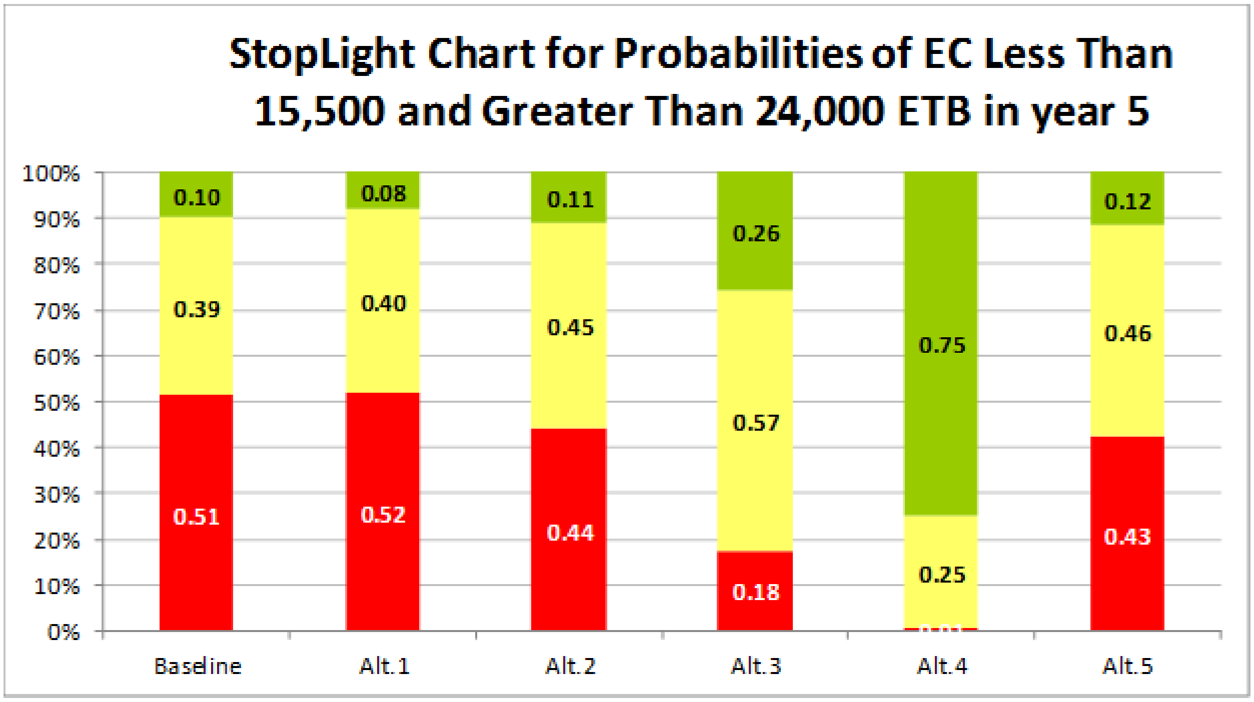

**Figure 14b.** Stoplight chart for the ending cash reserves (EC)

Since grain crops in the region are mainly used for family consumption, the increases in farm revenue in each of the alternative scenarios were due almost entirely to the sale of surplus irrigated onion. In alternative scenario 4 , the forecasted sales of irrigated onion would contribute, on average, 46% of the total crops receipts and 100% of the net cash (profit) for the five-year planning horizon. Maize contributed almost equally to onions at about 43% of crop receipts, but given its high costs of production, had a negative net cash contribution.

**Nutrition.** In general, adoption and proper use of SSI lead to an increase in the quantity and variety of crops produced. The implications for nutrition vary according to the types of crops grown and consumed; however, surplus food can be sold at market, and resulting revenues can be used to buy food items needed to complement nutrition requirements.

In this case, the simulation results showed that levels of calcium increased in all of the alternative scenarios as compared to the baseline scenario; however, there was no corresponding increase in calories, protein, fat, iron, or vitamin A. This lack of improvement may be explained by two factors.

First, the limited number of grain crops simulated (here, only teff and maize) meant that the variety of crops consumed and their nutritional contribution were limited. Second, the SSI interventions (irrigating dry-season onions) had limited impact on grain yields, and increased fertilization rates only impacted teff yields. In all of the alternative scenarios, the minimum requirements per adult equivalent per day were met for calories, protein, and iron; however, nutritional deficiencies in fat, calcium, and vitamin A persisted. Clearly, families in Dangila will require food supplements (whether obtained through purchase or farming) to meet minimum nutritional requirements for fat, calcium, and vitamin A. The analysis and comparison of alternative irrigated crops and their effects on farm-family nutrition are subjects for proposed future study.

## Conclusions

In Dangila, ILSSI proposed maximizing SSI of high-value, dry-season crops, using shallow groundwater and one of five alternative water-lifting technologies. Analysis and simulation with integrated and interactive IDSS models enabled us to assess:

- the amount of land appropriate for the proposed SSI interventions
- the amount of irrigation water required for the proposed SSI interventions
- the complete hydrology of the watershed with and without the proposed SSI interventions
- the rate of soil erosion with and without the proposed SSI interventions
- the impact of various farming practices (such as current versus recommended fertilization application rates) on crop yields, watershed hydrology, and farm economies, when implemented in conjunction with the proposed SSI interventions
- the economic viability and nutritional benefits to typical farm families of implementing the proposed SSI interventions

IDSS simulations indicated that the proposed SSI interventions can be sustained by the shallow groundwater recharge without affecting long-term groundwater storage, and would not compromise the environmental health of the watershed. The proposed SSI interventions would use less than 20% of the annual shallow groundwater recharge. Moreover, the proposed SSI interventions would reduce stream flow by only 8%, and should not compromise downstream flows.

The proposed SSI interventions (especially when combined with increased fertilization rates) increased wet-season grain yields significantly, presumably because crop rotation operations implemented in conjunction with the proposed SSI scenarios resulted in improvements in soil organic matter. Simulations also predicted that dry-season onion yields would increase with applied irrigation water of up to 391-392 mm (the irrigation depth required to reduce plant stress levels to 0%).

Economic analyses were conducted to estimate the effects of the proposed SSI interventions (in conjunction with the simulated, improved cropping system) on farm-family economics. These analyses compared the costs and benefits of five alternative water-lifting technologies: pulley-and-bucket irrigation, and rope-and-washer pumps operated by hand, animal, gasoline motor, and solar power. Of the alternative technologies examined, none of the water lifting technologies met the irrigation water requirements for the proposed SSI interventions in Dangeshta kebele (i.e., for all 856 ha of irrigable land in the kebele). However, implementation of the proposed SSI interventions using motor pumps produced by far the highest NPV, NCI, and EC reserves of the six scenarios simulated (including the baseline, non-irrigated scenario). In each of the alternative scenarios, the increase in farm revenue was due almost entirely to the sale of surplus irrigated onion. Where motor or solar pumps were used, the forecasted sales of irrigated onions contributed, on average, 46% of the total crops receipts and 100% of the net cash (profit) for the five-year planning horizon.

The main barrier to SSI with motor or solar pumps is the initial investment in the technology. The initial investment costs of an animal-powered pump or hand-operated pump are much lower; however, the NPV results strongly suggest that an investment in motor pumps would pay large dividends in increased income and wealth.  Moreover, individual farmers might benefit by spreading entry costs over more irrigated area, perhaps by having two or three farmers share a motor pump. Accordingly, in Dangila, ILSSI recommends implementing the proposed SSI interventions using motor pumps.

Despite improvements in farm-family economics resulting from the proposed SSI interventions, nutritional deficiencies persisted under the simulated, improved cropping system. We would also, therefore, propose expanding the types of crops irrigated in the dry season to increase family nutrition and net cash income, but only if such crops can be irrigated without causing excessive soil erosion or reduction in environmental benefits. The evaluation and comparison of alternative farming systems, including the types of crops grown, recommended management practices, and associated impacts on soil erosion and environmental benefits, are subjects for proposed future study.

# REFERENCES

Awulachew, S. B., P. Lemperiere, and T. Tulu. 2009. *Pumps for small-scale irrigation: Improving productivity and market access (IPMS) of Ethiopian farmers.* Addis Ababa: International Livestock Research Institute.

Brikke, F., and M. Bredero. 2003. Water-Lifting devices. In *Linking technology choice with operation and maintenance in the context of community water supply and sanitation*, ed. F. Brikke and M. Bredero, 42-63. Geneva: World Health Organization.

Brumbelow, K., and A. Georgakakos. 2007. Determining crop-water production functions using irrigation gradient algorithms. *Agric. Water Management* 87(2): 151-161.

Chen, Y., J. Yu, and S. Khan. 2010. Spatial sensitivity analysis of multi-criteria weights in GIS-based land suitability evaluation. *Environ. Model. Softw.* 25, doi:10.1016/j.envsoft.2010.06.001.

Central Statistical Authority of Ethiopia. 2012. http://www.csa.gov.et/ (area, production and agricultural practice documents; accessed March 2015).

CSA. See Central Statistical Authority of Ethiopia.

de Juan, J. A., J. M. Tarjuelo, M. Valiente, and P. Garcia. 1996. Model for optimal cropping patterns within the farm based on crop water production functions and irrigation uniformity: Development of a decision model. *Agric. Water Management* 31(1-2): 115-143.

Dile, Y. T., and R. Srinivasan. 2014. Evaluation of CFSR climate data for hydrologic prediction in data-scarce watersheds: An application in the Blue Nile River Basin. *J. Am. Water Resour. Assoc.*, doi: 10.1111/jawr.12182.

EIAR. *See* Ethiopian Agricultural Research Institute.

ENMSA. *See* Ethiopian National Meteorological Services Agency.

Ethiopian Agricultural Research Institute. 2007. *Crop technologies usage* [in Amharic]. Addis Ababa: EIAR.

Ethiopian Ministry of Water and Energy. 2012. *Hydrological data*. Addis Ababa: MoWE.

Ethiopian National Meteorological Services Agency. 2012. *Meteorological data*. Addis Ababa: ENMSA.

FAO. *See* Food and Agriculture Organization of the United Nations.

Food and Agriculture Organization of the United Nations. Natural Resources Management and Environment Department, Land and Water Development Division. 1997. Soil and terrain suitability for surface irrigation. Chap. 3 in *Irrigation potential in Africa: A basin approach.* Rome: FAO. http://www.fao.org/docrep/w4347e/w4347e08.htm.

HarvestChoice. 2014. *Crop Production: SPAM*. Washington, DC and St. Paul, MN: International Food Policy Research Institute. Available online at http://harvestchoice.org/tools/crop-production-spam-0).

IAASTD. *See* International Assessment of Agricultural Knowledge, Science and Technology for Development.

International Assessment of Agricultural Knowledge, Science and Technology for Development. 2009. *Summary for Decision Makers of the Sub-Saharan Africa Report, Assessment*. Johannesburg: IAASTD.

Kassam, A., N. Lutaladio, T. Friedrich, E. Kueneman, M. Salvatore, M. Bloise, and J. Tschirley. 2012. *Natural resource assessment for crop and land suitability: An application for selected bioenergy crops in Southern Africa region.* Rome: FAO, Plant Production And Protection Division.

Mati, B., T. Bock, M. Malesu, E. Khaka, A. Oduor, M. Nyabenge, and V. Oduor. 2007. *Mapping the potential of rainwater harvesting technologies in Africa: A GIS overview of development domains for the continent and ten selected countries. Technical Manual No. 6*. Nairobi: World Agroforestry Centre (ICRAF), Netherlands Ministry of Foreign Affairs.

NASA Landsat Program. 2003. Landsat ETM + scene [LC81700522013157LGN00, SLC-Off]. Lake Tana, Ethiopia: USGS.

Nederstigt, J. and A. van der Wal. 2011. *Rope Pump Manual: Technical Training Handbook on Rope Pump Production, Installation and Maintenance*. Papendrecht, Netherlands: PRACTICA Foundation. http://practica.org/wp-content/uploads/2014/08/ropepump-manual-EN-full.pdf

MoWE. *See* Ethiopian Ministry of Water and Energy.

USGS EarthExplorer. http://earthexplorer.usgs.gov/ (accessed 12.10.15).

Vaux, Jr., H.J., and W. O. Pruitt . 1983. Crop-water production functions. In *Advances in Irrigation Vol. 2*, ed. Daniel Hillel, 61-93. New York: Academic Press.