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Ex Ante Analysis of Small-Scale Irrigation Interventions in Adami Tulu

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The authors wish to acknowledge the following agencies and individuals who were instrumental in providing data and expert advice for this report: the Ethiopian Ministry of Water, Energy and Irrigation; the Ethiopian National Meteorological Services Agency; Immaculate Omondi and Adie Aberra of the International Livestock Research Institute; Mekonnen Dawitt and Simone Passarelli of the International Food Policy Research Institute; and Meneyahel Zegeye Tesfaye, an instructor at Wachemo University and M.Sc. student at Arba Minch University.

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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 Adami Tulu, a Feed-the-Future woreda in the Oromia region of Ethiopia. Farm-family livelihoods in the area are derived from mixed-subsistence farming, including cultivation of a main crop of cereals in the rainy season. Some families also produce irrigated vegetables in the dry season. SSI interventions can aid in the effective use of limited natural resources; however, groundwater potential in the area is modest. Moreover, decision makers have historically lacked means to assess the effects of increased SSI on crop production, farm-family economics, and environmental services.

In Adami Tulu, 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, teff, and wheat, 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 maize, teff, or wheat, fertilized at government-recommended rates, plus an irrigated, dry-season double crop (onion) grown 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 of watershed-scale hydrology suggested that recharge of the shallow aquifer may be inadequate to support a large amount of SSI in Adami Tulu. The average annual shallow groundwater recharge under baseline conditions was less than 21 mm across the 3070-ha watershed, and the average, area-weighted, annual irrigation required by the proposed SSI interventions was almost 89 mm. Since groundwater withdrawals would far outpace average groundwater recharge, we can conclude that the proposed SSI interventions may not be sustained by the shallow groundwater recharge without affecting long-term groundwater storage. It must be noted that some soils in the watershed may generate less runoff and greater recharge of the shallow aquifer, and recharge may occur via stream banks during the wet season. If such areas occur within the watershed, they could be used for SSI; however, this study was not detailed enough to identify such areas.

In contrast to the modest groundwater recharge rates, mean annual surface runoff across the watershed was estimated to be more than 250 mm, far exceeding the almost 89 mm of irrigation water required for the proposed SSI interventions. Therefore, surface runoff might be captured in ponds and

used either directly or to recharge shallow groundwater. Analyses of potential sites and likely costs and benefits of irrigating from small water-harvesting structures were beyond the scope of this study but could be addressed in future research.

Should they prove sustainable, the proposed SSI interventions (especially when combined with increased fertilization rates) were shown to increase wet-season grain yields. As expected, the proposed SSI interventions also resulted in significant onion yields, which were shown to increase with applied irrigation water of up to 150 mm (the irrigation depth required to reduce plant stress levels to 0%).

For purposes of analyzing the economic effects of the proposed SSI interventions (in conjunction with the simulated, improved cropping system) in Bochesa, a kebele in Adami Tulu woreda, we assumed that locations could be identified with sufficient recharge of shallow groundwater to support such interventions. These analyses also 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 technologies examined, only motor pumps met the irrigation water requirements for the proposed SSI interventions (i.e., for all 531 ha of irrigable land in the kebele). Implementation of the proposed SSI interventions using motor and animal-powered pumps produced 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 motor pumpswere used, the forecasted sales of irrigated onions contributed, on average, 96% of the total crops receipts and 100% of the net cash (profit) for the five-year planning horizon.

Assuming that future studies identify locations with sufficient recharge of shallow groundwater to support the proposed SSI interventions, the irrigation water requirements for these interventions could be met with motor pumps. Motor pumps can cover three times the area of animal-powered pumps, but with high entry and operational costs. Individual farmers might benefit by spreading entry costs over more irrigated area, perhaps by having two or three farmers share a 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 area and types of crops irrigated in the dry season to increase family nutrition and net cash income, but only if the additional area and crops can be irrigated without depleting the shallow aquifer, causing environmental degradation, or reducing environmental benefits provided by the land. Additional analyses would be needed to (1) identify local areas within the watershed with adequate groundwater recharge to support SSI, and (2) evaluate the hydrologic and economic feasibility of constructing small dams to capture runoff for use for SSI. 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 also 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 Adami Tulu, a Feed-the-Future woreda in the East Shewa zone of the Oromia region of Ethiopia. Bochesa, one of the rural kebeles located in the woreda, is located about 150 km south of Addis Ababa. 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 531 ha of cropland in Bochesa kebele, and about 187 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 Adami Tulu woreda are shallow groundwater and lakes. Currently, a number of households irrigate using a variety of lifting technologies, including rope-and-washer pumps, treadle pumps and motor pumps.

Rapidly increasing population, economic growth, and the movement of the rural population to cities provides 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 Bochesa’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 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, teff and wheat) 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 3070-ha watershed. (As noted above, onion was chosen as a 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 the effects of two fertilizer rates on maize, teff, and wheat, as well as seven irrigation amounts. FARMSIM used crop yields from APEX and socioeconomic data from surveys to simulate the effects on farm-scale economics of the proposed SSI interventions and various water-lifting technologies that could be used to implement these 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.

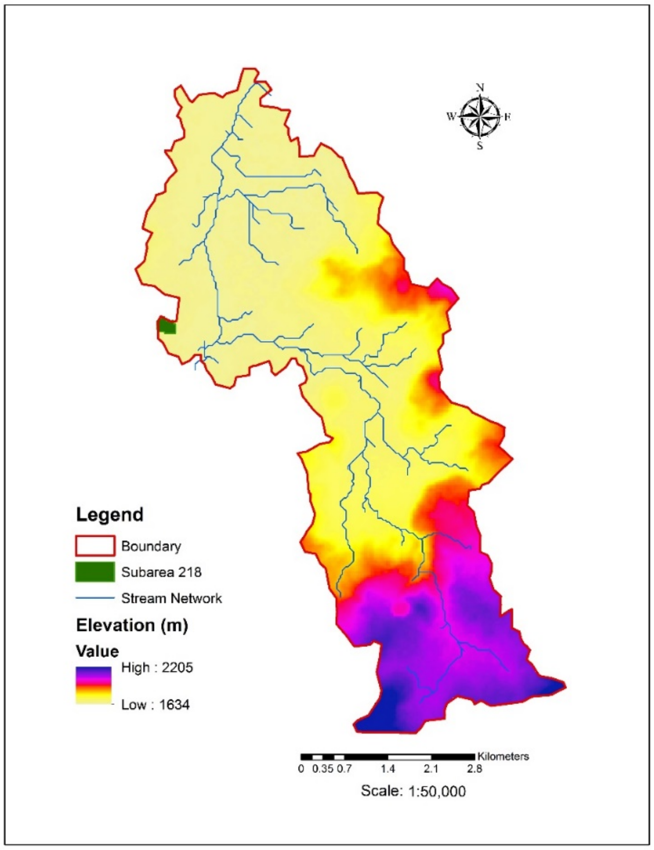

Figure 1. Bochesa watershed boundary, main streams and Subarea 218, simulated with APEX.

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 (NASA Landsat Program 2003) was 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 Andisols (An). Soil parameters used by SWAT and APEX were estimated with the SWAT soil parameter generating tool.

d) Thirty-five years of daily weather data, from 1979 to 2013, obtained from the National Centers for Environmental Prediction's Climate Forecast System Reanalysis (CFSR) climate data (Saha et al. 2010; Globalweather 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 Bochesa watershed.

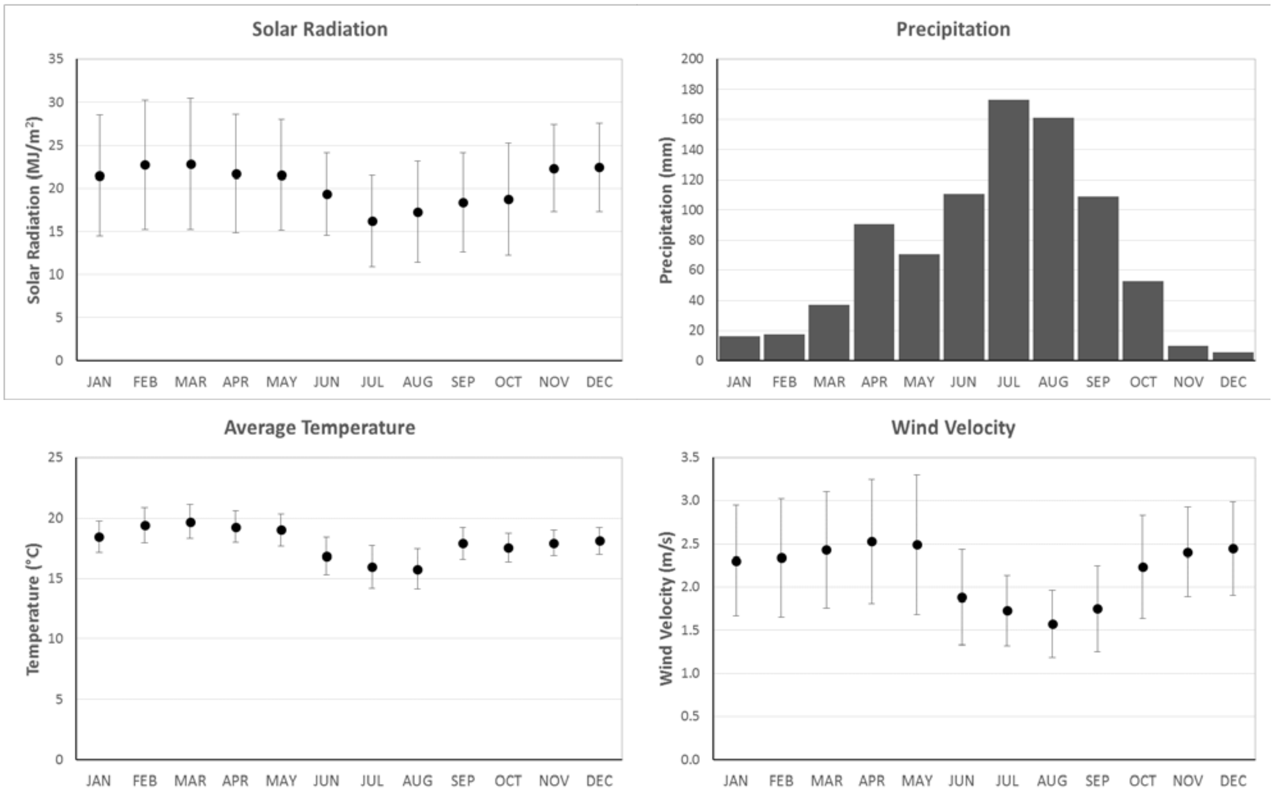

Figure 2. Monthly weather data for Bochesa from 1979 - 2013.

Subbasin Delineation. SWAT divided the 3070-hectare Bochesa watershed into 533 subbasins (referred to as subareas in APEX) with areas ranging from one to ten hectares. The SWAT watershed discretization and its calibrated results were used to calibrate APEX for runoff and sediment yields. The subbasins/subareas were defined to account for the International Water Management Institute's field studies, and to accommodate small-scale water management interventions. 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 218 (equivalent to SWAT's Subbasin 218) was selected for the simulation with APEX. Subarea 218 is 6.12 hectares, characterized as cropland, and entirely composed of An clay soils, with a depth of 1.6 m, and a slope of 0.053 m/m. The latitude and longitude of its centroid was: 7.864 and 38.723 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, teff and wheat as simulated by SWAT and APEX. The baseline maize and teff crop management schedules were based on farmer interviews and expert opinion. Fertilizer rates were based on International Food Policy Research Institute surveys.

Table 1. Crop management data used by APEX for maize, teff and wheat in the Bochesa watershed.

Date	Maize Practice	Amount
May-1	Tillage	
May-30	Tillage	
Jun-20	Tillage	
Jun-20	1st stage urea fertilizer application	32.9 kg/ha
Jun-20	DAP fertilizer application	57.0 kg/ha
Jun-20	Planting	
Aug-1	2nd stage urea fertilizer application	32.9 kg/ha
Oct-25	Harvest	

Date	Teff and Wheat Practice	Amount
May-1	Tillage	
May-30	Tillage	
Jul-22	1st stage urea fertilizer application	24.1 kg/ha
Jul-22	DAP fertilizer application	38.0 kg/ha
Jul-22	Planting	
Aug-22	2nd stage urea fertilizer application	24.1 kg/ha
Dec-5	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 within the watershed designated for agricultural land use and with slopes of less than 8% (as recommended by FAO). A total area of approximately 1594 ha (531 ha within the kebele) 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 Bochesa 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 Bochesa kebele, fertilizer rates for maize, teff, wheat and onion are low. Accordingly, APEX was also used to simulate crop yield responses to fertilizer application at recommended rates (table 3). However, increasing fertilizer rates did not increase grain yields, suggesting that current farmer fertilizer rates are adequate, and could even be excessive. To test this hypothesis, APEX was also used to simulate grain yields with fertilizer rates 20% less than current rates.

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 Meki gauging station (MoWE 2012). Complete observed stream flow data were available only from 1997 to 2003; thus, the observed stream flow data from this period were used to calibrate SWAT. The Nash-Sutcliff efficiency (NSE) and Percent Bias (PBIAS) values were 0.31 and 39.7%, respectively. According to Moriasi et al. (2007), SWAT showed less satisfactory performance in simulating the Meki river basin. This is mainly related to poor quality observed weather and stream flow data in the Meki watershed. Since all the relatively better-quality observed stream flow data were used for calibration, validation of the model was not performed. 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, teff and wheat were obtained from the 2005 Spatial Production Allocation Model (SPAM) dataset (HarvestChoice 2014) for an area including Bochesa (table 4). In SPAM, teff is included in the “other cereals” category, but it is by far the most important representative of that group in Bochesa. (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 wheat for the 2005 cycle (HarvestChoice 2014). Statistical analyses could not be performed for calibration of yields since only one SPAM grid cell covered the Bochesa watershed. Onion yield estimates used in model calibration were acquired from the Ethiopian Central Statistical Agency (2012).

Table 4. SPAM estimates of maize, teff and wheat yields for grid cell associated with the Bochesa watershed.

Region	Cell ID	Maize	Teff	Wheat
Adami	4257824	3.10 t/ha	1.36 t/ha	1.94 t/ha

Economic Analyses. FARMSIM was used to provide economic analyses of several promising SSI technologies 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 wheat crops was at rates currently used by farmers because government-recommended rates did not increase grain yields simulated by APEX. Onions were fertilized at government-recommended rates.

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

Baseline: no irrigation
Alt.1: pulley-and-bucket pump irrigation
Alt.2: hand-operated rope-and-washer pump irrigation
Alt.3: animal-powered rope-and-washer pump irrigation
Alt.4: gasoline motor-powered rope-and-washer pump irrigation
Alt.5: solar-powered pump rope-and-washer irrigation

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 irrigation:

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 three and half 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
    - 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)

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[1] Nederstigt and Van del Wal 2011/PRACTICA Foundation

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

[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/

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. Note that only the motor pump was able to provide the required irrigation water to grow onions (at 0% water stress level) for the total 531 ha of irrigable onion land within the kebele. The pulley irrigation system covered only 7.2% of total irrigable land, while the hand-operated, animal-powered, and solar pumps covered 18%, 54%, and 22%, respectively.

Other simulation assumptions

First, 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. Second, the markets were assumed to be accessible and to 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 be equal to 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.”

Results and Discussion.

Hydrology. Our results indicated that there is modest potential for additional SSI in the Bochesa watershed. The mean annual groundwater recharge simulated by SWAT was less than 21 mm (fig. 3), and the mean annual surface runoff was estimated to be more than 250 mm. For the Bochesa watershed, with a catchment area of 3070 ha, the mean annual volumetric groundwater recharge and surface runoff potentials are estimated to be 0.32 million m^3 and 3.4 million m^3, respectively. SSI interventions can aid in the effective use of these limited natural resources.

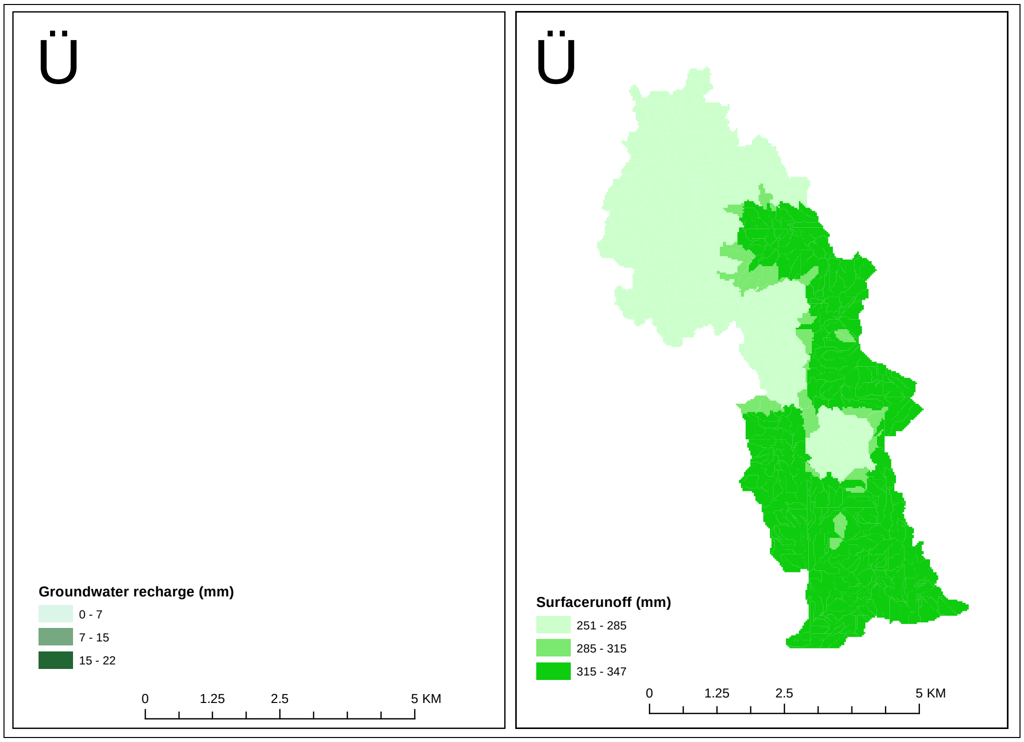

Figure 3. Water resources potential in the Bochesa watershed; a) the average annual groundwater recharge, and b) surface runoff.

Irrigation from shallow groundwater was simulated by SWAT to determine whether shallow groundwater recharge could support irrigation water requirements of irrigated, dry-season onions. The average annual shallow groundwater recharge under baseline conditions was less than 21 mm across the 3070-hectare watershed, and the average annual irrigation was less than 89 mm over the 1594 ha of irrigated onion within the watershed (fig. 4). Since groundwater withdrawals would far outpace average groundwater recharge of the area cropped to onion, we can conclude that irrigation of onion during the dry season may not be sustained by the shallow groundwater recharge without affecting long-term groundwater storage. However, some soils in the watershed may generate less runoff and greater recharge of the shallow aquifer, or recharge may occur via stream banks during the wet season. If such areas occur within the watershed, they could be used for SSI; however, this study was not detailed enough to identify such areas. In contrast, irrigation water requirements constituted only 35% of average annual surface runoff, which was more than 251 mm. Therefore, surface runoff might be utilized by building water harvesting structures that could be used directly for irrigation or to recharge the shallow aquifer. Analyses of potential sites and likely costs and benefits of irrigating from small water harvesting structures were beyond the scope of this study but could be addressed in future research (Dile et al. 2013).

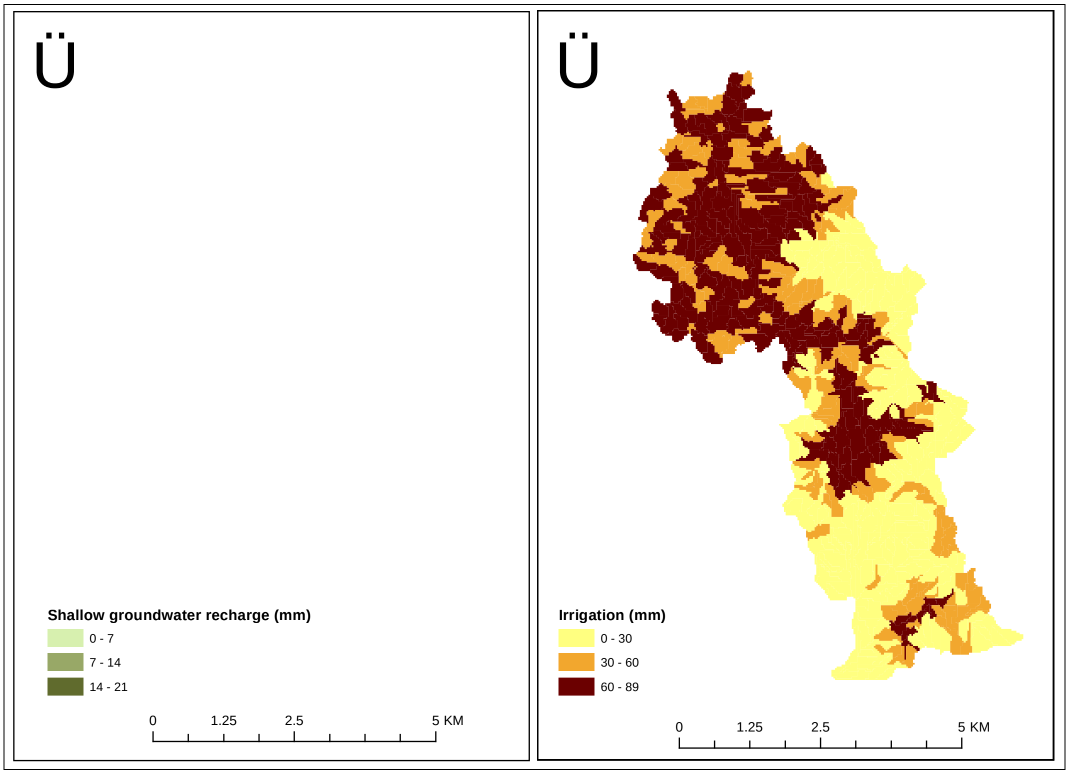

Figure 4. a) Average annual shallow groundwater recharge under baseline conditions, and b) average annual irrigation for cultivating onion during the dry season.

Annual water balance components for maize, teff and wheat estimated by APEX are illustrated in figure 5. The results indicate that evapotranspiration was very similar for wheat, maize and teff, though deep percolation is slightly less where wheat is cultivated.

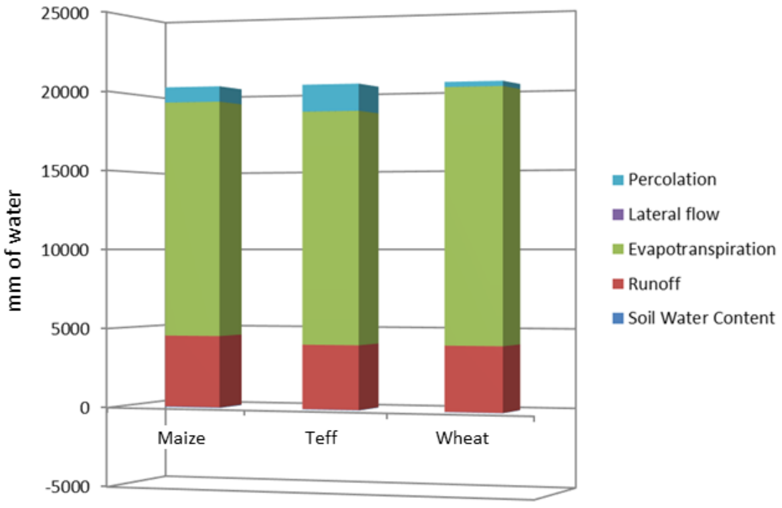

Figure 5. Water balance for maize, teff and wheat in Bochesa watershed estimated by APEX.

The average annual rainfall in the Bochesa watershed for the period 1990 to 2013 was 526 mm. About 39% of the annual rainfall became stream flow and 59% was evaporated back into the atmosphere (fig. 6). Surface runoff contributed 95% of stream flow and base flow contributed 5%.

Figure 6 illustrates the simulated hydrology of the Bochesa 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 did not result in a reduction in stream flow. The percentages of stream flow derived from surface runoff was also the same in both the baseline and irrigated onion scenarios. Actual evaporation increased slightly when irrigated, dry-season onions were cultivated, but the ratios of percolation to rainfall and deep recharge to rainfall did not change. In both scenarios, deep groundwater recharge was negligible.

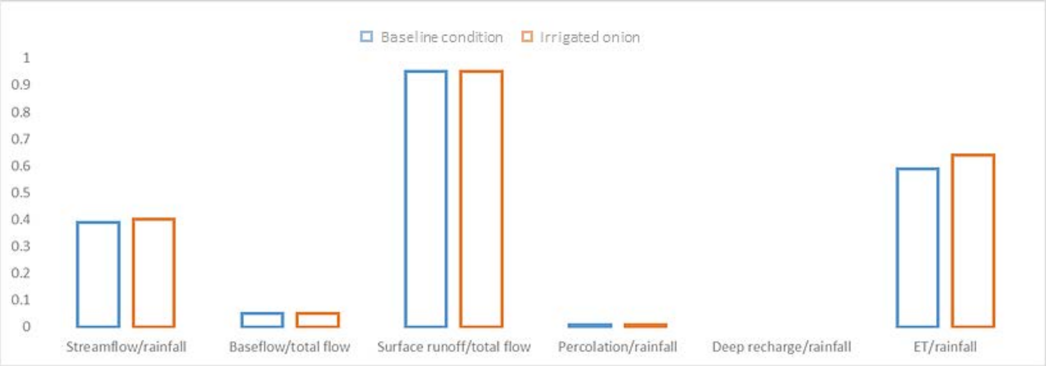

Figure 6. Water balance partitioning for the Bochesa watershed for the baseline cropping system without irrigated onion and for the same cropping system with irrigated onion.

The average monthly stream flow at the outlet of the Bochesa watershed for the non-irrigated baseline scenario from 1995 to 2013 (except model warm-up period) was 0.3 m^3/sec. Irrigation of dry-season onion and increase in fertilization to recommended rates did not cause a reduction in average stream flows simulated by SWAT; in fact, average stream flows were virtually identical for the baseline and irrigated onion scenarios (fig. 7). These results suggest that implementation of SSI on 1594 of the 3070 ha in the watershed (all cropland within the watershed with less than 8% slope) to produce high-value, dry-season crops should not compromise downstream flows.

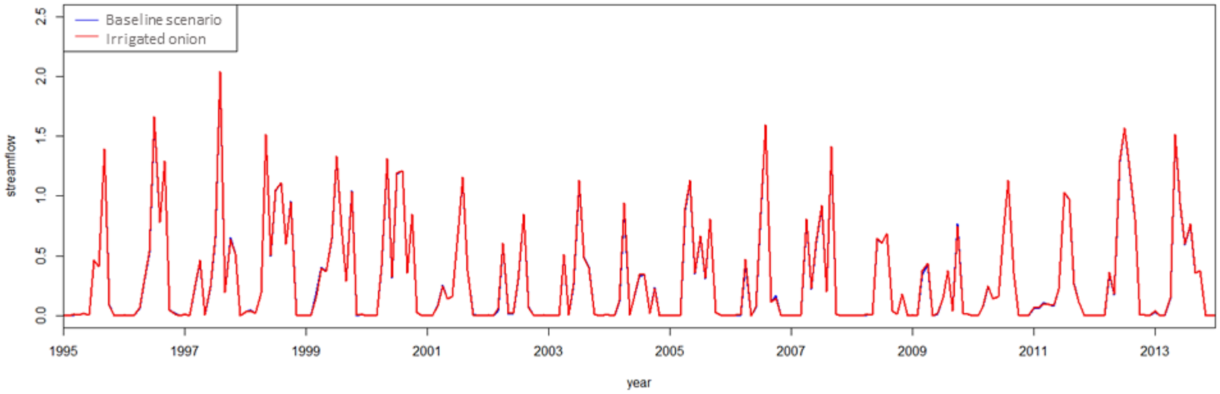

Figure 7. Stream flow at the outlet of the Bochesa watershed for the baseline cropping system and for the same cropping system with irrigated onion.

Crop yields. Calibrated APEX cereal yields were similar to those estimated by SPAM for 2005, though average crop yields for 24 years were substantially higher for maize and wheat, and lower for teff (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.

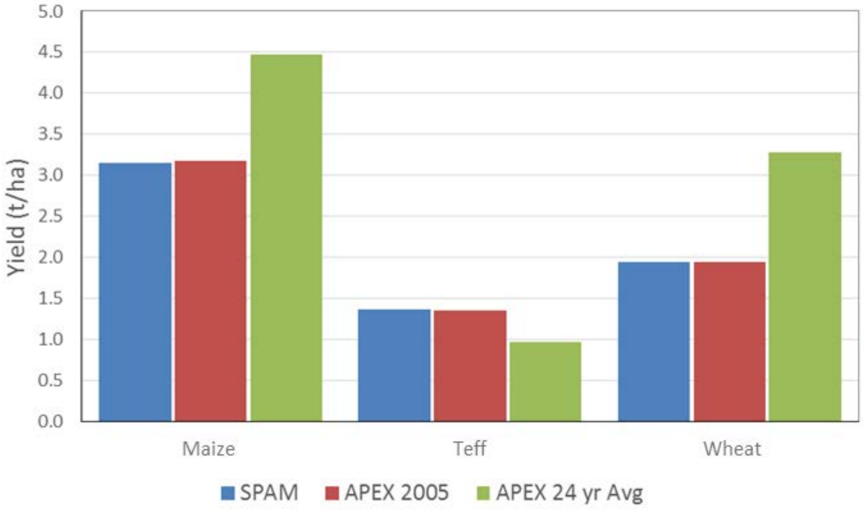

Figure 8. Comparison of maize, teff and wheat yield from SPAM 2005 with APEX-simulated yields in 2005 and APEX-simulated yields averaged over the 24-year period (t/ha dry weight).

APEX simulated two fertilizer rates: current and low (20% less than current levels). Yields of all three crops were higher at current fertilizer rates than at lower rates. At both fertilizer rates, APEX-simulated crop yields of maize and wheat were greater but more variable over the 24-year period than those of teff (fig. 9).

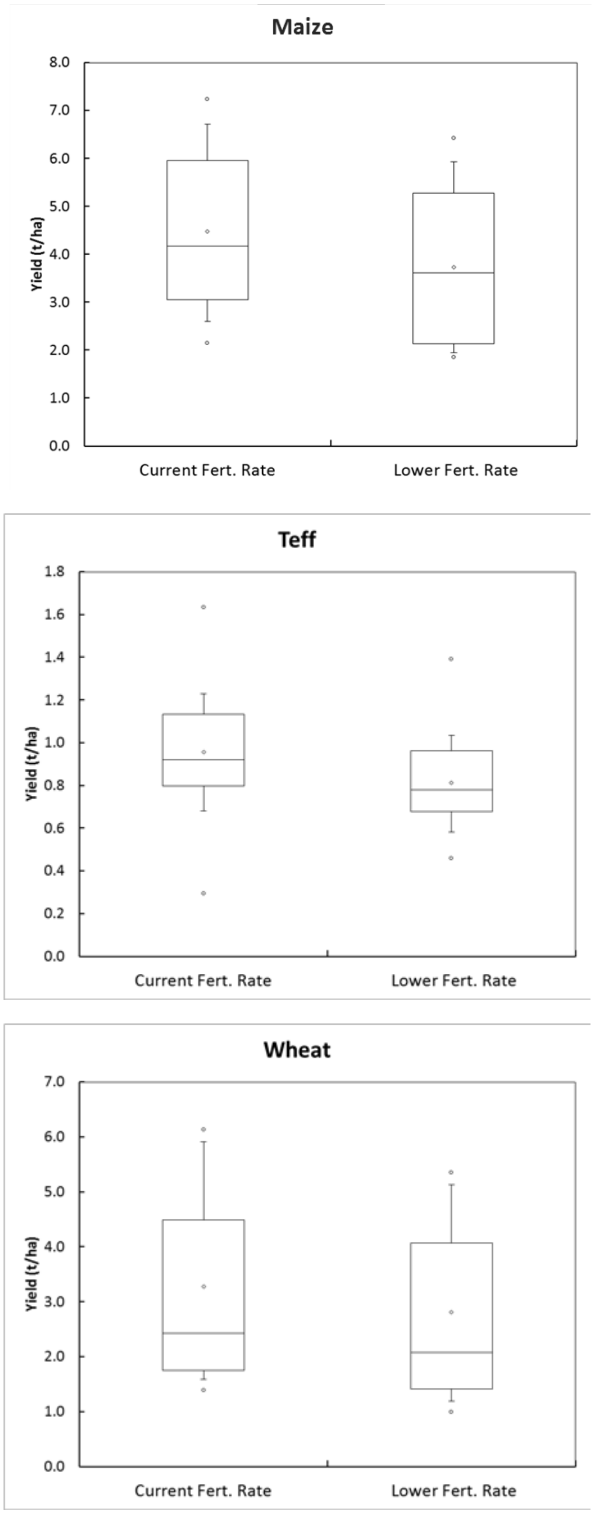

Figure 9. APEX-simulated crop yield for normal soil (current tillage) and two fertilization practices.

Runoff and Soil Erosion. Simulated field-scale runoff and edge-of-field sediment yield were simulated with APEX. There was no significant difference in runoff from maize, teff or wheat at a p-value of 0.05; however, throughout the study period, runoff from maize fields was consistently higher than from fields planted with teff or wheat. In contrast, sediment yields were higher for wheat and maize than for teff. Average sediment yields for the three crops ranged from 15 to 20 t/ha, well within the national norm of 1.4 to 33 t/ha (Lulseged 2005). Similarly, studies of the Tigray region in the northern part of Ethiopia reported sediment yields of 10 t/ha (Haregeweyn et al. 2005; Haregeweyn et al. 2008).

APEX simulations suggest that cultivation of teff may reduce runoff and sediment yield, a finding consistent with studies that recommend teff for erosion control (Narayanan and Dabadghao 1972). Hence, mixed cropping of corn with teff and wheat with teff may help lower runoff and sediment yields. Leaving the crop residues on poorly drained soils following harvest can also reduce runoff and erosion.

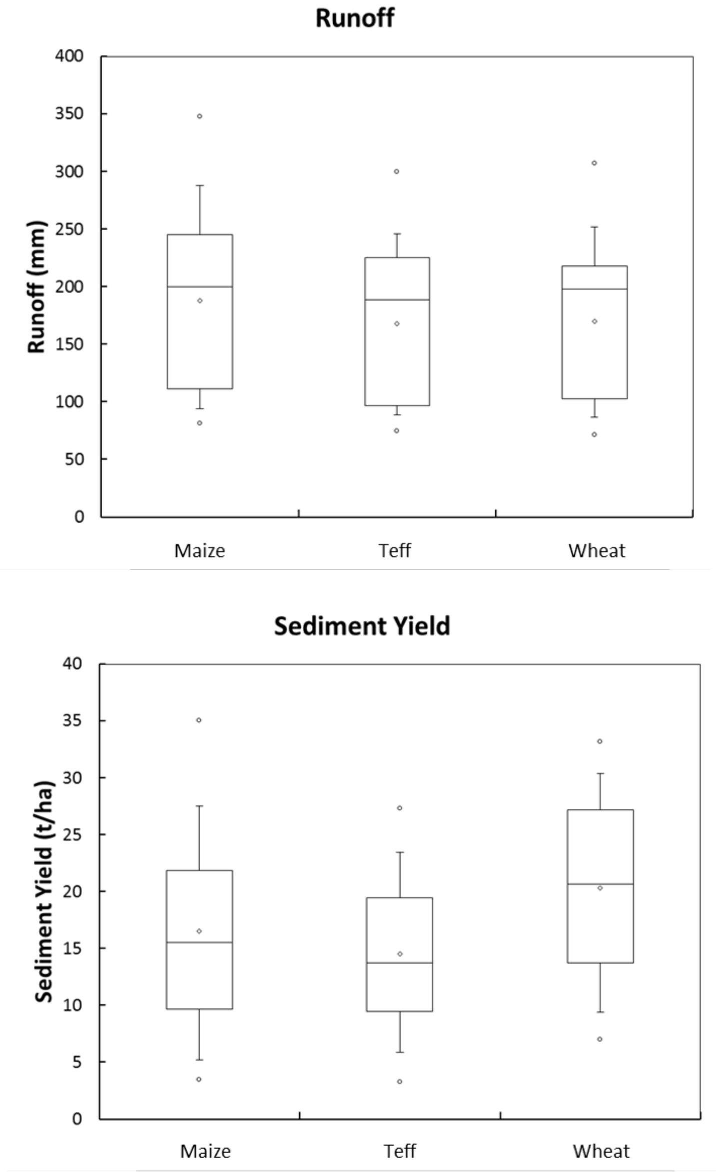

Figure 10. Runoff and sediment yield for rain-fed monocrops.

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.

$$Y = -0.00001x^2 + 0.0051x + 1.16 \ (R^2 = 0.5) \qquad [\text{Eq. 1}]$$

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

As expected, onion yields increase with applied irrigation water.

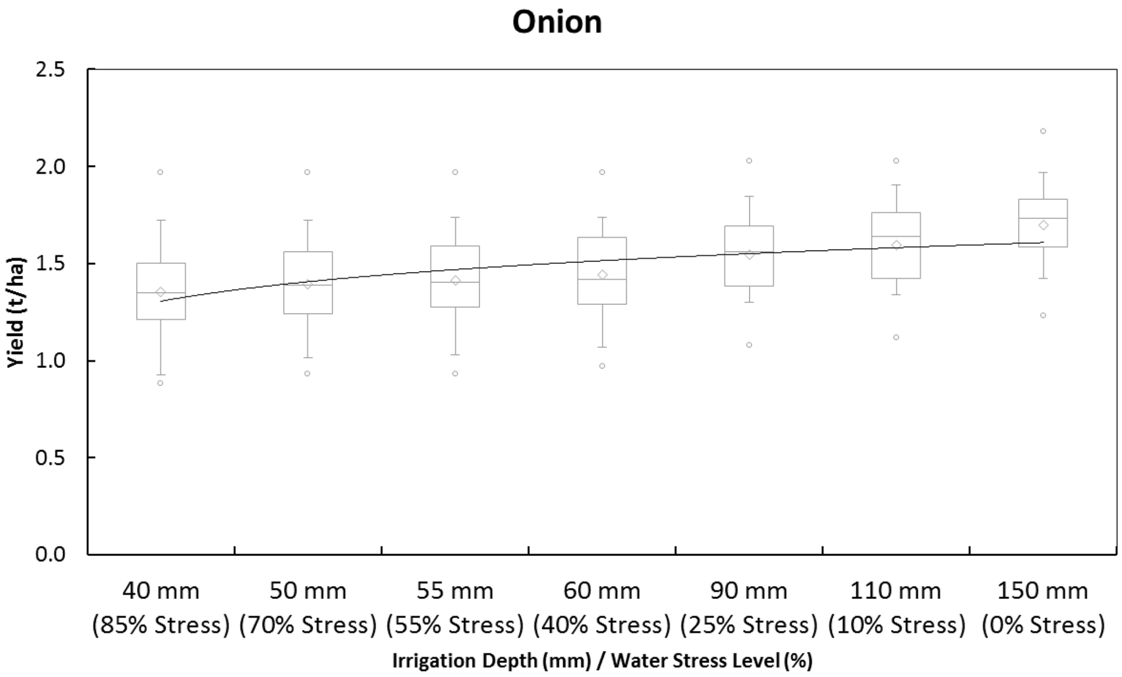

Figure 11. Onion yield (t/ha oven-dry weight) in Bochesa as a function of irrigation water applied.

In Bochesa, diverted river water is used to irrigate areas near the river, which is fed by Lake Ziway. In Ethiopia, irrigation from hand-dug, shallow wells is common in areas far from a river. 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 rope-and-washer pump (0.6 l/s) and a gasoline motor-powered rope-and-washer pump (1.36 kW; 14.0 l/s) (pumping rates taken from Awulachew et. al 2009; Brikke and 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 14.4 t/ha (fresh weight) on 0.25 ha required application of about 60.8 mm of irrigation water (0.06 Ml /ha). To deliver this quantity of water to the crop over the growing season required 67.6 hours with a pulley and bucket, 28.2 hours with a hand-powered rope-and-washer pump and 1.2 hours with a gasoline motor-powered rope-and-washer 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 irrigation by animal-powered or motor pumps (Alts. 3 and 4) were by far the most economically profitable alternatives, in that 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 pump or a solar pump (Alts. 2 and 5). Irrigation by pulley and bucket (Alt. 1) and the baseline scenario (without irrigation) were the lowest performing scenarios.

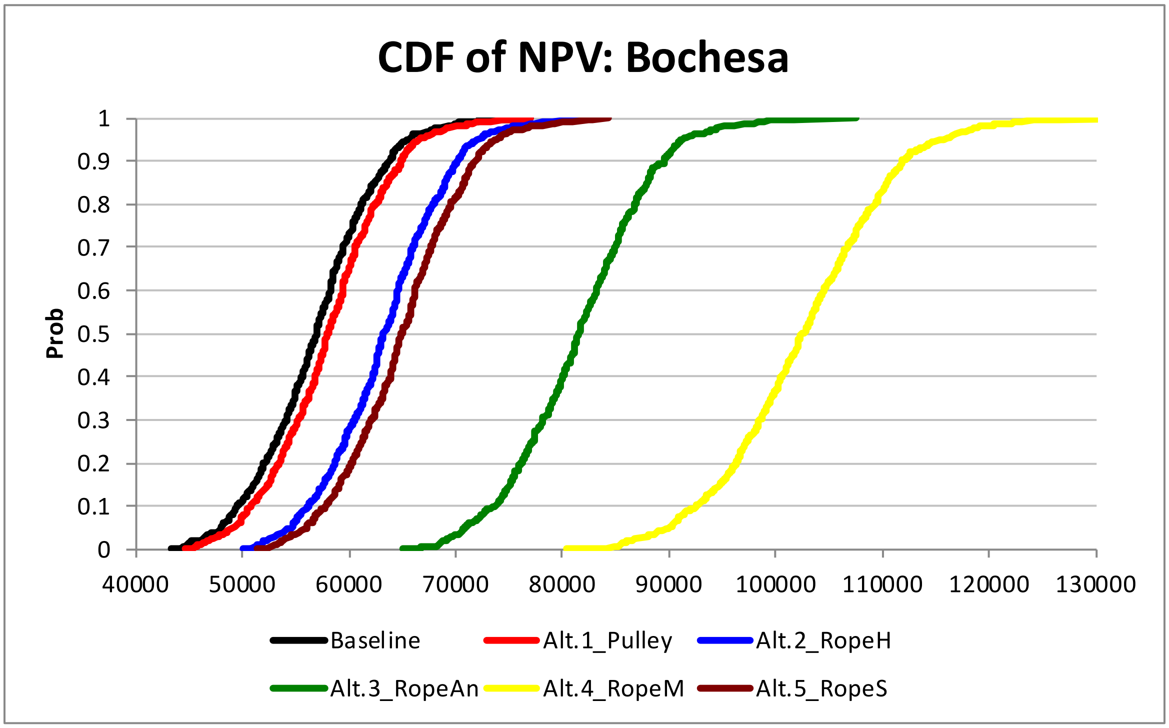

Figure 12a. Net present value for the six scenarios

The stoplight chart presents the year-three probabilities of NPVs of less than 56,000 Ethiopian Birr (ETB) (red), greater than 90,000 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 in the baseline scenario or irrigating with pulley and bucket (Alt. 1), there was a 43% and 34% chance, respectively, that NPV would be less than 56,000 ETB, and a 0% chance that NPV would exceed 90,000 ETB (fig. 12b). For farmers who implemented animal-powered or solar pump irrigation (Alts. 3 and 5), the probability that NPV would fall between 56,000 ETB and 90,000 ETB was 91% and 95%, respectively. In contrast, a farmer who irrigated with a motor pump (Alt. 4) had a 95% chance of NPV exceeding 90,000 ETB. The main barrier for the best-performing scenario, the motor pump, is the initial investment in the technology. The cost of a motor or solar pump is about two times higher than the cost of an animal-powered pump; however, the NPV results strongly suggest that the investment in both motor and animal-powered pump technologies would pay large dividends in increased income and wealth compared with current unirrigated farming systems. Note that the comparatively lower operating, maintenance, and environmental costs of solar technologies may make them more promising in the long-term.

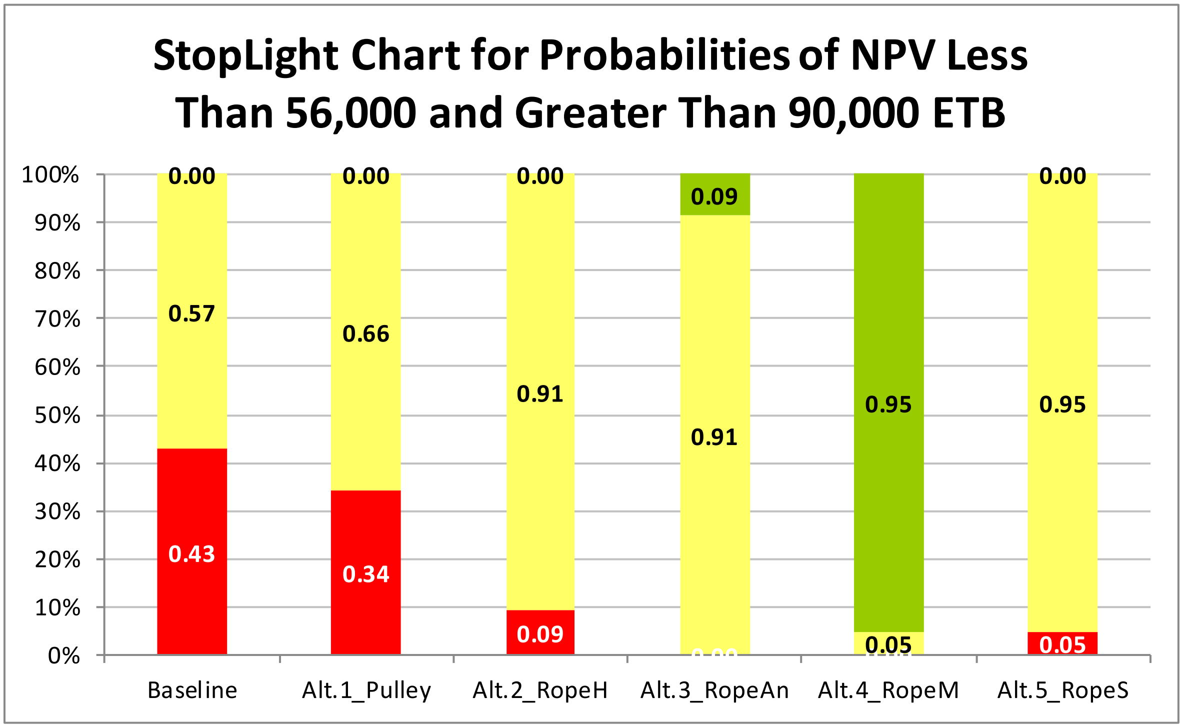

Figure 12b. Stoplight chart for the NPV for the six scenarios

The CDF graph for annual net cash farm income (NCFI) shows a clear difference between irrigation with animal-powered or motor pumps (Alts. 3 and 4) and the rest of the scenarios (fig. 13a). Alternatives 3 and 4 generated much higher levels of NCFI at all probability levels because these technologies enabled the irrigation of significantly more irrigable cropland, and thereby the production of larger quantities of surplus onion to sell at market. Irrigation by hand-operated or solar pump (Alts. 2 and 5) were the next-best alternatives. The baseline scenario (without irrigation) performed slightly better than pulley-and-bucket irrigation (Alt. 1), suggesting that investing in the pulley-and-bucket system to cover more irrigable cropland would cost more than growing non-irrigated onions.

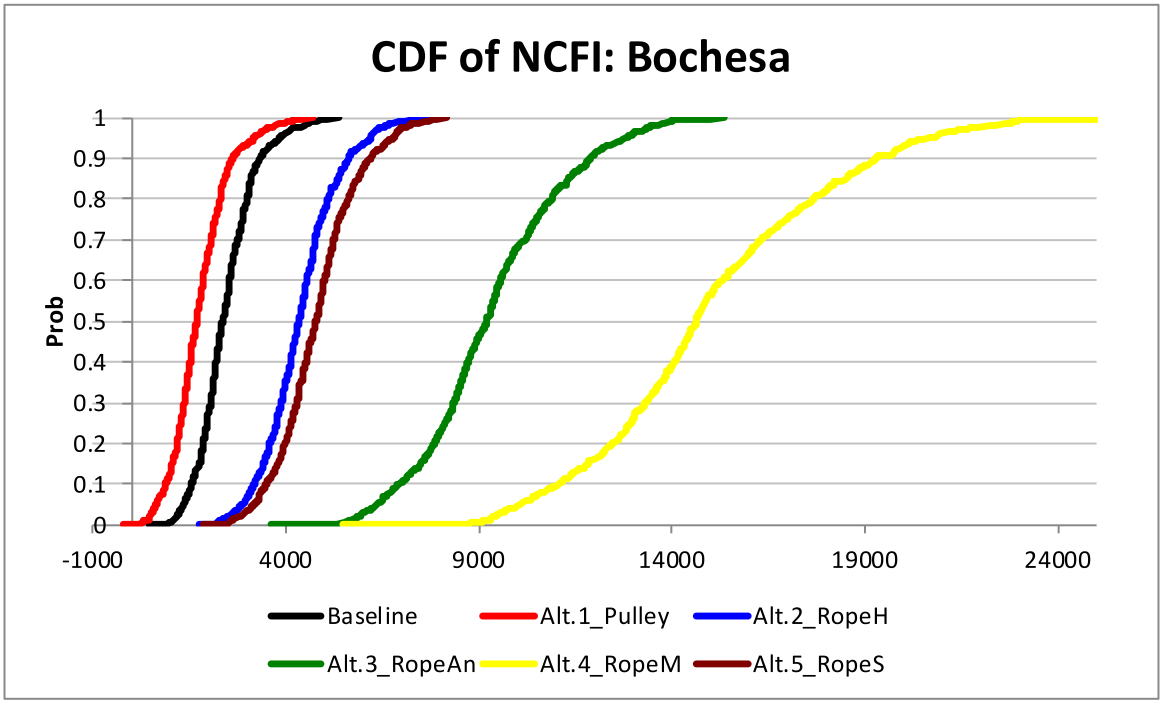

Figure 13a. Net cash farm income for the six scenarios

The stoplight chart for NCFI in year three of the five-year planning horizon shows that, in the baseline scenario, there was a 57% probability that a farm would generate NCFI of less than 2,500 ETB, and a 0% chance that NCFI would exceed 12,000 ETB (fig. 13b). A farm that irrigated with a pulley and bucket (Alt. 1) was even more likely (87%) to generate NCFI of less than 2,500 ETB than a farm that did not irrigate, because of the costs involved in using the irrigation system. For a farm that adopted hand-operated or solar pump irrigation (Alts. 2 and 5), there was a 98% and 99% probability, respectively, that NCFI would fall between 2,500 ETB and 12,000 ETB. In contrast, for a farm that irrigated with an animal-powered or motor pump (Alts. 3 and 4), there was a 9% or 84% chance, respectively, that NCFI would exceed 12,000 ETB.

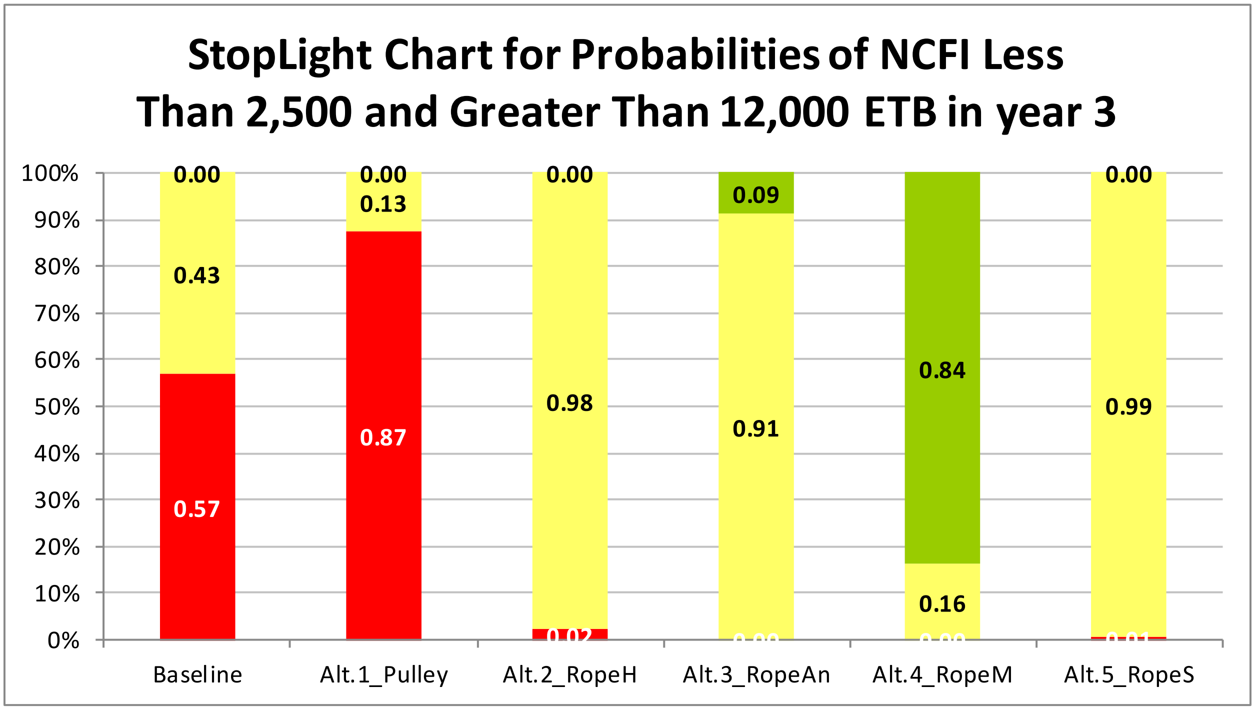

Figure 13b. Stoplight chart for NCFI for the six scenarios.

The EC reserve indicator (fig. 14a) highlighted once again the superior performance of irrigation by animal-powered or motor pump (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 (Alts. 2 and 5) had higher EC reserves than one who did not irrigate or who irrigated with a pulley and bucket (Alt. 1). Note that, again, a farmer who did not irrigate (baseline) generally performed better than one who adopted pulley-and-bucket irrigation (Alt. 1) even though the amount of EC is very low.

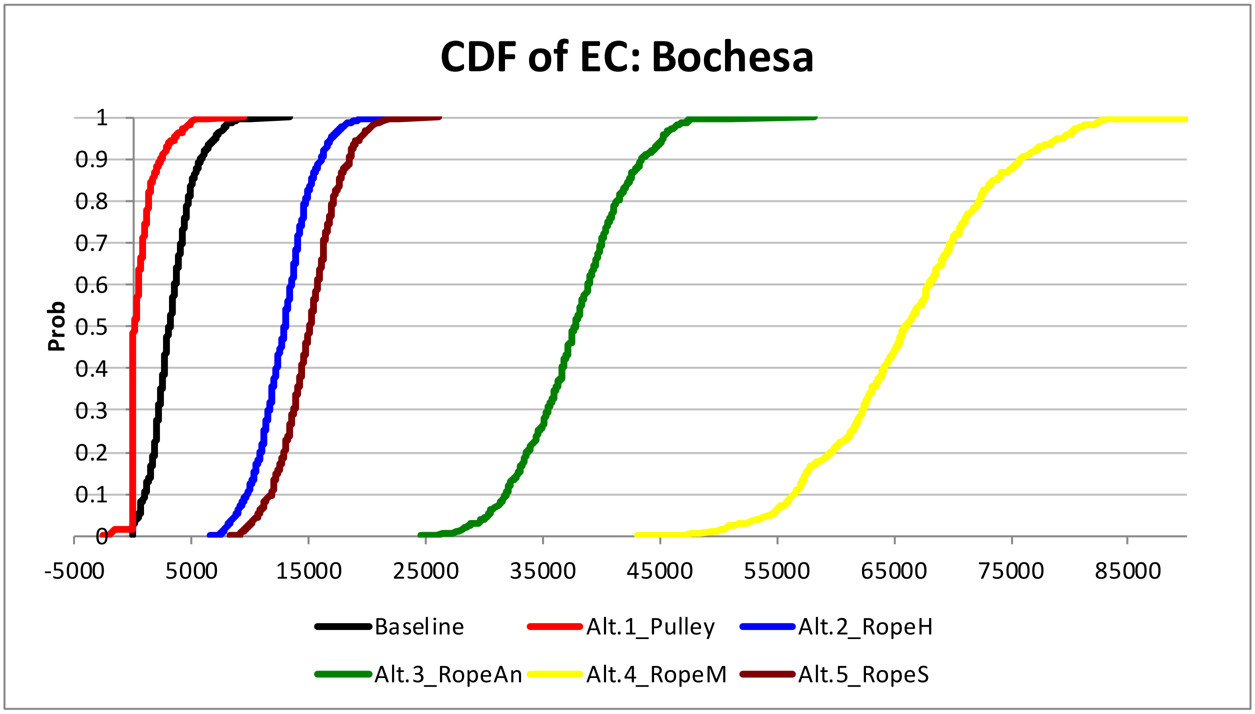

Figure 14a. Ending cash reserve (EC) for six scenarios

The stoplight chart for EC reserves (fig. 14b) shows that, in year five, a farmer who did not irrigate (baseline) had a 55% probability of having EC reserves of less than 3,300 ETB (baseline average) and a 0% probability of having EC reserves of more than 60,000 ETB. A farmer who irrigated with a hand-operated, animal-powered or solar pump (Alts. 2, 3, and 5) had a 100% probability of having EC reserves between 3,300 ETB and 60,000 ETB. In contrast, a farmer who irrigated with a motor pump (Alt. 4) had a 79% probability of EC reserves of more than 60,000 ETB and a 0% probability of EC reserves under 3,300 ETB. Again, a farmer who irrigated with a pulley and bucket (Alt. 1) was more likely to generate EC reserves under 3,300 ETB than one who did not irrigate at all.

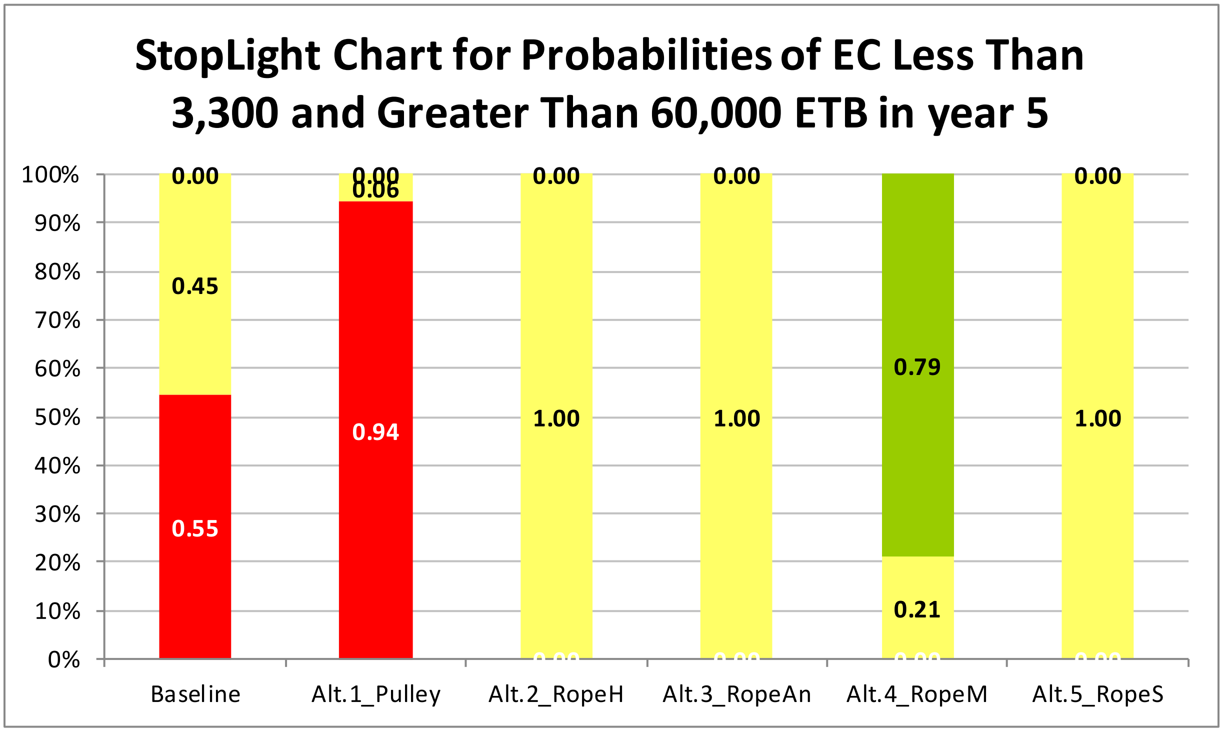

Figure 14b. Stoplight chart for the ending cash reserves (EC)

Since grain crops in Bochesa 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 onion. In alternative scenario 4, the forecasted sales of onions contributed, on average, 96% of the total crops receipts and 100% of the net cash (profit) for the five-year planning horizon.

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, as compared to the baseline scenario, the nutrition variables (calories, proteins, fat, calcium, iron, and vitamin A) available to the farm family increased under all of the alternative scenarios except irrigation by pulley and bucket (Alt. 1). Also, the minimum requirements per adult equivalent per day were met for calories, protein, and iron in all of the alternative scenarios; however, nutritional deficiencies in fat, calcium, and vitamin A persisted. Clearly, families in Bochesa would require food supplements (whether obtained through purchase or farming) to meet the 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 Adami Tulu, 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

Simulations of watershed-scale hydrology suggested that recharge of the shallow aquifer may be inadequate to support a large amount of SSI in Adami Tulu. However, surface runoff might be captured in ponds and used either directly or to recharge shallow groundwater. For purposes of analyzing the effects of the proposed SSI interventions, we assumed that locations could be identified within the watershed with sufficient recharge of shallow groundwater to support the proposed SSI interventions, or that runoff could be captured and used to recharge shallow groundwater. Additional, more detailed spatial analysis of the watershed would be required to identify appropriate locations and costs for construction of dams to capture runoff for use in SSI during the dry season.

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 Bochesa. These analyses also 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 alternate technologies examined, only motor pumps met the irrigation water requirements for the proposed SSI interventions in Bochesa (i.e., for all 531 ha of irrigable land in the kebele). Implementation of the proposed SSI interventions using motor pumps produced the highest NPV, NCI, and EC reserves of the six scenarios simulated (including the baseline, non-irrigated scenario); the scenario utilizing animal-powered-pump irrigation was the second-best-performing scenario. Alternative scenarios involving hand-operated and solar pumps were the third-best-performing scenarios, with both showing a similar level of performance. In each of the alternative scenarios, the increase in farm revenue was due almost entirely to the sale of surplus irrigated onion. Where motor pumps were used, the forecasted sales of irrigated onions contributed, on average, 96% of the total crops receipts and 100% of the net cash (profit) for the five-year planning horizon.

Assuming that future studies identify locations with sufficient recharge of shallow groundwater to support the proposed SSI interventions, the irrigation water requirements for these interventions could be met with motor pumps. Note that simulations showed that investments in both motor- and animal-powered-pump irrigation will generate profits for the farmer. Motor pumps can cover three times the area of animal-powered pumps, but with much higher entry and capital costs. Individual farmers might benefit by spreading entry costs over more irrigated area, perhaps by having two or three farmers share a motor or solar pump. Finally, despite its low pumping capacity and high capital cost, the solar-pump system may be a more promising option for the future due to its low operating, maintenance, and environmental costs.

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 area and types of crops irrigated in the dry season to increase family nutrition and net cash income, but only if the additional area and crops can be irrigated without depleting the shallow aquifer, causing environmental degradation, or reducing environmental benefits provided by the land. Additional analyses would be needed to (1) identify local areas within the watershed with adequate groundwater recharge to support SSI, and (2) evaluate the hydrologic and economic feasibility of constructing small dams to capture runoff for use for SSI. 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 also subjects for proposed future study.

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