# An example IDSS gap and constraints analysis for small scale irrigation systems in the Robit watershed

### Feed the Future Innovation Laboratory for Small Scale Irrigation (ILSSI)

## Introduction

Over the past 2.5 years, the ILSSI has conducted field studies and household surveys, and has employed the Integrated Decision Support System (IDSS) to compare the production, economic, and environmental consequences of a number of candidate small scale irrigation (SSI) systems for use by smallholders in Ethiopia, Ghana, and Tanzania. These initial studies show major opportunities for the introduction of SSI in each of these three countries, and the relative merits of a number of SSI interventions suggested initially by national stakeholders. The studies also identify constraints or limitations to the use of these systems. Assessing the value of SSI interventions requires that they be studied in the context of a total farming system. Thus purchased inputs, farming practices, and sale of product are illustrative of variables that contribute to the outcome of the intervention. The analysis can also be used to seek the best (optimal) combination of farming system variables, including SSI. Further analysis is planned to define the limitations associated with these interventions – such as the amount of water available for sustainable application of SSI and the amounts of fertilizers that take best advantage of irrigation.

The next step in the development of SSI systems in each country is to better define and select the highest priority constraints and their mitigation for further evaluation and for development of recommendations to stakeholders at multiple levels of scale. The research done to date has suggested a number of limitations and constraints, and has indicated possible ways to mitigate these constraints. Further engagement of stakeholders is now needed to assure that the most important constraints facing decision makers, especially at the national level, are identified for further study. The country-level stakeholder workshops planned for June-July 2016 are intended to seek and secure this advice. Following these workshops, the constraints and mitigation analyses will be conducted using the IDSS in July-September 2016 on a prioritized list of topics identified by the stakeholder workshops. The intent is to draw on the expertise of national stakeholders to identify and prioritize constraints to the use of SSI systems and to better understand their institutional plans for the use of SSI.

When this study is completed, stakeholders will have a comparison of the utility of multiple SSI systems across multiple regions in each country, and a quantitative estimation of the constraints on the use of these systems and strategies for mitigation. The modeling capacity and relevant databases will allow stakeholders to use one or more or the entire suite of IDSS models to address specific scenarios or questions. The ability to concurrently assess the production, economic, and environmental consequences of the interventions under consideration will provide a new, integrated capacity for analysis to inform strategies and specific applications.

To provide a better perspective for stakeholders participating in the workshop on the product coming from the future constraints and mitigation analyses, an example taken from a single watershed in northern Ethiopia has been developed and is presented in this paper. The analysis takes advantage of both historical data and initial (ongoing) field and survey studies in this area.

## Robit watershed case study

This document presents the constraints to the use of SSI in the Robit watershed, identified using the IDSS, as well as gaps in knowledge needed to better implement proposed SSI interventions. These gaps and constraints were studied at different scales. The SWAT model was used to study the environmental gaps and constraints of the use of SSI at the watershed scale, while the APEX model was used to assess the resource constraints and knowledge gaps preventing optimum agricultural production at the field scale. The FarmSIM model was used to assess the economic and nutritional gaps and constraints at the household level. The integrated application of the three components of the IDSS allowed us assess tradeoffs of system inputs, and thereby to seek best outcomes through iterative analysis. Alternative mitigations for the identified gaps and constraints were also discussed.

## Watershed-scale analysis of resource and environmental constraints

Before irrigation development is initiated, SWAT identifies areas that are potentially suitable for irrigation by analyzing and integrating available data and expert opinion on: (1) surface and ground water location and quantity; (2) soil characteristics; and (3) land slopes within the watershed. Moreover, SWAT helps to define the sustainable use of these natural resources—i.e., the number and location of farms that can and should be irrigated, especially in the dry season—by simulating proposed SSI interventions and evaluating their environmental impacts at the watershed scale.

### *Land and water availability*

The Robit watershed has a catchment area of 1,506 ha. SWAT analysis using biophysical parameters indicated that about 50% of the watershed is suitable for irrigation. The three major rain-fed crops, cultivated from June to November, are maize, teff and finger millet. Onion and tomato are two of the most common vegetable crops, and are grown as irrigated crops in the dry season (January to April).

Analysis using the SWAT model indicates that there are substantial water resources in the Robit watershed. The average annual rainfall in the Robit watershed for the period from 1990 to 2013 was 1400 mm. The average annual groundwater recharge and generated surface runoff across the watershed were 280 mm and 521 mm, respectively. In volumetric terms, the average annual groundwater recharge and surface runoff potentials were over 4 million $m^3$ and 7 million $m^3$, respectively. Availability of this abundant water resource suggests that SSI technologies could be utilized to make use of the water resources more efficiently.

In the Robit area, most of the streams dry out at the end of the rainy season. The main source of irrigation water in the dry season, as confirmed by field studies, is shallow groundwater. Thus, the SWAT model used shallow groundwater as source of irrigation water for irrigation. The IDSS analysis showed that there was sufficient groundwater recharge to support the irrigation water requirement for cultivating vegetables in the dry season. The total annual volume of irrigation water in the watershed was 1,540,167 $m^3$, or about 40% of the annual groundwater recharge. This suggests that, at the watershed scale, the irrigation water requirement for cultivating vegetables on suitable lands can be sustained by the shallow groundwater recharge without affecting long-term groundwater storage.

### *Impacts of SSI at the watershed scale*

When SSI interventions were not implemented (i.e., under baseline conditions), about 46% of the annual rainfall became streamflow, 43% evaporated back into the atmosphere, and the remaining percentage went into the groundwater aquifer. The implementation of SSI interventions changed the hydrological dynamics of the watershed (fig. 1). For example, in the SSI ("ex ante") scenario, only about 43% of the annual rainfall became streamflow, and the percentage of rainfall evaporating back into the atmosphere increased to 50%. Additionally, implementation of SSI for dry-season vegetable production reduced average monthly stream flow at the outlet of the Robit watershed by about 6%; the proposed SSI interventions also resulted in minor reductions in high flows. Proposed mitigations for this constraint at the watershed level, such as the use of water harvesting structures to collect surface runoff as a supplemental source of irrigation water, are discussed below.

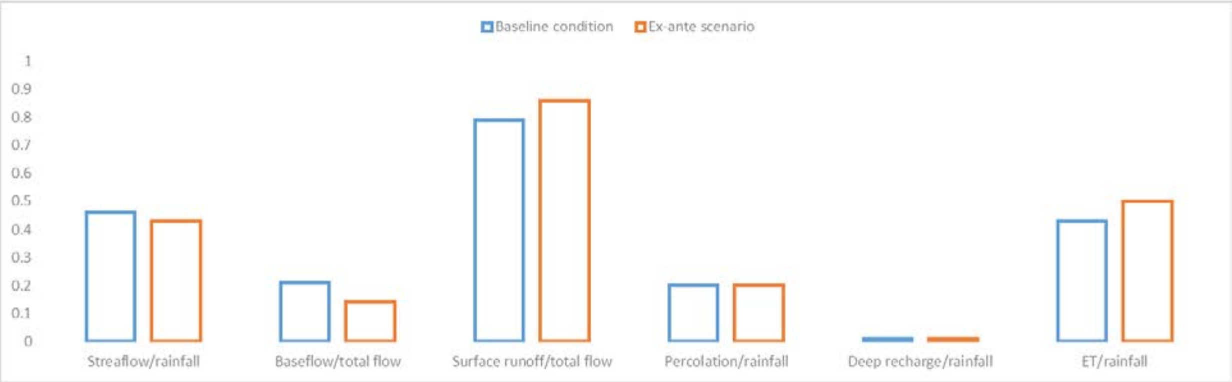

**Figure 1. Water balance partitioning for the Robit watershed before and after intensification of small scale irrigation ("Baseline condition" and "Ex-ante scenario," respectively).**

## Field-scale analysis of resource constraints

The APEX model was used to identify major resource constraints on SSI interventions in the Robit watershed, using tomato as a case study crop. The analysis was centered on water and nutrient availability/limitation for tomato production.

### *Field-scale irrigation water management*

Farmers in the Robit area use simple water-lifting technologies like pulley-and-bucket irrigation and rope-and-washer pumps. Irrigation water management practices, and levels of skill at optimizing tomato production, are highly variable from farmer to farmer. Farmers tend to irrigate more frequently in the earlier stage of the crop's production than in the development and maturity stages. While irrigating, farmers tend to apply water until the soil is saturated, or until there is excess water on the soil surface.

The APEX model was used to develop a water production function (fig. 2a) which indicated that the optimal volume of water for tomato production is approximately 840 mm, out of which 270 mm are contributed by rainfall over the growing season (period 1994-2015). The optimal water requirement was compared with the available water in the watershed, as estimated by the SWAT model (i.e., average annual surface runoff and groundwater recharge of 520 mm and 280 mm, respectively). At the field scale, the shallow groundwater was not sufficient to support the irrigation water requirement; however, analysis at the watershed scale (as discussed above) indicated that there was sufficient groundwater recharge within the entirety of the watershed to support irrigation. Proposed mitigations for this constraint at the field level, such as the use of water harvesting structures to collect surface runoff as a supplemental source of irrigation water, are discussed below.

APEX also estimated the pumping hours required to irrigate a 202 $m^2$ plot for a two-day irrigation interval with various water-lifting technologies. Results indicated an insignificant difference in working hours required to irrigate, up to optimal irrigation volume, with a pulley and bucket, rope-and-washer pump, and solar-powered pump. However, as the irrigation depth and area increase, the pump operating time increases slightly for a gasoline-motor-powered pump, and more dramatically for a solar pump, pulley and bucket, and rope-and-washer pump.

Field results indicated that area farmers apply more irrigation water than the actual plant water requirement. Over-irrigation may cause increased surface runoff, resulting in the leaching and loss of nutrients. The field studies, together with the hydrological models, indicated that with a proper knowledge and efficient use of water, there is enough water to cultivate irrigated, dry-season tomato in the area, especially if surface runoff is stored in water harvesting structures and used as supplementary irrigation water to that derived from the groundwater recharge.

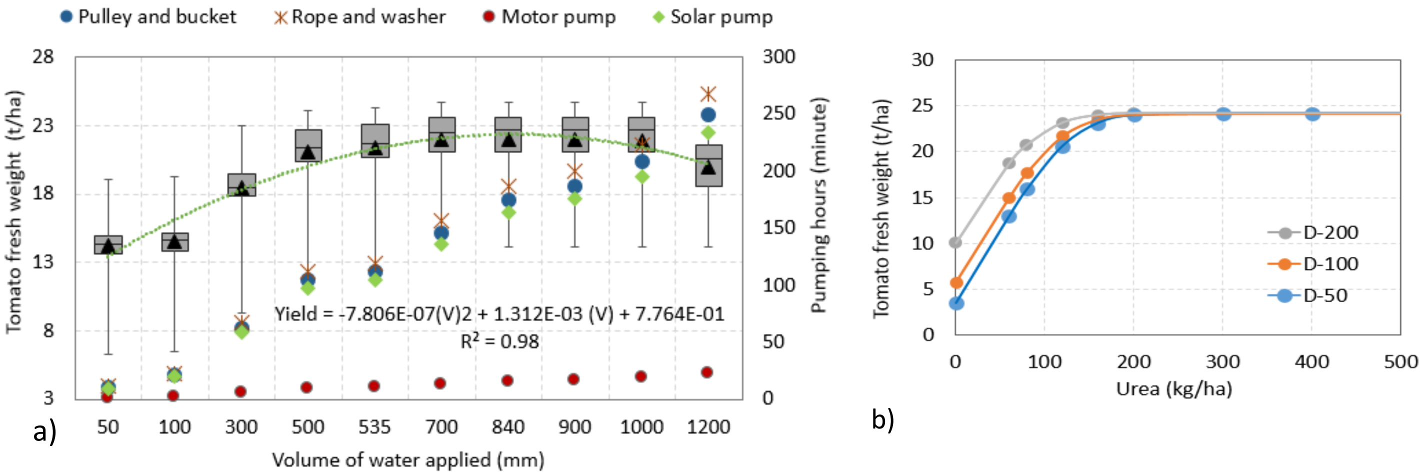

**Figure 2: (a) Tomato water production function simulated from 1994 to 2015. Irrigation was applied every two days for a growing period of 131 days. For example, 10.7 mm of water was applied in two-day intervals for a total volume of 700 mm of irrigation water. The rectangle box represents the first and the third quartile, the median is represented by a segment inside the rectangle, and whiskers above and below represent minimum and maximum. (b) Tomato fertilizer production function for 50, 100, and 200 kg/ha DAP, with different amounts of urea.**

### *Fertilizer use*

Surveys conducted by the Central Statistical Authority (CSA) and the Livestock and Irrigation Value chains for Ethiopian Smallholders (LIVES) have indicated an incremental trend towards increased fertilizer use in Ethiopia. Nonetheless, current fertilizer application rates are lower than rates recommended by the Ethiopian Agricultural Research Institute (EARI). It is estimated that in Ethiopia only 30-40% of smallholders use fertilizer. Lower applications of fertilizer inputs have kept agricultural production and productivity low, and prolonged Ethiopia's status as a food insecure nation.

Using the APEX model, a fertilizer production function was developed by varying the quantities of urea and diammonium phosphate (DAP) applied. Urea serves as a source of nitrogen, while DAP is a source of phosphorus and nitrogen commonly used in Ethiopia. The fertilizer production function indicated that yield increases as the urea and DAP application rates increase; however, after a certain amount of fertilizer, the yield response to a change in fertilizer is insignificant (fig. 2b). For example, increasing the urea amounts after 200 kg/ha for a 50 kg/ha DAP or more would not increase tomato yield.

### *Soil erosion*

Simulated soil erosion rates were very high in Robit, suggesting that the current and alternative cropping systems simulated with the IDSS cannot be sustained without substantial efforts to reduce soil erosion. Every effort should be made to identify and implement cropping systems that reduce the rates of soil erosion. Proposed mitigations for this constraint are discussed below.

## Household-scale analysis of economic and nutritional constraints

The collection of field data in the Robit area helped update the information on costs of agricultural inputs and irrigation equipment, as well as the capacities of water lifting technologies (WLTs) used in the irrigation of tomato. The FARMSIM model was used to evaluate the economic and nutrition benefits of adopting SSI technologies, assuming (as indicated by the SWAT model) that there is sufficient water at the watershed scale to irrigate dry-season tomato. Although the economic and nutrition evaluation covered all the crops and livestock on the farm in Robit, the majority of cash benefit came from the sale of the dry-season tomato crop, which contributed 100% to total benefits. A baseline scenario, built using the household survey data collected by the LIVES-ILRI project, was compared to several alternative scenarios associated with different WLTs set up on the ground. The WLTs studied were: pulley and bucket, rope-and-washer pump, motor pump, and solar pump. Each WLT represented an alternative irrigation scenario for producing tomato during the dry season. The alternative scenarios were compared to the baseline, minimally irrigated scenario, to evaluate the economic and nutrition benefits of irrigation. Based on field data and simulation results from the APEX model—which determined the optimal amount of irrigation water needed to produce the highest dry-season tomato yield—each WLT was evaluated as to its capacity to pump enough irrigation water to cover the total potential irrigable land in Robit. However, in this study process, constraints and gaps were identified to evaluate the economic consequences and possibly suggest mitigation strategies for an optimal farm profit.

### *Economic gaps and constraints*

Constraints related to WLTs include labor, maintenance, and capital costs, as well as equipment breakdowns (table 1). Generally, the cost of a WLT increases with its capacity to extract water, and more powerful WLTs can pump enough water to irrigate large areas of irrigable land. (The solar pump is a notable exception to this rule, as discussed below.) The revenue from producing and selling large quantities of an irrigated, dry-season crop can offset the costs of the WLT and generate a profit. During field trials in Robit, the ability of the rope-and-washer pump to extract water from shallow wells (its "flow rate") was inferior to the flow rates of these pumps as recorded in literature (14 l/ min vs. 35 l/min). This discrepancy could be due to frequent breakdowns of the tool recorded during the trial. However, if well-maintained, the tool is more appropriate for SSI than the pulley-and-bucket system, which requires more labor to lift water from wells. Conversely, despite its high extraction capacity, the motor pump entails high operating costs in terms of maintenance and fuel. The similarly high investment and capital costs of a solar pump (2 to 4 times greater than the other WLTs) makes it less affordable for farmers; it has also a low water extraction capacity.

In general, the costs of the agricultural inputs required for the production of irrigated tomato (e.g., additional seed) were deemed reasonably affordable; however, ILSSI field data from commercial kitchen garden experiments in the Lake Tana region indicated that the cost of irrigation labor was 20 times more expensive than the labor used in the current (baseline) farming system (table 2). For this reason, the economic and nutritional analysis was divided into two case studies: one with low irrigation labor cost; and the other with high irrigation labor cost. To evaluate the possible cash benefit of low irrigation labor cost, the irrigation labor cost in the high cost category was reduced by 65 percent (or cut by 2/3). Note that all the initial costs for the water lifting technology tools were input in the FARMSIM model as a loan/credit payable within the 5 year planning horizon.

**Table 1. Water lifting technologies (WLT)**

| Types of WLT | Operated by | Flow rate (l/min) | Cost WLT (ETB) | Issues/Constraints |
|---|---|---|---|---|
| Pulley/bucket | Hand | 15 | 1310 | require more labor |
| Rope and washer pump | Hand | 14 | 3700 | frequent breakdowns |
| Motor pump | Fuel | 170 | 8500 | high maintenance costs |
| Solar pump | Solar | 16 | 16000 | high capital costs |

<u>Note</u>: we did not include the cost of digging wells since this was not part of the experiment

**Table 2. Input cost and yields of tomato**

| Technology scenarios | Avg. tomato Yield (Kg/ha) | Cost seed (ETB/ha) | High Cost Irrig. labor (ETB/ha) | Low Cost Irrig. labor (ETB/ha) |
|---|---|---|---|---|
| Baseline minimum irrig | 4800 | 420 | 760 | 760 |
| Alt. scen w/ irrig. | 21700 | 380 | 18100 | 6000 |

<u>Note</u>: family labor was exclusively used for irrigation in the baseline scenario while the hired labor was used in the alternative technologies

### ***Economic and nutritional comparison of the different technologies***

The stoplight chart for net cash farm income (NCFI) in year 3 of the 5-year planning horizon shows that a farmer in any of the simulated scenarios (including the baseline scenario) has an 18-51% probability of generating NCFI of less than 13,000 ETB and a 15-50% chance of generating NCFI in excess of 22,000 ETB (fig. 3). Both cut-off values are averages of the upper and lower NCFI limits. Each WLT represented in the figure shows the NCFIs when high and low irrigation labor costs are considered. Basically, the scenarios with low irrigation costs show higher cash profit. Since the irrigation times recorded on field in Robit lasted on average 90 minutes per application, this amount of time can be split between hired and family labor to reduce the costs (forgoing the opportunity cost). Figure 3 shows that the motor pump associated with low irrigation labor costs (MotorP_L) is the most preferred scenario, generating higher NCFI than other WLTs. The simulation results show that the quantities of food produced and consumed (a small portion is purchased), under the baseline and alternative scenarios, were able to provide nutritional requirements for calories, proteins and iron, but were deficient in fat, calcium and vitamin A.

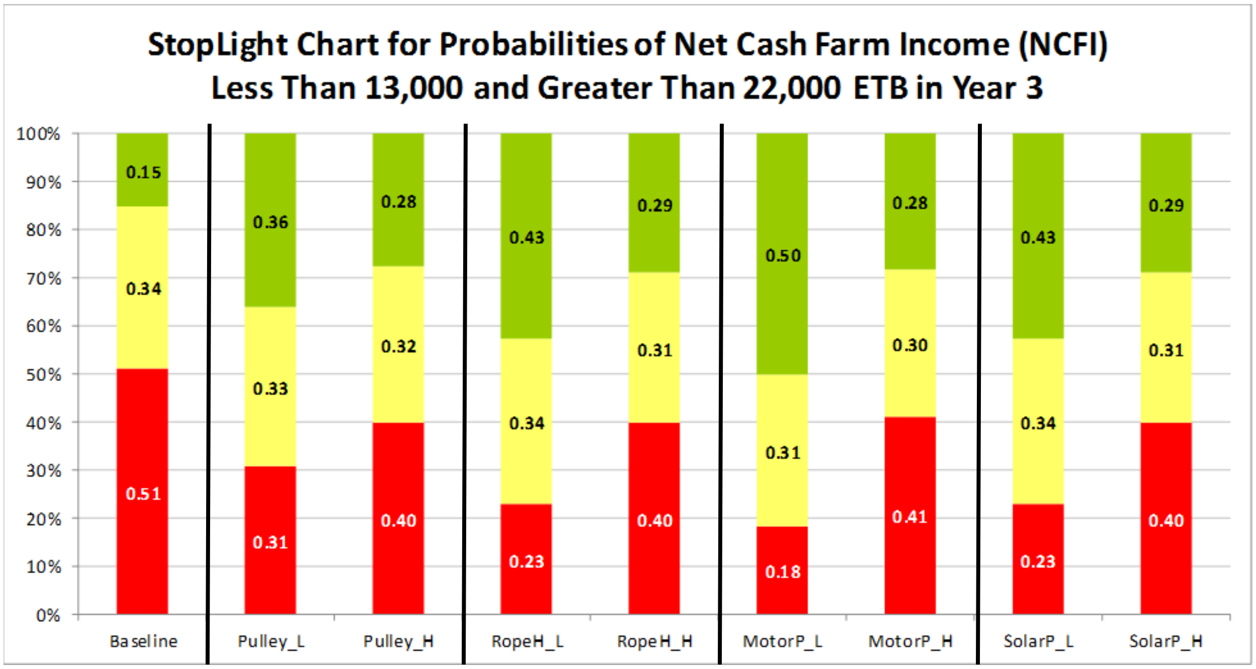

**Figure 3. Comparison of the different irrigation technologies using Net Cash Farm Income (NCFI).**
Note: H and L mean high and low irrigation labor cost

## Mitigation of constraints and identification of gaps

In Robit watershed, SWAT analyses suggested that shallow groundwater was sufficient to meet irrigation water requirements at the watershed scale—assuming that the roughly 50% of non-irrigable areas can contribute groundwater for irrigation of irrigable land. At the field scale, however, insufficient irrigation water may be a constraint. To meet the irrigation water requirements at the field scale, it may be necessary to store locally-generated surface runoff within a field using water harvesting structures. SWAT analyses also indicated that the environmental effects of SSI (e.g., reduction in average monthly stream flows and peak flows) could serve as constraints on SSI in the Robit watershed. Combining shallow groundwater and harvested surface runoff for dry-season irrigation could mitigate adverse impacts on both long-term groundwater storage and dry-season stream flows. The analysis of alternative types, costs and locations of water harvesting structures, as well as the exact impact of such structures on water resources and the environment, warrant further study.

APEX analyses showed that low soil fertility, coupled with ineffective management practices (e.g., insufficient fertilization application rates and over-watering), are also significant constraints on SSI in the Robit area. The field studies and simulation models indicated that application of specified rates of irrigation and fertilizers at appropriate times will optimize productivity. For example, applying 200 kg/ha of Urea and 50 kg/ha of DAP (in split application) to the dry-season tomato crop at the planting and flowering stages will optimize the crop yield. The evaluation and comparison of additional crops for cultivation, recommended management practices, and associated impacts on soil erosion and environmental benefits, are subjects for proposed future study.

APEX simulations also indicated that high rates of soil erosion are a constraint on SSI in the Robit watershed. Potential mitigating strategies, such as terracing, the identification and implementation of alternative cropping systems that reduce erosion rates, and the use of water harvesting structures to minimize runoff (as discussed above) are subjects for proposed future study.

The production of irrigated, dry-season crops could improve the economic and nutritional well-being of farm families in Robit if production and marketing costs are minimized. FarmSIM analyses indicated that high irrigation labor costs are a significant constraint on the profitability of irrigated tomato production and sale in Robit. The use of family labor and other less labor-intensive irrigation methods, such as drip irrigation, may reduce labor costs. Additionally, proper training on the operation and repair of new WLTs can save resources and limit frustration (as noted during the field experiment) for new users of these technologies. Lastly, the change in policies to encourage the acquisition at affordable costs of new and clean sources of power (e.g., solar) for irrigation pumps, could help smooth the transition from old and non-environmental friendly tools (e.g., motor pump) to new and environmental friendly tools such as the solar pump. Each of these subjects merit additional inquiry.

## Conclusions

ILSSI applied the IDSS to evaluate the production, economic, and environmental consequences of proposed SSI interventions—and associated farming systems—in the Robit watershed. IDSS analyses revealed a number of constraints on the introduction and use of the proposed SSI systems in Robit, including: environmental effects of SSI (e.g., reductions in average monthly stream flows and peak flows) at the watershed level; a lack of adequate irrigation water at the field scale; low soil fertility and ineffective management practices (e.g., irrigation and fertilizer rates and schedules); high soil erosion rates; high irrigation labor costs; the need for training in the operation and troubleshooting of WLTs; and policy limitations (such as high import taxes on solar technologies). IDSS analyses also identified a number of knowledge gaps requiring additional study, including: the possible types, costs, locations, and effects of water harvesting structures; additional crops for cultivation with SSI, and the optimal management practices for and environmental impacts of each; the costs and possibility of implementing terracing or alternative farming systems to reduce soil erosion rates; additional methods of reducing irrigation labor costs; and potential improvements to training and policy. National stakeholders are asked to consider the constraints and gaps identified above, to identify additional opportunities for and constraints on the application of SSI interventions at multiple levels of scale, and ultimately, to develop a relatively short list of important opportunities and constraints to guide further IDSS analyses.