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# Multi-Dimensional Evaluation of Simulated Small-Scale Irrigation Intervention: A Case Study in Dimbasinia Watershed, Ghana

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**Abstract:** This paper studied the impacts of small-scale irrigation (SSI) interventions on environmental sustainability, agricultural production, and socio-economics using an Integrated Decision Support System (IDSS). The IDSS is comprised of a suite of models, namely the Soil and Water Assessment Tool (SWAT), Agricultural Policy/Environmental eXtender (APEX), and Farm Income and Nutrition Simulator (FARMSIM). The IDSS was applied in Dimbasinia watershed in northern Ghana using irrigation water from shallow groundwater. The watershed has a modest amount of shallow groundwater resources. However, the average annual irrigation water requirement exceeded the average annual shallow groundwater recharge. It was found that the current crop yield in Dimbasinia watershed was only ~40% of the potential crop production. This is mainly related to climate variability, low soil fertility, and land-management practices. For example, application of 50 kg/ha urea and 50 kg/ha DAP doubled maize and sorghum yield from the current farmers' practices. Better income was obtained when irrigated vegetables/fodder were cultivated in rotation with sorghum as compared to in rotation with maize. Investment in solar pumps paid better dividends and also supplied clean energy. The socio-economic analysis indicated that having irrigated dry season vegetables will improve household nutrition. Since shallow groundwater recharge alone may not provide sufficient water for irrigation in a sustainable manner, surface water may be stored using water-harvesting structures to supplement the groundwater for irrigation. Integrated use of the water resources will also reduce depletion of the shallow groundwater aquifer. We conclude that IDSS is a promising tool to study gaps and constraints as well as upscaling of SSI.

**Keywords:** small-scale irrigation; SWAT; APEX; FARMSIM; IDSS; Ghana

## 1. Introduction

The number of malnourished people in the world has dropped substantially [1,2]; however there are still more than 1 billion poor people [3]. The majority of poor people live in developing countries [4,5]. Sub-Saharan Africa has the largest share [1], and the poor in sub-Saharan Africa mostly live in rural areas [6,7].

Agriculture is the major source of income for most developing countries [6,7]. For example, in Ghana, agriculture employs more than half of the population on a formal and informal basis and contributes a quarter of gross domestic product (GDP) and export earnings [8]. This suggests that investment in agriculture can contribute to food security and poverty reduction for the majority of the rural poor [5,7]. Research around the world e.g., [5,9–11] has shown that investment in agriculture can result in a sharp increase in economic development and poverty reduction.

Rainfed agriculture is the dominant source of staple food production in sub-Sharan Africa [4,12,13]. The rainfed agricultural systems in the region are characterized by low productivity [14,15]. The lower level of agricultural production in sub-Saharan Africa is linked to extreme rainfall variability, a high frequency of dry spells and droughts [16,17], and low agricultural inputs such as fertilizer and pesticides [4,17–20].

Research shows that there are no agro-hydrological limitations to double or triple on-farm staple food production in rainfed agriculture in drought-prone environments [21]. Small-scale water management interventions are believed to provide improvements in crop yield [19,21–24]. There is limited research that shows the holistic impacts of small-scale irrigation (SSI) interventions like adopting irrigation technologies, proper use of fertilizer and improved seed varieties on environmental indicators in terms of soil erosion and sediment loadings as well as on family income and nutrition in small watersheds in drought-prone areas. For example, Adeoti [25] and Bhattarai, et al. [26] focused on the impact of irrigation technology adaptation on crop production and farm income while [27,28] studied the effect of SSI on soil loss and the environment. Bizimana and Richardson [29] and Richardson and Bizimana [30] estimated the impact of agricultural practices on household income and nutrition. Impacts of SSI interventions will have different effects in diverse agro-economic contexts. Thus, the impact of these technologies in diverse agro-ecological regions warrants thorough investigation. Such investigations can provide better insights to policymakers in developing countries and to the international agencies that currently provide assistance to improve agricultural productivity, e.g., the United States Agency for International Development (USAID), Swedish International Development Agency (SIDA), United Nations Food and Agriculture Organization (FAO), etc. This study, therefore, developed a framework of an Integrated Decision Support System (IDSS) to study the holistic impacts of SSI on environmental sustainability, crop and water productivity, and household income and nutrition in a watershed in northern Ghana. The IDSS tool includes the Soil and Water Assessment Tool (SWAT) [31], Agricultural Policy/Environmental eXtender (APEX) [32], and Farm Income and Nutrition Simulator (FARMSIM). SWAT analyzes biophysical impacts of intensification at the watershed scale, APEX analyzes the impacts of interventions at the individual fields, and FARMSIM assesses economic feasibility and nutritional impacts at the household level.

## 2. Materials and Methods

### *2.1. Study Area*

This study was conducted in the Dimbasinia watershed in Ghana, which is located at 10°55′14.60″ N, 1°02′14.78″ W in the Upper East Navrongo Region (Figure 1). The catchment area of the watershed is approximately 35 km$^2$. The elevation for the watershed ranges from 173 m to 257 m. The watershed is characterized as flat to gentle slope with an average slope of ~2.6%.

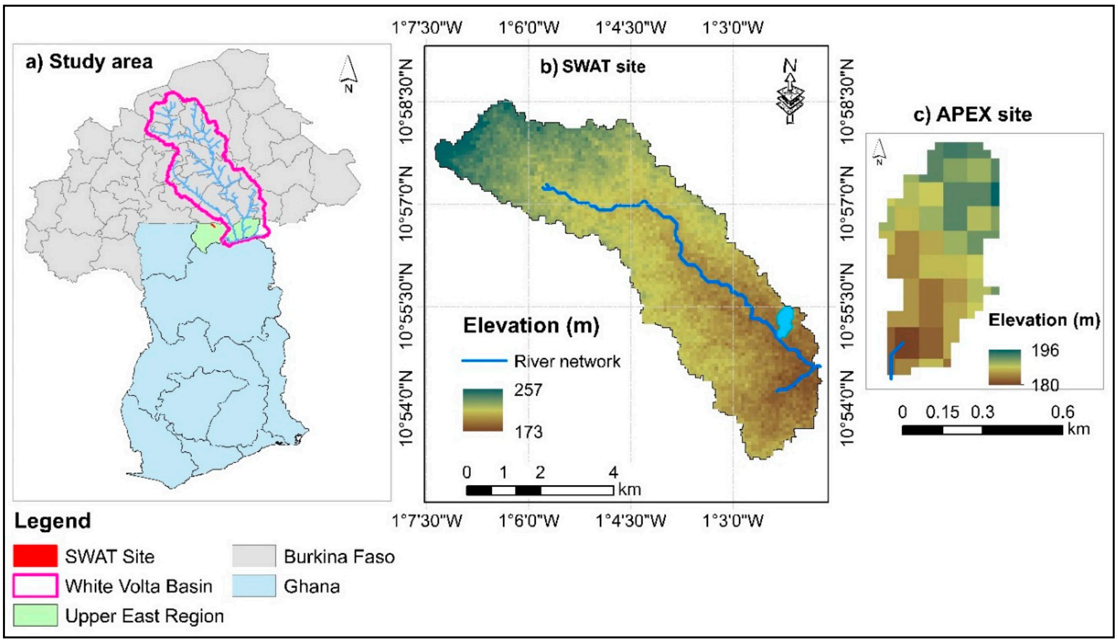


**Figure 1.** Location of study areas for model calibration and Integrated Decision Support System (IDSS) analysis. (**a**) Regional map of Ghana with Upper East Region; (**b**) Dimbasinia watershed with drainage pattern and digital elevation model (DEM) background (Soil and Water Assessment Tool (SWAT) site); and (**c**) Agricultural Policy/Environmental eXtender (APEX) site for field-scale analysis.

### 2.2. Data

The biophysical models require temporal, spatial, land management practices, and crop yield data for model setup, calibration and validation. The socio-economic model uses a household survey on crop and livestock production, historical price estimates for commodities, and consumption patterns to forecast economic and nutrition outcomes. A summary of the IDSS input data, spatial and temporal resolution, is provided in Table 1.

**Table 1.** Summary of input data source, spatial and temporal resolution used for the IDSS analysis.

| Data | Source | Spatial Resolution | Time Period |
|---|---|---|---|
| Climate data | Ghana Meteorological Agency (GMA) | Point | 1980–2013 |
| Climate data | Climate Forecast System Reanalysis (CFSR) | 38 km | 1980–2013 |
| Streamflow | Water Resources Institute of Ghana (WRIG) | Point | 1980–2006 |
| Land use | Volta Basin Authority Geoportal (VBAG) | 250 m | 2010 |
| Soil | Food and Agriculture Organization (FAO) | 1 km | 2007 |
| Digital elevation model (DEM) | United States Geological Survey (USGS) Earth Explorer | 30 m | 2000 |
| Crop management | Africa Rising (AR) project and the International Food Policy Research Institute (IFPRI) | Dimbasinia village | 2013 |
| Crop yield | Spatial Production Allocation Model (SPAM) | 10 km | 2005 |
| Crop yield | FAO Statistics | Country level | 1980–2013 |
| Socio economic data | Africa Rising (AR) project and IFPRI | Dimbasinia village | 2013 |

#### 2.2.1. Temporal Data

The temporal data includes weather and streamflow data. The weather data was used to simulate various biophysical processes in the SWAT and APEX models. It was collected from the Ghana Meteorological Agency. Missing weather data were completed using data from the Climate Forecast System Reanalysis (CFSR) [33], which were obtained from the Texas A & M University Spatial Sciences Lab website [34]. The monthly average meteorological data from 1980–2013 are presented in Figure 2. The area receives a monthly average solar radiation of 20.9 MJ/m$^2$ (Figure 2a). The region has two distinct seasons: a prolonged dry season from November to March and a wet season from April to September (Figure 2b). The annual average rainfall is approximately 900 mm. The watershed receives 75–90% of the annual rainfall from May to September (Figure 2b). The average monthly temperature ranges from 27–33 °C (Figure 2c). The air temperature shows a large diurnal variation but smaller seasonal variability with a monthly standard deviation of 2.2 °C. The monthly average wind speed is highly variable in September, January and February (Figure 2d).

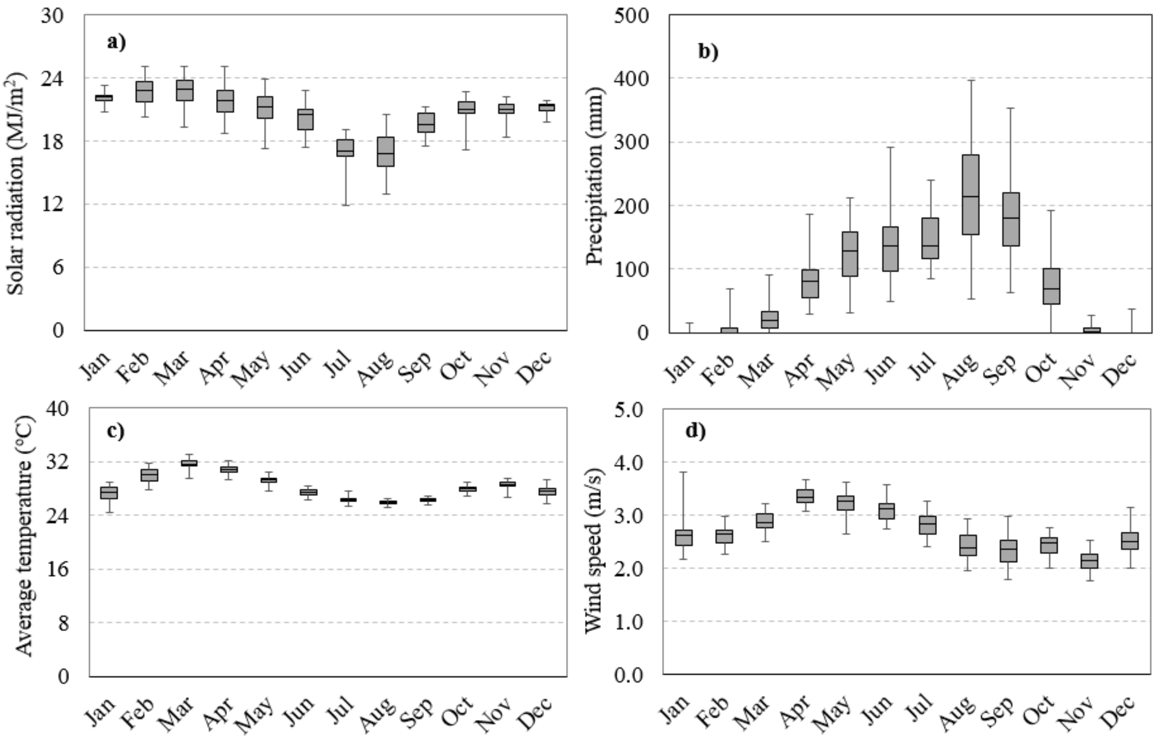


**Figure 2.** Monthly average weather data from 1980–2013 at a synoptic meteorological station. (**a**) solar radiation (MJ/m$^2$), (**b**) precipitation (mm), (**c**) average temperature (°C), and (**d**) wind speed (m/s).

Streamflow data were necessary to calibrate the SWAT model. The streamflow data at Pwalugu River gauging station were obtained from the Water Resources Institute of Ghana (WRIG). The Pwalugu River gauging station measures daily streamflow from a tributary to the White Volta basin from 1951 to 2006; however, complete data were available only from 2003 to 2005. The streamflow data from 2003 to 2004, and 2005 was used to calibrate and validate the hydrological model, respectively.

### 2.2.2. Spatial Data

The spatial data necessary to set up the biophysical models include a digital elevation model (DEM) as well as land-use and soil data. DEM data of 30 m resolution were obtained from the Shuttle Radar Topographic Mission (SRTM) website. The land-use data were obtained from the Volta Basin Authority Geoportal (VBAG) at a resolution of 250 m. Five types of land use were identified in the Dimbasinia watershed. Agricultural land covers 59% of the watershed, and forestland covers 35% of the watershed. The remaining land is covered by pastureland (3%), wetland (2%) and water body (1%). The soil data used were Harmonized World Soil obtained from the Food and Agriculture Organization (FAO) [35]. The harmonized soil database has a 30 arc-second (1 km) spatial resolution, and the data was developed by combining existing regional and national soil data. The harmonized soil database has been used as input to hydrological models and performed well in capturing the observed streamflow [36–38]. Most of the soil in the Dimbasinia watershed was dominated by sandy clay loam.

#### 2.2.3. Land Management and Crop Yield

The crop management information was obtained from a household survey. Crop yield was collected from the Spatial Production Allocation Model (SPAM) dataset [39], the household survey, and FAO Statistics Division [40]. The SPAM data have a spatial resolution of 10 km and were available for 2005. The household survey was conducted in 2013, and the data include crop yield and crop-management practices such as fertilizer type, fertilizer rates, and application dates. Detailed information on crop-management schedules and fertilizer type and application rates for different crops collected through household survey is provided in Tables A1–A3. FAO Corporate Statistical Database (FAOSTAT) (2015) data provide annual crop yield at country level from 1961 to 2013.

#### 2.2.4. Socio-Economic and Farm-Management Data

Farm-level analyses were conducted to evaluate the adoption of agricultural technologies in Dimbasinia village. Much of the data for the farm-level socio-economic analysis were collected using the household survey, which provided data on the production and consumption patterns of a representative household in Dimbasinia. The survey was conducted in 2014 under the Ghana Africa Rising Baseline Evaluation Survey (ARBES). The data collected includes assets, liabilities, agriculture production, costs for agricultural inputs (e.g., fertilizers, seeds, and irrigation), and use of livestock on the farm. Fractions of crop production and livestock consumed and sold are also reported in the household survey. The household survey also provides information on annual fixed costs, loans, and other assets such as land. The survey showed that major cereal crops grown in Dimbasinia village were maize and sorghum. Vegetables such as tomatoes and red pepper were produced in the dry season. The sample size comprised 32 households (out of a total number of 374) and 15% of interviewed farmers reported use of irrigation for crop production. Half of those who irrigate use mainly groundwater (wells) while the rest uses surface water. The use of fertilizer is moderate where around 42% of the households indicated that they applied fertilizer, mainly the N-P-K (Nitrogen-Phosphorus-Potassium). The survey indicates that the majority of the population in the area live on subsistence farming.

### *2.3. Methods*

#### 2.3.1. Model Integration

The Integrated Decision Support Systems (IDSS) was designed to enable comprehensive assessment of impacts of agricultural intervention technologies on biophysical and socio-economic systems at different scales. This study used SWAT, APEX and FARMSIM models in an integrated manner to assess the impacts of SSI technologies on environmental sustainability, agricultural production, economic and nutrition outcomes. SWAT is a physically based model developed to predict the impact of land-management practices on water, sediment, and agricultural yields in watersheds with varying soil, land-use, and management conditions [41]. APEX evaluates the effects of various land-management strategies on the environment (e.g., flow, erosion, water quality, soil etc.), crop growth, and crop yield at field or small watershed scale [32]. FARMSIM is a Monte Carlo simulation model to analyze the economic and nutritional impacts of alternative farming technologies on small farms. In this study, the SWAT model was used to analyze the environmental sustainability of the interventions at the watershed scale, while the APEX model was applied to examine cropping systems at field scale and quantify the changes on crop yields as a result of implementation of the interventions. The FARMSIM model was used to assess the economic and nutrition impacts at household level.

The SWAT model was set up to provide information at a watershed scale. In SWAT, the watershed is divided into sub-basins based on topography, and the sub-basins will be further divided into hydrologic response units (HRUs) based on soil, slope and land use. SWAT was calibrated using streamflow data collected at the Pwalugu River gauging station. APEX was set up in one of the SWAT sub-watersheds that is dominated by agricultural land. The calibrated SWAT flow was used to calibrate the APEX model since the two models share several biophysical equations and use the same input data such as land use, soil, DEM, weather, and crop management. For example, both models estimate potential evapotranspiration, surface runoff and soil erosion using Penman Monteith, Soil Conservation Service (SCS) Curve number, and Modified Universal Soil Loss Equation (MUSLE) methods, respectively. The suitable land for irrigation was estimated with a multi-criteria evaluation based on slope, soil, and land use. The crop related parameters were calibrated with the APEX model at field scale. The crop parameters that were calibrated by APEX were used by the SWAT model to improve its crop growth simulation. The calibrated APEX model was used to simulate crop yield for 32 years of weather data. The simulated crop yield was used as input by the FARMSIM model. Using inputs from APEX and SWAT models and data from the household survey, the FARMSIM model was used to estimate economic and nutrition outcomes at the household level. The framework for the integration of the three models is presented in Figure 3.

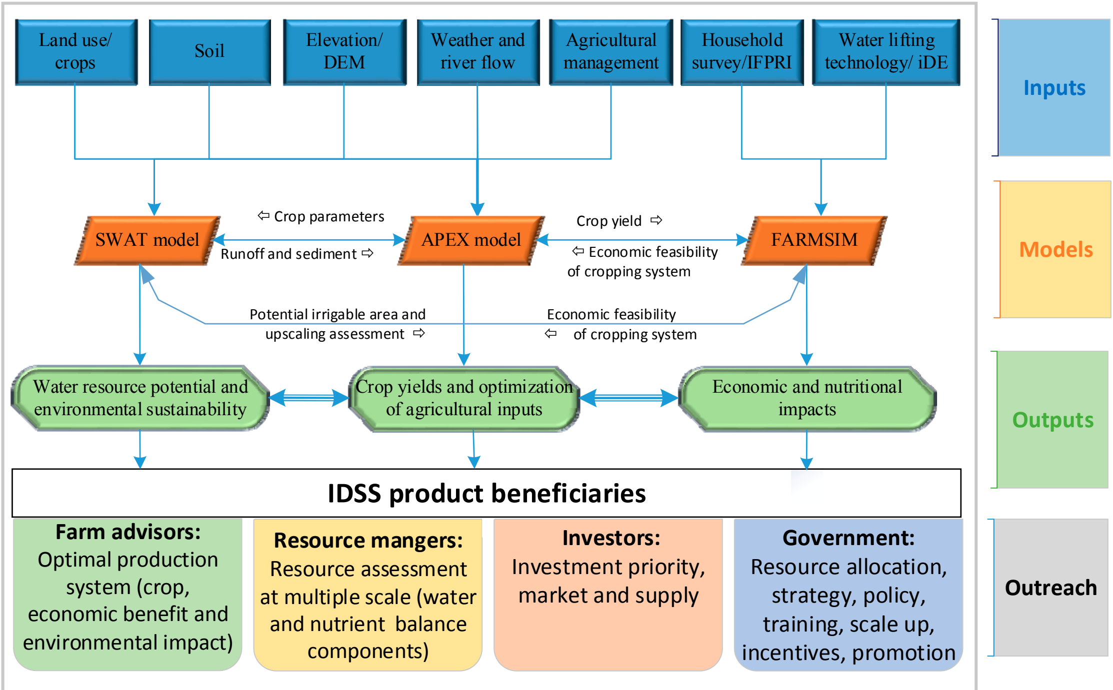


**Figure 3.** Framework for the IDSS of the SWAT, APEX and Farm Income and Nutrition Simulator (FARMSIM) integration.

### 2.3.2. Integrated Decision Support System (IDSS) Model Setup and Calibration

#### Soil and Water Assessment Tool (SWAT) Model Setup and Calibration

The watershed delineation for the Dimbasinia watershed covered an area of ~35 $km^2$. The accuracy of the watershed delineation was checked by overlaying with high-resolution satellite data from Google Earth and an ESRI (Environmental Systems Research Institute) basemap. The watershed delineation process provided 132 sub-basins. Five slope classes were defined in the watershed in order to identify the most suitable land for irrigation requirements [42–44]. The slope classes were <2%, 2–8%, 8–12%, 12–20%, and >20%. The Hydrologic Response Unit (HRU) definition considered all land-use, soil, and slope classes. Maize and sorghum, the dominant crops in the watershed, were simulated with SWAT.

The Dimbasinia watershed was calibrated using streamflow data at the Pwalugu River gauging station located on a tributary of the White Volta basin. The White Volta basin, upstream of the Pwalugu River gauging station, covers an area of 57,564 $km^2$. The model parameters were calibrated using SUFI-2 [45,46] in the SWAT Calibration and Uncertainty Programs SWAT-CUP [47]. After the model was calibrated at the Pwalugu River gauging station, the calibrated parameters were transferred into the Dimbasinia watershed. The calibrated model parameters were transferred to Dimbasinia watershed since the two watersheds has similar characteristics [48–53].

The SWAT model was calibrated from 2003–2005 since streamflow data were available for this time period. The simulated streamflow reasonably captured the monthly observed streamflow (Figure 4). Nash–Sutcliffe efficiency (NSE) and percent bias (PBIAS) were calculated to be 0.77 and 25.5%, respectively. According to Moriasi, et al. [54], the model calibration provided satisfactory performance.

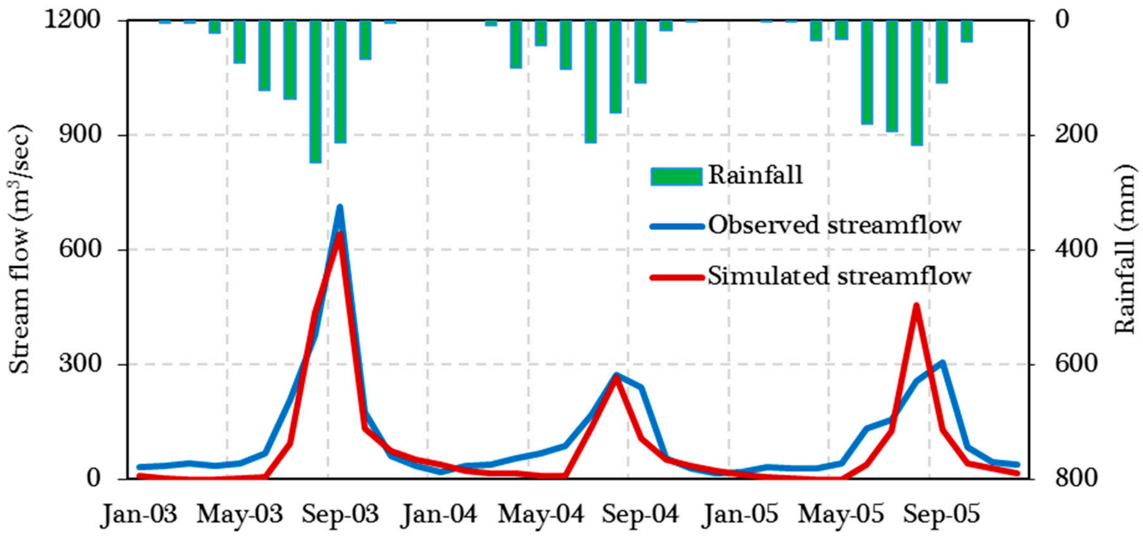


**Figure 4.** Hydrograph for the monthly observed vs. simulated streamflow for the White Volta basin at the Pwalugu River gauging station. The average monthly rainfall in the White Volta basin is presented in the upper panel in the secondary y-axis.

Agricultural Policy/Environmental eXtender (APEX) Model Setup and Calibration

The APEX model was set up using one of the sub-basins of the SWAT model. The sub-basin/sub-area is located at the outlet of the Dimbasinia watershed (Figure 1) and has an area of ~27.6 ha. The elevation for the sub-area varies from 180 to 196 m and has an average slope of ~2.8%. Maize and sorghum are the two dominant crops. The soil in the sub-area consists of 20% clay, 73% sand, and 7% silt, which is classified as sandy clay loam soil by FAO. The APEX model was calibrated for flow for the period 1984 to 2013 using data from SWAT simulations. The APEX streamflow simulation for the calibration period showed satisfactory performance, with NSE and R-square values of 0.88 and 0.89, respectively.

APEX crop parameters were calibrated to capture crop yield of 2005 SPAM crop yield and 2013 household survey. The difference between APEX simulated crop yield and SPAM yield was 8.3% and 8.6% for maize and sorghum, respectively. The simulated crop yield was validated using data from the FAOSTAT for the period 1984 to 2013. The APEX simulated crop yield and FAOSTAT crop yields have a very good agreement. The difference between APEX simulated and FAOSTAT crop yield for maize and sorghum for the study period on average were 7.5% and 4.5%, respectively. While the root mean square error (RMSE) between APEX-simulated and FAOSTAT crop yield for maize and sorghum were 0.57 t/ha and 0.42 t/ha, respectively. The boxplot (Figure 5) presents the simulated crop yield of APEX and FAOSTAT for the period 1984 to 2013. The household survey data and SPAM crop yield data are plotted as point data in Figure 5.

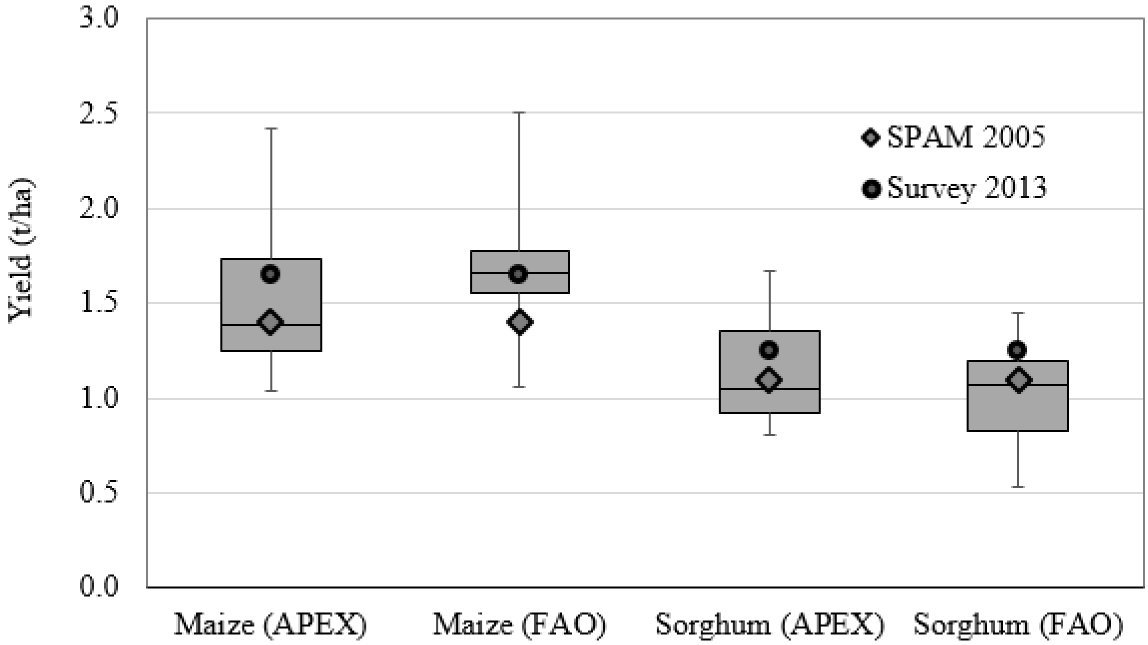


**Figure 5.** APEX simulated and Food and Agriculture Oorganization Corporate Statistical Database (FAOSTAT) maize and sorghum yield for the period 1984 to 2013 are plotted as boxplots. The APEX simulated crop yield is for the Dimbasinia site while the FAO crop yield data is representative for the entire Ghana. The SPAM crop yield is representative for 2005 and the household survey data was gathered in 2013.

Farm Income and Nutrition Simulator (FARMSIM) Model Setup

The FARMSIM model was set up to simulate stochastic prices and production for five years using a multivariate empirical distribution procedure. Stochastic prices are simulated based on a historical range of prices for the region, while stochastic crop yields are based on a multivariate distribution estimated from long-term (32 years) APEX-simulated crop yields representing diverse weather conditions.

The crop production, after satisfying family and livestock consumption, is assumed to be sold. Receipts are simulated as the product of stochastic prices and residual crop and livestock production. While expenses are summations of individual cost per hectare (fertilizer/ha, seed/ha, irrigation/ha, labor/ha, etc.) times the total cultivated land and initial costs of production from the survey. Cash expenses for the family are obtained from the household survey. The results from FARMSIM are interpreted using net cash farm income (receipts minus cash expenses), ending cash (net cash income minus family cash expenses), and net present value (present value of family withdrawals and change in real net worth) over a five-year planning horizon.

### 2.3.3. Scenario Analysis

The baseline simulation was based on the household survey. The majority of the households (85%) use minimal or no irrigation while around 42% reported use of fertilizer. The three models were used to assess different implications of SSIs. The scenarios applied in SWAT, APEX and FARMSIM are discussed in "SWAT Scenario" and depicted in Figure 6.

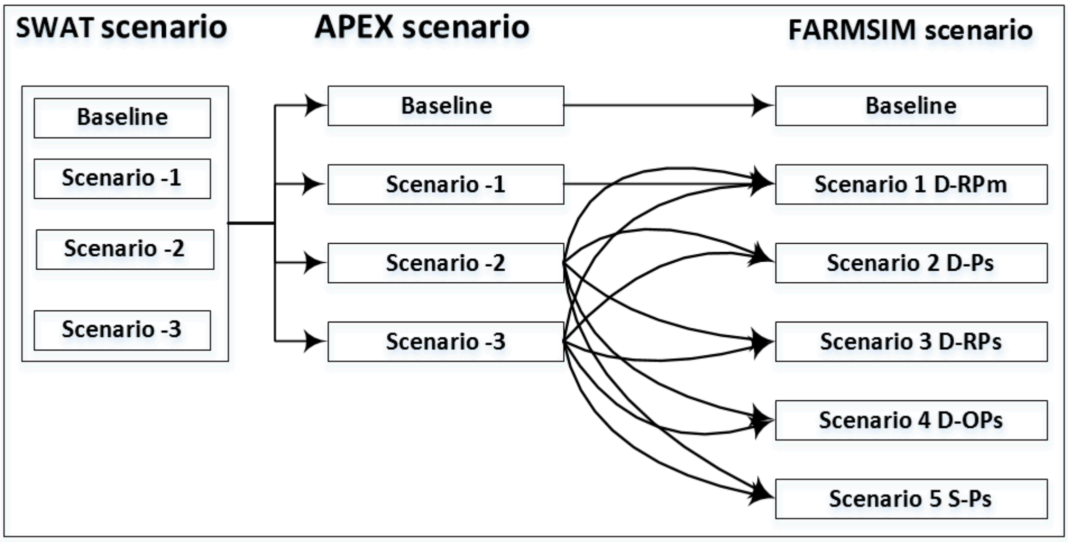


**Figure 6.** Baseline and alternative scenarios integration to evaluate the integrated impact of SSI. Since SWAT is a watershed model with several fields, all these scenarios were implemented in parallel but in different fields. This was to capture the different farmer preferences and practices in the watershed.

SWAT Scenario

Areas that have a slope of less than 8% are generally considered suitable for irrigation [50,55]. In SWAT scenario analysis, irrigation was implemented in areas where the slope is less than 8%. Since SWAT is a distributed model, the scenarios were implemented across the watershed at different spatial locations. The agricultural land in the Dimbasinia watershed covers 2064 ha. The total area that is suitable for irrigation is 1677 ha, which accounts for ~48% of the agricultural land. The scenario considered in SWAT was:

(a) On the other half of the agricultural land with slope of less than 8%: maize was planted during the rainy season, and pepper during the dry season;
(b) On half of the agricultural land with slope of less than 8%: sorghum was planted during the rainy season, and tomato and pepper during the dry season; and
(c) In the remaining land, Napier grass was cultivated as permanent fodder crop in lands where the slope is ~6–8%.

Pepper and tomato were cultivated on 1579 ha agricultural land (each covering 50% of the land) and Napier grass was cultivated on 98 ha of land. The household survey indicated that smallholder farmers in the Dimbasinia watershed used shallow groundwater for irrigation. Thus, shallow groundwater was used as a source of irrigation for the SWAT simulations.

APEX Scenario

Similar to SWAT, rainfed maize and sorghum were cultivated in APEX simulations for the baseline conditions with no fertilizer applications. Three scenarios were simulated with the APEX model to assess the impacts of alternative conditions:

(a) Scenario 1: multiple cropping of rainfed fertilized maize in rotation with irrigated tomato/pepper during the dry season. The fertilized maize was cultivated with 50 kg/ha of urea in split application (i.e., 25 kg/ha during planting and the remaining 25 kg/ha after 30 days of planting) and 50 kg/ha of diammonium phosphate (DAP) at planting. Tomato and pepper were cultivated by applying 50 kg/ha of urea in split application and 50 kg/ha of DAP at planting.
(b) Scenario 2: multiple cropping of rainfed fertilized sorghum in rotation with irrigated tomato/pepper during the dry season. The fertilized sorghum was cultivated with 50 kg/ha of

urea in split application and 50 kg/ha of DAP at planting; Tomato and pepper were cultivated by applying 50 kg/ha of urea in split application, and 50 kg/ha of DAP at planting. Comparison was also done between unfertilized continuously planted maize and fertilized maize.

(c) Scenario 3: continuous cultivation of Napier grass as a perennial crop with supplemental irrigation.

FARMSIM Scenario

FARMSIM was used to assess the economic and nutrition outcomes during the baseline scenario of rainfed crops and five alternative scenarios. The scenarios included cultivation of maize and sorghum in the rainy season, and irrigated vegetables (tomatoes, pepper and fodder) in the dry season. The FARMSIM simulations also considered three different water-lifting technologies such as pulley-and-bucket, diesel motor pumps (rented and owned), and solar pumps. These technologies were evaluated based on their capacity to provide required irrigation water to a maximum irrigable cropland of 1677 ha in the village, taking into account the cost of the equipment and pumping rates. The pumping rate for diesel and solar pumps (40 L/min) is approximately five times the pumping rate of a hand-operated pulley-and-bucket system (8 L/min). Combinations of multiple cropping and three water-lifting technologies provided five alternative scenarios.

In each scenario, the area allocated to vegetable and fodder production was limited by the pumping capacity of the water-lifting technologies. The FARMSIM model was run 500 times for each of the scenarios to sample variation in crop yields due to weather and other stochastic variables. Their economic indicators such as net present value, net cash farm income, and ending cash reserves were used to determine which of the five scenarios would be the most beneficial to farm families. Their respective economic indicators such as net cash farm income and nutrients were used to evaluate the performance of the scenarios. The baseline and five scenarios studied with the FARMSIM model include:

(a) Baseline scenario: current fertilizer application and no or minimal irrigation;
(b) Scenario 1-D-RPm: multiple cropping of rainfed maize with dry-season vegetables/fodder using a rented diesel-pump water-lifting technology;
(c) Scenario 2 D-Ps: multiple cropping of rainfed sorghum with dry-season vegetables/fodder using a pulley water-lifting technology;
(d) Scenario 3 D-RPs: multiple cropping of rainfed sorghum with dry-season vegetables/fodder using a rented diesel pump for water lifting;
(e) Scenario 4 D-OPs: multiple cropping of rainfed sorghum with dry-season vegetables/fodder using owned diesel pump for water lifting; and
(f) Scenario 5 S-Ps: multiple cropping of sorghum with dry-season vegetables using owned solar-pump for water lifting. The solar pump is a new technology in the watershed and there is no sufficient data on rental cost yet. Hence, the option of rented solar pump was not studied as an alternative scenario.

The capital costs of drilling wells were not considered in the analysis since the costs can vary from household to household depending on the type of well-built [56]. However, capital costs related to the water-lifting technology and the operating costs were included in the analysis. To show the full potential of using the alternative farming technologies, a 100% adoption rate was assumed. The markets were assumed to be accessible and function at a competitive level where supply and demand determine the market prices. However, in the five-year economic forecast, the market price in each of the five years was assumed to be equal to the average selling price of year one for each crop sold.

## 3. Result

Implementation of SSI should start with assessment of resource availability at the field as well as watershed scale. If sufficient resources are available, implementation of the irrigation will be proposed. However, the impacts of such interventions on biophysical and socio-economic situations should be studied. This study, therefore, presents such an assessment as follows.

## 3.1. Watershed-Scale Potentials and Impacts

### 3.1.1. Water Resources Potential

The spatial distribution of the annual average groundwater and surface water resources in the Dimbasinia watershed for the baseline (rainfed) scenario is presented in Figure 7. The average annual groundwater recharge was in the order of 147 mm to 295 mm (Figure 7a), and the annual generated surface runoff was estimated to be 45 mm to 97 mm (Figure 7b). Much of the area has an annual groundwater recharge of 200–250 mm and annual surface runoff of 75–97 mm. The average annual volumetric groundwater recharge and surface runoff potentials were over 8.3 million $m^3$ and 3 million $m^3$, respectively.

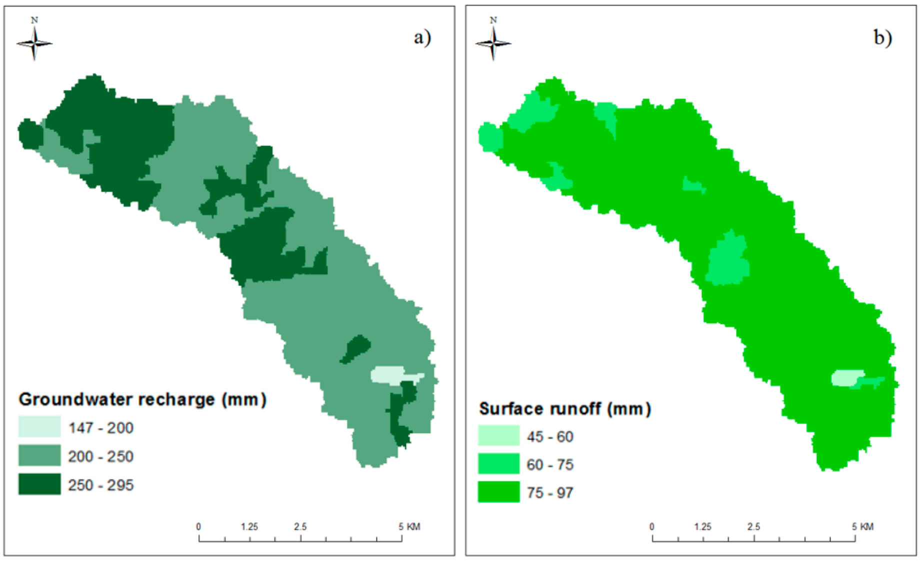


**Figure 7.** Water-resources potential in the Dimbasinia watershed; (**a**) the average annual groundwater recharge (mm), and (**b**) surface runoff (mm).

### 3.1.2. Availability of Shallow Groundwater for Irrigation across the Watershed

The irrigation water for cultivating pepper, tomato and Napier grass was derived from shallow groundwater in the SWAT simulation. Therefore, it was necessary to determine whether there was sufficient shallow groundwater recharge to meet the irrigation water requirements. The average area-weighted irrigation water requirement over the Dimbasinia watershed was 247 mm, and the average area-weighted shallow groundwater recharge was 226 mm. This suggests that the annual shallow groundwater recharge cannot support the irrigation water requirement for producing pepper, tomato, and Napier grass during the dry season.

The area weighted average annual shallow groundwater recharge in the Dimbasinia watershed ranges between 140 and 280 mm (Figure 8a). On the other hand, the average annual irrigation requirement across the watershed ranges from zero to 483 mm (Figure 8b). In a large part of the watershed (~60%), the shallow groundwater recharge was less than the irrigation water requirement. This suggests that irrigation for cultivating pepper, tomato, and Napier grass during the dry season cannot be sustained by the shallow groundwater recharge without affecting the long-term groundwater storage.

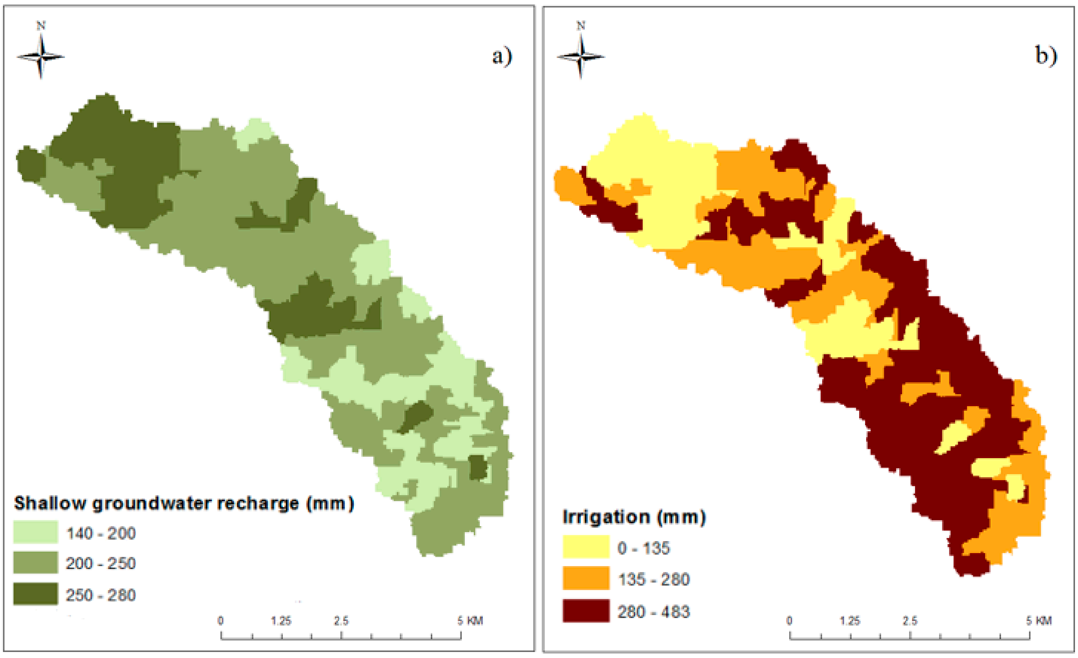


**Figure 8.** (**a**) Average annual shallow groundwater recharge (mm) during the baseline condition, and (**b**) average annual irrigation for cultivating pepper and Napier grass (mm) during the dry season.

#### 3.1.3. Impacts of Small-Scale Irrigation on Watershed Water Balance and Downstream Streamflow

The average annual rainfall in the Dimbasinia watershed for the period of 1980 to 2010 was ~900 mm. About 28% of the annual rainfall was turned into streamflow, and 67% evaporated back into the atmosphere (Figure 9a). Baseflow contributed a larger share (69%) to the streamflow compared to the surface runoff contribution (31%).

Implementation of the scenario of pepper, tomato, and Napier grass production using irrigation from the shallow groundwater aquifer caused a modest effect on the overall water balance dynamics as predicated with SWAT model. With implementation of irrigation, the baseflow contribution to streamflow decreased and the contribution from surface runoff increased (Figure 9a). The groundwater contribution decreased since the irrigation was withdrawn from the shallow aquifer. The increase in surface runoff was due to the increase in soil moisture from irrigation, which could result in an increase in surface runoff generation. The percolation to the soil showed a minor change after irrigation, and deep recharge increased after irrigation.

Implementation of the irrigation scenario resulted in modest reduction to the average monthly streamflow at the outlet of the Dimbasinia watershed (Figure 9b). The average monthly streamflow from 1984 to 2013 during the baseline scenario was 0.32 $m^3/s$. During this time period, implementation of the irrigation scenario reduced the average monthly streamflow to 0.24 $m^3/s$. This is equivalent to a 25% reduction in average monthly streamflow.

The flow duration curve indicates a consistent reduction of the streamflow, including both the high and low flows (except the very low flows) with the implementation of irrigation from the shallow aquifer (Figure 9c). For example, at the 10% probability of exceedance, there was a 24% reduction in streamflow, and at 80% probability of exceedance there was a 32% reduction in streamflow. There was an increase in streamflow with the implementation of irrigation from the shallow aquifer after the 98% probability of exceedance. This may be related to an increase in percolation with the irrigation scenario.

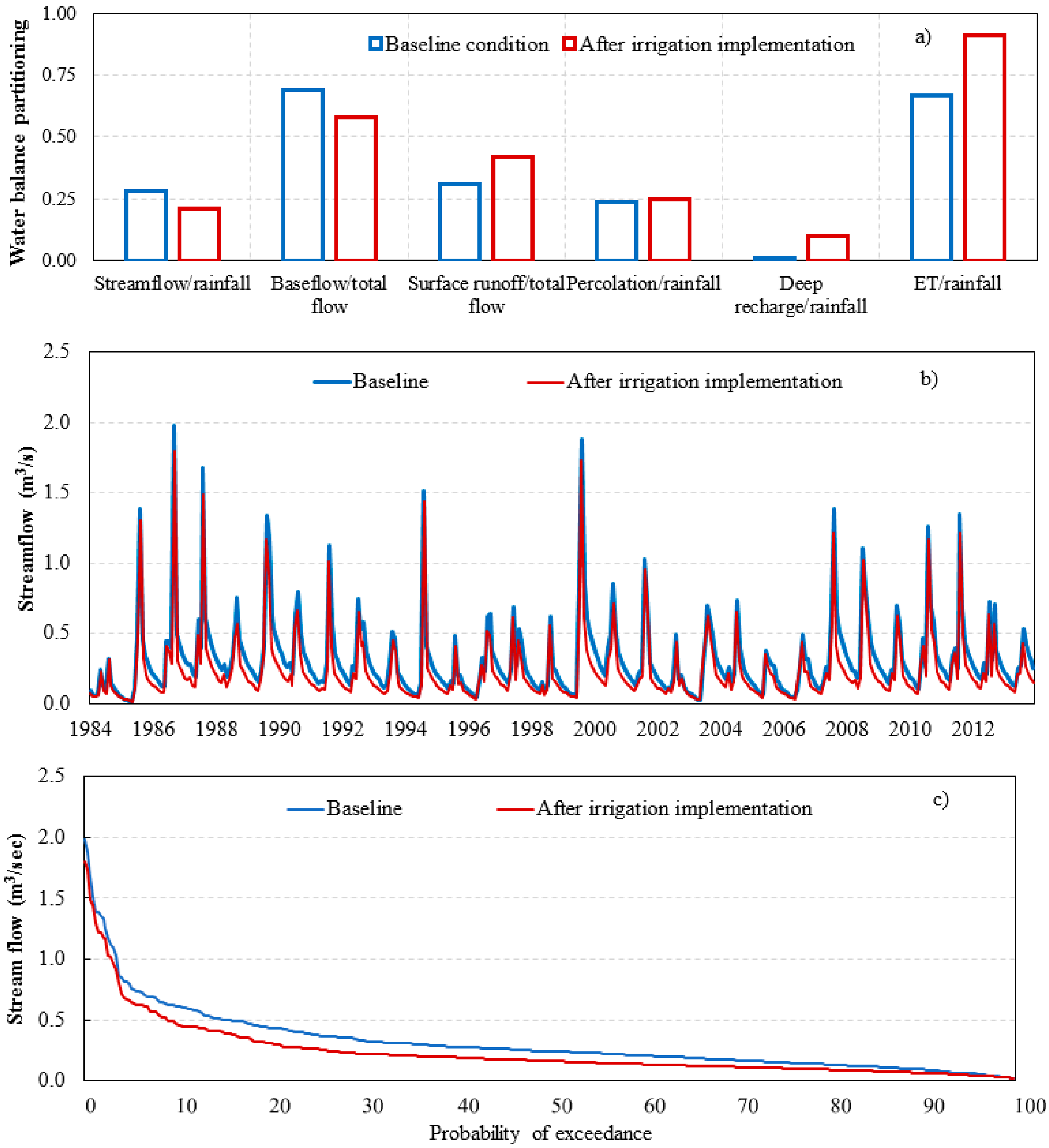


**Figure 9.** Impacts of small-scale irrigation at watershed scale. (**a**) Water balance partitioning for the Dimbasinia watershed before and after irrigation scenario; (**b**) streamflow at the outlet of the Dimbasinia watershed before implementation of irrigation (baseline scenario) and after implementation of irrigation (ex-ante scenario); and (**c**) flow duration curve for the monthly streamflow at the outlet of the Dambiasinia watershed during the baseline and ex-ante scenario.

## *3.2. Field-Scale Potentials and Impact Assessment*

### 3.2.1. Effect of Fertilizer and Multiple Cropping of Maize with Tomato and Pepper—Dynamics in Scenario 1

The result of multiple cropping of rainfed maize in rotation with irrigated crops (scenario-1) is presented in Figure 10a. Temperature and water were not limiting factors for the growth of maize in the Dimbasinia area. However, when maize was cultivated without fertilizer, nitrogen was the main limiting factor. The average nitrogen stress was about 74 days over the growing period. When rainfed maize was cultivated continually with 50 kg/ha urea and 50 kg/ha of DAP, the nitrogen stress days reduced by 25% and the yield increased by 115% compared to the non-fertilized maize (Figure 10a).

However, there was high nitrogen stress even with the added fertilizer, which indicates a potential to increase yield with the application of additional fertilizer. Multiple cropping of maize with pepper and tomato further reduced the nitrogen stress of fertilized maize to 46 and 43 days/year, respectively (Figure 10a). Consequently, the fertilized maize yield increased by 16% and 25% when cultivated after pepper and tomato, respectively. The water and nitrogen stress days were computed by comparing the available amount of soil water and nutrient in the root zone and daily crop demands required for optimal growth. For example, water stress days are estimated as 0.1 days if the root zone available soil moisture meets only 90% of the optimal crop water requirement.

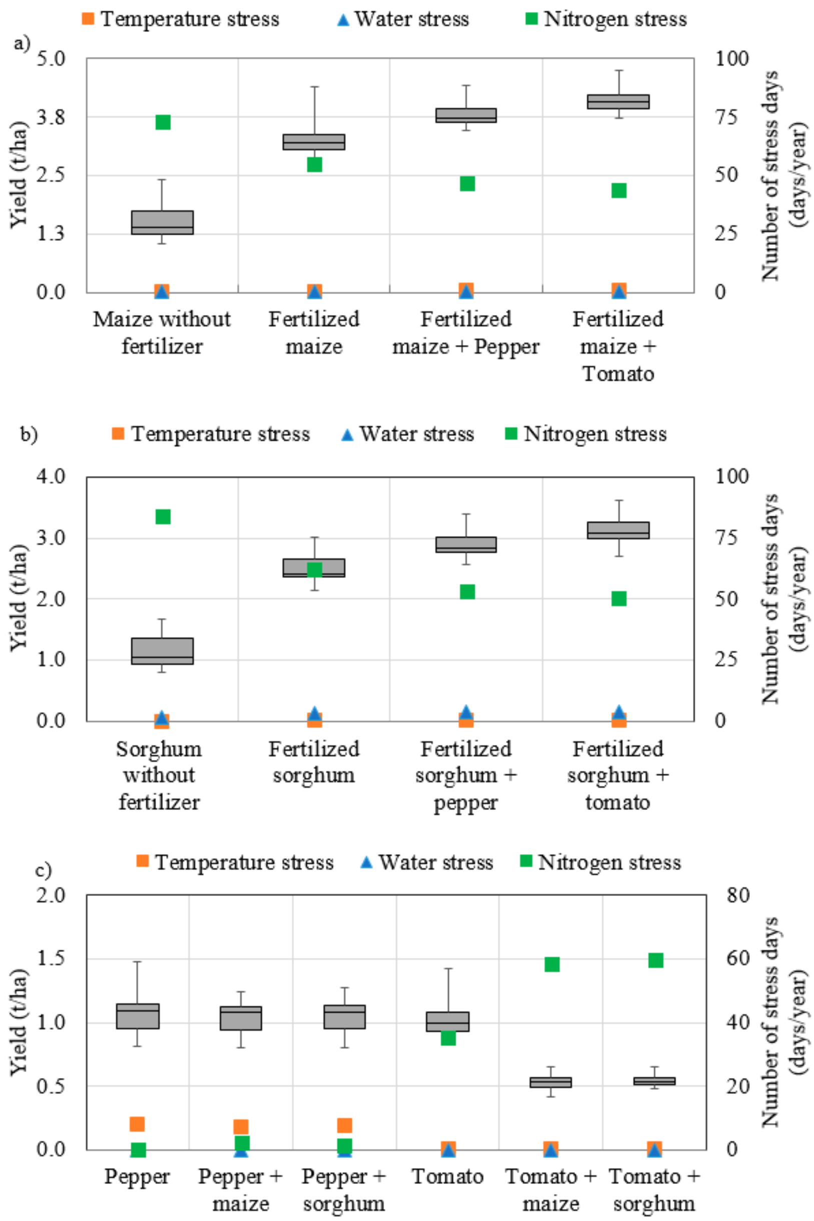


**Figure 10.** (**a**) Comparison of continuously cultivated non-fertilized maize, continuously cultivated fertilized maize, and fertilized maize cultivated in rotation with pepper and tomato. (**b**) Comparison of continuously cultivated non-fertilized sorghum, continuously cultivated fertilized sorghum, and fertilized sorghum cultivated in rotation with pepper and tomato. (**c**) Comparison of irrigated alternative crops cultivated continuously and in rotation with fertilized maize and sorghum. The x-axis shows the cropping pattern; the primary y-axis shows the dry harvested yield (ton/ha) for irrigated crops and the secondary y-axis indicates the number of temperature, nitrogen and water stress days.

#### 3.2.2. Effect of Fertilizer and Multiple Cropping of Sorghum with Tomato and Pepper—Dynamics in Scenario 2

Similar to maize, the simulations with sorghum indicated that nitrogen fertility is the major limiting factor affecting sorghum yield in the Dimbasinia area. Likewise, temperature and water were not limiting factors for the growth of sorghum. When sorghum was cultivated continuously without fertilizer, there were 84 days of nitrogen stress over the growing period (Figure 10b). However, the application of 50 kg/ha urea and 50 kg/ha DAP helped to reduce the nitrogen stress days by 11% and increased crop yield by 119%. The nitrogen stress of fertilized sorghum was further reduced when it was cultivated after irrigated vegetables (Figure 10b). For example, when sorghum was cultivated in rotation with dry-season irrigated crops (pepper and tomato), the nitrogen stress was reduced by 14% and 18%, respectively, which resulted in an increase in sorghum yield by 16% and 24%, respectively, compared to continuously cultivated fertilized sorghum. The increase in yield when sorghum is cultivated in rotation with dry-season irrigated crops was due to the presence of residual nutrient in the soil and nutrient from dry-season crop residue.

#### 3.2.3. Effect of Multiple Cropping of Irrigated Crops with Rainfed Crop—Dynamics in Scenarios 1 and 2

Temperature and nitrogen were found to be the limiting factors for irrigated pepper and tomato, respectively (Figure 10c). Continuously cultivated pepper had a temperature stress of 7 days. Multiple cropping of pepper with maize and sorghum increased the nitrogen stress level by 2 days compared to the continuously cultivated pepper; however, the pepper yield was not significantly affected. Continuously planted tomato was under nitrogen stress for about 35 days. Multiple cropping of tomato with maize and sorghum increased the nitrogen stress days by 67% and 70%, respectively. This caused a reduction of tomato yield by 49% and 48% when cultivated in rotation with maize and sorghum, respectively (Figure 10c).

#### 3.2.4. Irrigated Napier Grass—Dynamics in Scenario 3

Napier grass was planted as a perennial crop with supplemental irrigation applied in the dry season. Irrigation was applied to fill the root-zone soil moisture to field capacity, and a maximum annual irrigation volume of 800 mm was budgeted. The first Napier harvest was scheduled after three months with a subsequent cutting every 60 days over three years before replanting. Napier yield varies from 15–19 ton/ha. Napier grass yield was limited by high temperature, water and nitrogen stress. On average, Napier was stressed for 28, 80, and 82 days per year for high temperature, water, and nitrogen, respectively.

### *3.3. FARMSIM Economic and Nutrition Impacts*

#### 3.3.1. Economic Impacts

Net present value (NPV) is an indicator that assesses the feasibility and profitability of an investment or project over a certain period of time. The NPV results, as illustrated by the cumulative distribution function (CDF) graph in Figure 11a, indicate the importance of investing in certain methods of irrigation, fertilizers, and multiple cropping of dry-season crops with sorghum. Scenarios 3, 4 and 5 (multiple cropping of rainfed sorghum with irrigated crops, using diesel and solar-pump irrigation) showed outstanding performance. Their CDF values lie distinctly to the right of the other scenarios for all 500 simulations of the model. Of the alternative scenarios, scenario 2 (multiple cropping of rainfed maize with irrigated crops, using diesel-pump irrigation) and scenario 1 (multiple cropping of rainfed sorghum with irrigated crops using pulley irrigation) were the lowest performing, although both performed considerably better than the baseline scenario. The increase in NPV from scenario 2 to scenario 3 is solely attributable to the shift from maize to sorghum since all other conditions remain the same.

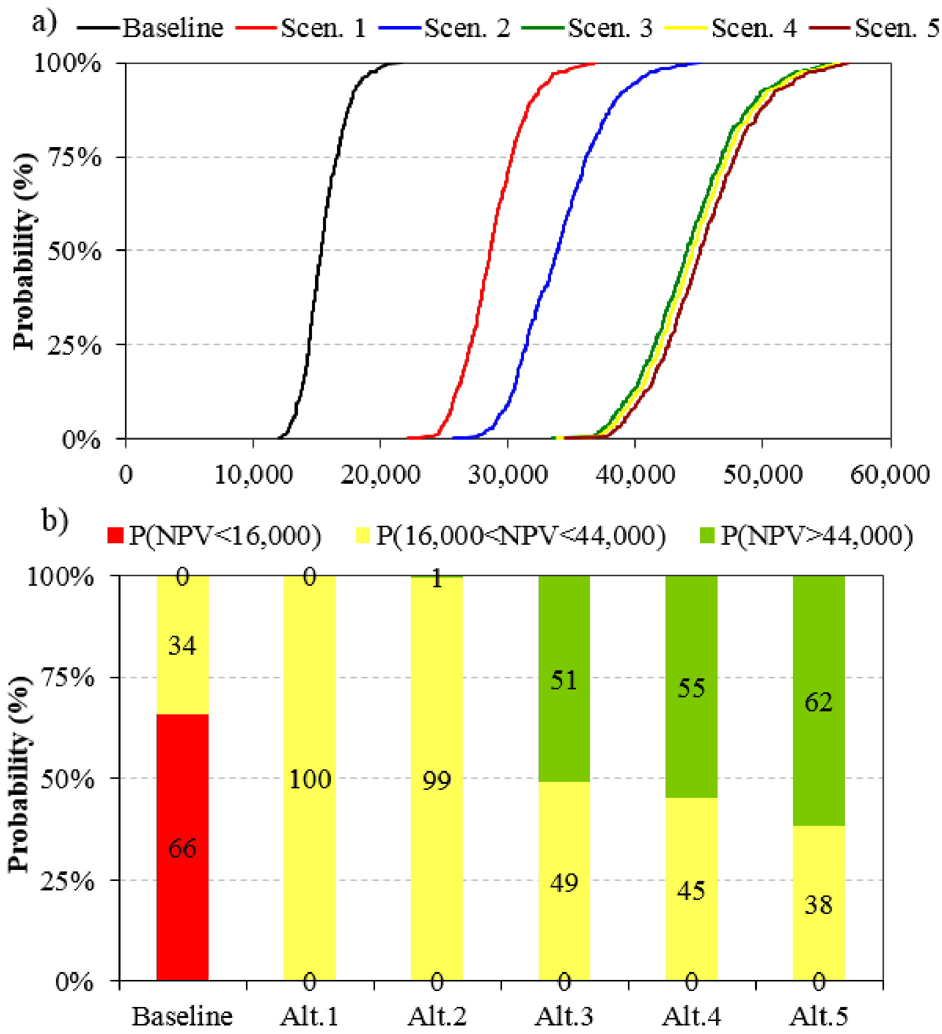


**Figure 11.** (**a**) Cumulative distribution function of net present value (NPV) of the baseline and alternative scenarios, and (**b**) stoplight chart of the probability of NPV less than 16,000, between 16,000 and 44,000 and above 44,000 of Ghanaian cedi (GH₵) for the baseline and alternative scenarios in Dimbasinia village. Scen. 1, Scen. 2, etc refer to the FARMSIM scenarios.

The stoplight chart (Figure 11b) presents the probabilities in each of the six scenarios of NPV less than 16,000 GH₵ (Ghanaian Cedi, 1 USD ~4.25 GH₵) (red), greater than 44,000 GH₵ (green), or between the two target values (yellow) for the five-year planning horizon. The target values are the average of NPV for the lowest performing scenario (baseline) for the lower bound (16,000 GH₵) and the average of the two best-performing scenarios (alternative scenarios 4 and 5) for the upper bound (44,000 GH₵). For a farmer operating in the baseline scenario, there is a 66% chance that NPV will be less than 16,000 GH₵ and a 0% chance that NPV will exceed 44,000. In contrast, for a farmer who implements alternative scenarios 3, 4, or 5, there is a 0% chance that NPV will be less than 16,000 GH₵; moreover, the probability that NPV will exceed 44,000 GH₵ is 51%, 55%, and 62%, respectively. The main barrier to the best-performing scenario (alternative scenario 5, which uses solar-pump irrigation) is the initial investment in the solar pump, which is twice that of a diesel pump. However, because the long-term maintenance and environmental costs of solar pumps are much lower than those of diesel pumps, the NPV results strongly suggest that an investment in solar water-lifting technologies will pay dividends in the long run.

The net cash farm income (NCFI), which indicates the actual annual profit of each of the scenarios, indicated a similar pattern to the NPV. Figure 12 shows that scenarios 3, 4 and 5 generated much higher NCFI than the other scenarios, as their CDF values lie to the right of the other scenarios for all 500 simulations. Scenario 1 and Scenario 2 were the lowest-performing scenarios, although both performed considerably better than the baseline scenario. The large increase in NCFI from alternative scenario 2 to alternative scenario 3 was solely attributable to the shift from maize to sorghum production. On the other hand, the choice to rent or own a diesel pump (alternative scenarios 3 and 4, respectively) did not have a significant effect on NCFI.

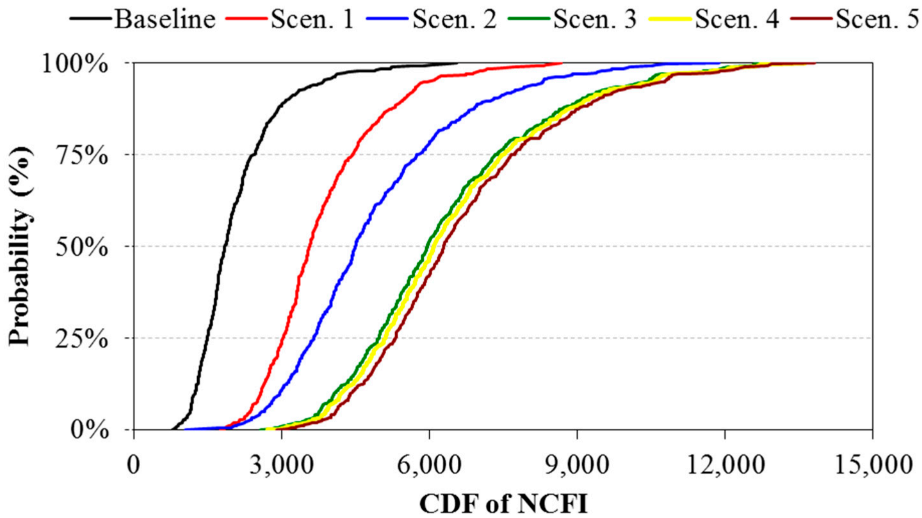


**Figure 12.** Cumulative distribution function of the net cash farm income (NCFI) of the baseline and alternative scenarios.

### 3.3.2. Nutrition Impacts

Adoption and proper use of agricultural technologies generally lead to an increase in the quantity and variety of crops produced [50]. The implications for nutrition vary depending on the type of crops cultivated and consumed; however, surplus food can be sold at market with the resulting revenues used to supplement individual nutrition requirements.

In Dimbasinia, the quantities of crops and livestock products consumed by families in the baseline scenario were insufficient to meet daily requirements for calories, protein, fat, calcium, iron, and vitamin A [57,58]. In the alternative scenarios, increases in crop production and yields led to significant increases in the quantities of nutrients produced and consumed. In the alternative scenarios, levels of calories, protein, and fat met and even exceeded daily requirements for an adult while levels of calcium, iron, and vitamin A were adequate.

## 4. Discussion

The findings suggest that there is modest water resources potential for irrigation in the Dimbasinia watershed. The total annual groundwater recharge was more than 147 mm, and the annual generated surface runoff was more than 45 mm. However, the average annual irrigation water requirement for cultivating pepper, tomato, and Napier grass exceeded the average annual shallow groundwater recharge. Implementation of irrigation for dry-season pepper, tomato, and Napier grass production caused modest reduction in the monthly streamflow. The peak flows and low flows were reduced with the implementation of irrigation in the dry season.

In the Dimbasinia watershed, groundwater is used for cultivating vegetables. However, in a large part of the watershed, the annual irrigation water requirement for cultivating vegetables was more than the annual shallow groundwater recharge. Thus, using the groundwater for vegetable cultivation during the dry season is not a sustainable practice. Rather, surface runoff should be used in combination with groundwater to meet the irrigation water requirement. The surface runoff can be stored using water-harvesting structures [59]. Moreover, cultivating water-efficient crops and use of efficient water application practices (e.g., drip irrigation) for the dry season can help to improve agricultural production while reducing negative externalities on the environment.

Improved irrigation efficiency on distribution, conveyance and application of irrigation can enhance agricultural production in Ghana. For example, traditional or conventional irrigation efficiency in the Upper East Region of Ghana is low ~48% [60,61] that leads to a loss of ~27% of the potential maximum profit [61,62]. Improving irrigation efficiency by applying irrigation at the right time and amount will improve water productivity as well as ensure environmental sustainability, e.g., through a reduction of groundwater depletion.

Generally, agriculture in sub-Sharan Africa is often described as a low input and low output system (CA, 2007). For example, the rainfed crop (e.g., maize and sorghum) yield in Dimbasinia watershed was only ~40% of the potential crop production. This is mainly related to the management of the agricultural fields in terms of providing the right amount of water and nutrients at the right time. In this research, we found that nitrogen was the most limiting nutrient for rainfed crops such as maize and sorghum. For example, the average annual yield for non-fertilized maize and non-fertilized sorghum was about 1 ton/ha. Application of a modest amount of fertilizer (50 kg/ha urea and 50 kg/ha DAP) almost doubled the crop yield. Multiple cropping via crop rotation is found to increase maize and sorghum yield. The increase in crop yield is related to improvement in soil fertility as a result of increased crop residue and residual nutrient from dry-season vegetable crops (pepper and tomato). On the other hand, for cultivating vegetable crops in the dry season, temperature and nitrogen were found to be the limiting factors for crop growth and better crop yield. Crop rotation between pepper and maize/sorghum showed insignificant changes for pepper yield compared to continuous pepper cultivation, while crop rotation between tomato and maize/sorghum showed a reduction in tomato yield compared to continuous tomato cultivation. This suggests that it requires a proper understanding of the agricultural system to enhance agricultural production. In fact, our findings highlight the fact that proper crop management can lead to significant improvement in agricultural productivity at the field scale. If the achievements at field scale exemplified in this research are adopted nationally in Ghana, it can improve its food security.

Multiple cropping in a year, besides providing more agricultural production per year, can reduce crop land expansion in search of more produce, thereby minimizing negative externalities on the environment. Moreover, multiple cropping reduces the exposure of the soil to wind and water erosion since the land is in cultivation for most of the year. This practice may help to maintain soil fertility.

Our economic analysis showed that crop rotation between sorghum and vegetables is more economical than crop rotation between maize and vegetables. Diesel pumps and solar pumps were the most profitable technologies for irrigation. Given that solar technologies are environmentally friendly, we recommend solar pumps as the best option. Per capita income in Ghana is US$ 1858 (~7900 GH₵) (FAO, 2015). Using the solar pump irrigation technologies, at the end of the five-year planning horizon the probability of getting a net present value of more than 44,000 GH₵ is 62%. Currently, Ghana is a middle-income West African country. Ghana has the ambition to become the first African developed country between 2020 and 2029 and a newly industrialized country between 2030 and 2039 through the integration of science and technology in governmental programs, including in the agricultural sector (FAO, 2015). Agriculture accounts for 23% of Ghana's national GDP in 2012 (FAO, 2015). Our findings highlight the fact that use of small-scale and sustainable irrigation practices can contribute to meeting Ghana's national goal.

Even though the IDSS suite of models (i.e., SWAT, APEX and FARMSIM) are independent of each other, the output of one model was used as an input to the other model and helped to develop a compelling approach that estimates the holistic impacts of SSI on agricultural production, environmental sustainability and economic and nutrition outcomes. In fact, there are some uncertainties that could be improved to enhance the robustness of the findings. For example, lack of availability of long-term observed streamflow data compelled us to relay parameter transfer based on watershed similarity in order to establish a calibrated hydrologic model for impact analysis. Perhaps the presence of long-term observed data could provide more reliable estimations. However, every effort was made to use the best available local and global data to reduce the uncertainty of the model predictions. The other limitation was also the assumption of 100% adoption probability of SSI in the socio-economic model, which may not be the case in practice. However, this assumption was made to show the full potential and impacts of SSI for wide-scale adoption. Overall, the IDSS framework proved to be a valuable tool for investigating gaps and constraints of SSI, and also for upscaling.

## 5. Conclusions

The impacts of SSI on local biophysical and socio-economic factors were studied using three models in an integrated manner. The use of groundwater alone was not a sustainable approach to improve agricultural production in the Dimbasinia watershed in Ghana. However, the combined use of groundwater and surface water can enhance agricultural production while reducing negative externalities on the environment. The current agricultural system in Dimbasinia watershed is underperforming. The application of modest amounts of fertilizer can double agricultural production. Multiple cropping in a year can improve rainfed production by improving soil fertility and producing additional vegetation crops in the dry season. Since multiple cropping helps to produce more from the same field, it will reduce cropland expansion to other land-use types. This, therefore, reduces the negative externalities of agricultural expansion. Multiple cropping is also found to be economically viable. Use of solar pumps to cultivate sorghum in rotation with vegetable crops is the most economical and sustainable option. We conclude that the IDSS analysis is a useful tool to study the holistic implications of SSI on environmental sustainability, agricultural production and household income and nutrition. Such an analysis can help to study the gaps and constraints in upscaling SSI.

**Author Contributions:** A.W.W. did the APEX work, Y.D.T. did the SWAT work, J.-C.B. did the FARMSIM work. A.W.W., Y.D.T. and J.-C.B. wrote the paper. J.J., T.G., R.S., J.W.R. and N.C. supervised the research.

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## Appendix A

Crop-management schedules and fertilization (type and application rate) for (a) maize, (b) sorghum, (c) tomato and pepper, and (c) Napier grass

**Table A1.** Maize schedule with and without fertilizer.

| Maize Practice | Dates | Without Fertilizer | With Fertilizer |
|---|---|---|---|
| Tillage | 15-May | | |
| Tillage | 1-June | | |
| Tillage | 15-June | | |
| Diammonium phosphate (DAP) fertilizer application | 15-June | Don't apply | 50 kg/ha |
| Planting | 15-June | | |
| 1st stage urea fertilizer application | 15-July | Don't apply | 25 kg/ha |
| 2nd stage urea fertilizer application | 15-August | Don't apply | 25 kg/ha |
| Harvest | 15-October | | |

**Table A2.** Sorghum schedule with and without fertilizer.

| Sorghum Practice | Dates | Without Fertilizer | With Fertilizer |
|---|---|---|---|
| Tillage | 15-May | | |
| Tillage | 1-June | | |
| Tillage | 15-June | | |
| DAP fertilizer application | 15-June | Don't apply | 50 kg/ha |
| Planting | 15-June | | |
| 1st stage urea fertilizer application | 15-July | Don't apply | 25 kg/ha |
| 2nd stage urea fertilizer application | 15-August | Don't apply | 25 kg/ha |
| Harvest | 23-October | | |

**Table A3.** Tomato and pepper.

| Operation | Irrigated Tomato | Irrigated Pepper |
|---|---|---|
| Tillage | 10-November | 23-November |
| Tillage | 25-November | 8-December |
| DAP application (50 kg/ha) | 25-November | 8-December |
| Planting | 25-November | 8-December |
| 1st stage urea application (25 kg/ha) | 25-November | 8-December |
| 2nd stage urea application (25 kg/ha) | 25-November | 7-Janary |
| Harvest | 11-April | 26-April |

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