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# Rainfall variability adaptation strategies: An ex-ante assessment of supplemental irrigation from farm ponds in southern Burkina Faso

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ABSTRACT

This study assesses the economic value of supplemental irrigation as a rainfall variability adaptation strategy in a small catchment in south-western Burkina Faso. The bio-economic model built for the catchment maximises net cash income by optimally allocating land, labour, water and capital. Yields vary according to soil type, agricultural practice and the type of rainy season. We introduced farm ponds as an adaptation strategy – called supplemental irrigation – for grain crops during long dry spells in the rainy season. Simulation results show that supplemental irrigation can be cost effective and increase incomes, particularly during years with poor rainfall. However, in this catchment, gains from supplemental irrigation are limited because labour and capital are constraints on pond implementation.



## 1. Context and issues

Agricultural production in sub-Saharan Africa is mainly rain-fed and as such is particularly vulnerable to rainfall variability, such as long dry spells. African rainy seasons experience recurrent dry spells, as described in many climate-related studies (Modarres, 2010; Barron, 2004; Barron et al., 2003; Sivakumar, 1992). These dry spells are important factors in crop failures, depending on when they occur during the cropping season, and their duration and frequency (Barron et al., 2003).

This variability has a direct impact on the primary production, diets and monetary incomes of rural families and food supply (Failler, 2014; Badolo and Kinda, 2014). Farmers have developed strategies to counter this rainfall variability. Soil and Water Conservation (SWC) techniques such as zaï, half-moons and stone bunds help concentrate water and fertilizer around crops' roots (for more details, see Zougmoré et al., 2014)

These techniques are rendered ineffective when dry spells, sometimes exceeding two weeks, are too long (Roose, 1993; Sultan et al., 2013). Furthermore, some SWC techniques have been found to be barely cost effective for individual farmers, as grain yield increases do not necessarily cover labour inputs and construction costs. For example, it has been shown that in central Burkina Faso, yield increases do not cover the cost of constructing stone bunds in the community because of the large amount of labour required to collect and transport the stones from their original locations to the fields (Barry et al., 2008). The construction of stone bunds was found to be profitable when the investment costs were reduced by providing free transportation of stones.

With the projected increase in the occurrence of extreme weather events, there should be a focus on techniques that increase production while reducing the impact of rainfall variability. Supplemental irrigation from farm ponds has long been identified as a production technique that should reduce such uncertainties and ensure better food security. Supplemental irrigation is implemented during dry spells in the rainy season to prevent crops from suffering excessive water stress. Sané et al. (2008) described the characteristics of such dry spells. In Burkina Faso, the implementation of supplemental irrigation depends on farm size, available water resources, and technical and financial considerations (Narayan et al., 2008; CNID-B, 2009). Many authors have shown supplemental irrigation's potential to minimise risks and increase crop yields in sub-Saharan Africa. Dugué (1986) tested supplemental irrigation from small farm ponds in northern Burkina Faso and assessed how it could secure production, especially in years with poor rainfall. Fox et al. (2005) have shown that the use of farm ponds and supplemental irrigation can be cost-effective in rain-fed agriculture in Kenya, Tanzania and Burkina Faso. In 2005, the National Agricultural Research Institute (INERA) in Burkina Faso tested supplemental irrigation on

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sorghum production in Saria under a Sudanese climate (average annual rainfall of 750 mm) and in Sabouna under a Sahelian climate (average annual rainfall of 400 mm). Compared to hand tillage (with hoes), the trial showed that supplemental irrigation has more of an effect on grain yields in the Sahel while tied ridges were more efficient under the Sudanese climate (Somé and Ouattara, 2005). The variability (long dry spells) of current rainfall in the Sahel does not allow SWC techniques to be more efficient than supplemental irrigation. However, the authors found that deep ploughing with animal power was an important element that allowed yield gains with supplemental irrigation. Also, the Burkinabe National Committee on Irrigation and Drainage (CNID-B, 2009; Coulibaly et al., 2011) has conducted supplemental irrigation tests in the Sourou Valley on 200 ha of maize over a period of three years (2008–2010). Yields were above 4 tonnes per hectare and increased by between 230% and 300%, providing a significant return on investment. In Burkina Faso, the National Programme on Climate Change Adaptation Strategies (PANA) has incorporated supplemental irrigation in its priority project.

Drawing on the experience of a pilot project, Burkina Faso's Ministry of Agriculture launched a ‘maize garden’ development project mainly in the Sahelian and Sudano-Sahelian agro-climatic zones in 2012. Several thousand farmers were given subsidies of US$ 163 to dig farm ponds of 300m$^3$. Farmers dug a total of 3000 farm ponds and, though the impact of the project still has to be evaluated, the Burkina Faso government has initiated another pilot project to promote supplemental irrigation. This project seeks to add thousands of new small ponds collecting runoff water to secure around 2500 ha throughout the country.

Most of the studies reviewed were limited to measurements of yields and agronomic impact but did not quantify the economic impact of supplemental irrigation at the farm scale. Supplemental irrigation has been tested in northern Burkina Faso, but not in the more humid southwest. The southwest region is the most favourable for agricultural production in the country and is increasingly marked by strong spatial and temporal rainfall variability, thereby affecting production choices and farmers' incomes. These rainfall disruptions are becoming recurrent, causing a high risk of food insecurity.

The purpose of this study is to assess the economic impact of building farm ponds for supplemental irrigation in southwest Burkina Faso. Using a bio-economic model, we compared a baseline scenario to a scenario with supplemental irrigation in which farmers in the catchment dig farm ponds to irrigate their crops during long dry spells in the rainy season. We quantified the impact of the technology on catchment incomes. After an in-depth description of the study area, we present the model built to test the technology (Section 2) and discuss the results (Section 3).

## 2. Method

### 2.1. The study area

This study was conducted in the village of Pontièba located in the municipality of Dano in southwest Burkina Faso (Fig. 1). The average annual rainfall is 850 mm and the rainy season extends from May to October. It is followed by a dry and cold season from November to January and then a dry and hot season from February to May. The length of the growing period is quite variable, ranging from 70 to 100 days. The number of dry days within the growing season has increased significantly, indicating a change in rainfall distribution.

The farming system in the village of Pontièba is typical of the Dano catchment area. The main rainfed crops include maize, sorghum, millet, cotton and, to a lesser extent, cowpea, groundnut and sesame. Sorghum, cotton and maize are grown in the best soils; millet and sorghum are grown on shallower soils and maize in home gardens. Cowpea is usually grown in combination with a cereal. Rice is grown in flooded lowlands during the rainy season. In lowlands with a low flood risk one can also find maize. In irrigated areas, farmers grow rice during the rainy season and vegetables during the dry season, but not necessarily on the same plots.

Hand tillage (with traditional hoes) is commonly used for soil preparation and weeding. Only 20% of households in the catchment area use animal traction. Sowing and harvesting are manual.

The traditional SWC techniques are not common in the catchment and fallowing soils is becoming rare. In the mid-1990s the average fallow period was about six years, but this has dropped to three years today (DPASA, Ioba, 2013). The use of organic fertilizers depends on the quantities of manure available and usage is still very low because the region is not livestock-oriented. Inorganic fertilizer use is low because of the difficulties obtaining credit from banks. Fertilizers are mainly applied to cotton, as the cotton company distributes inputs on credit (fertilizers, seed and pesticides), with the cost of these inputs deducted from the revenues generated after harvest.

### 2.2. Sampling and data collection

Data about the Pontièba farms in the catchment come from several sources. A survey of a sample of 100 households randomly selected in the village of Pontièba by Yili (2006) was conducted in two phases in order to describe the farmers' activities and constraints, and generate data that can help aggregate and parameterise the catchment model. In the first phase, the author identified the characteristics of the households in the area (family size, labour, consumption expenditures, capital, etc.). The catchment is composed of about 300 households with an average of 6 people per household. Cereals such as sorghum, maize and millet are the most consumed. Grain demand per individual per year is estimated at 200 kg according to the standards of the Ministry of Agriculture. In the second phase, the survey focused on land use with plot identification using a Global Positioning System (GPS).

Yields, prices and climate data (long-term records: 1981–2013) available for Dano and the surrounding provinces from the Ministry of Agriculture and the Burkina Meteorological Department served to estimate average crop yields and prices. Finally, we held two focus group discussions (FGDs), the first with selected farmers and the second with local agricultural technicians to cross-check the data on yields and prices and discuss some aspects of the cropping patterns and the model.

The irrigated area of Pontièba, from the common reservoir, covers about 25 ha or about 2% of the surface area of the catchment (about 13 km$^2$). The reservoir located upstream has a capacity of 300,000 m$^3$. When it is full, it allows rice and two successive crops to be irrigated: usually, rice during the rainy season, and then maize or vegetables during the dry season. Dry season production is not always possible because the size of the catchment area means that the reservoir is not completely filled every year. Therefore, the irrigated area varies between 17 and 25 ha, depending on the water available in the reservoir after the rainy season.

### 2.3. Formulation of the model

The model used in this study is a bio-economic optimisation model that seeks to represent the interactions between a stock of natural capital and the economic activity supported by it (Pacini et al., 2004). In our case the natural stock is the stock of water in the reservoir. Bio-economic models help describe the combination of activities that maximise income and as such are more likely to be implemented by farmers. They are ex-ante assessment tools (Torkamani, 2005; Pacini et al., 2004; Hazell and Norton, 1986) that help test some key innovations, in our case supplemental irrigation.

We have chosen not to represent animal breeding in the model because the region is not livestock-oriented. Given the relative isolation of the area, we have also chosen not to include off-farm activities.

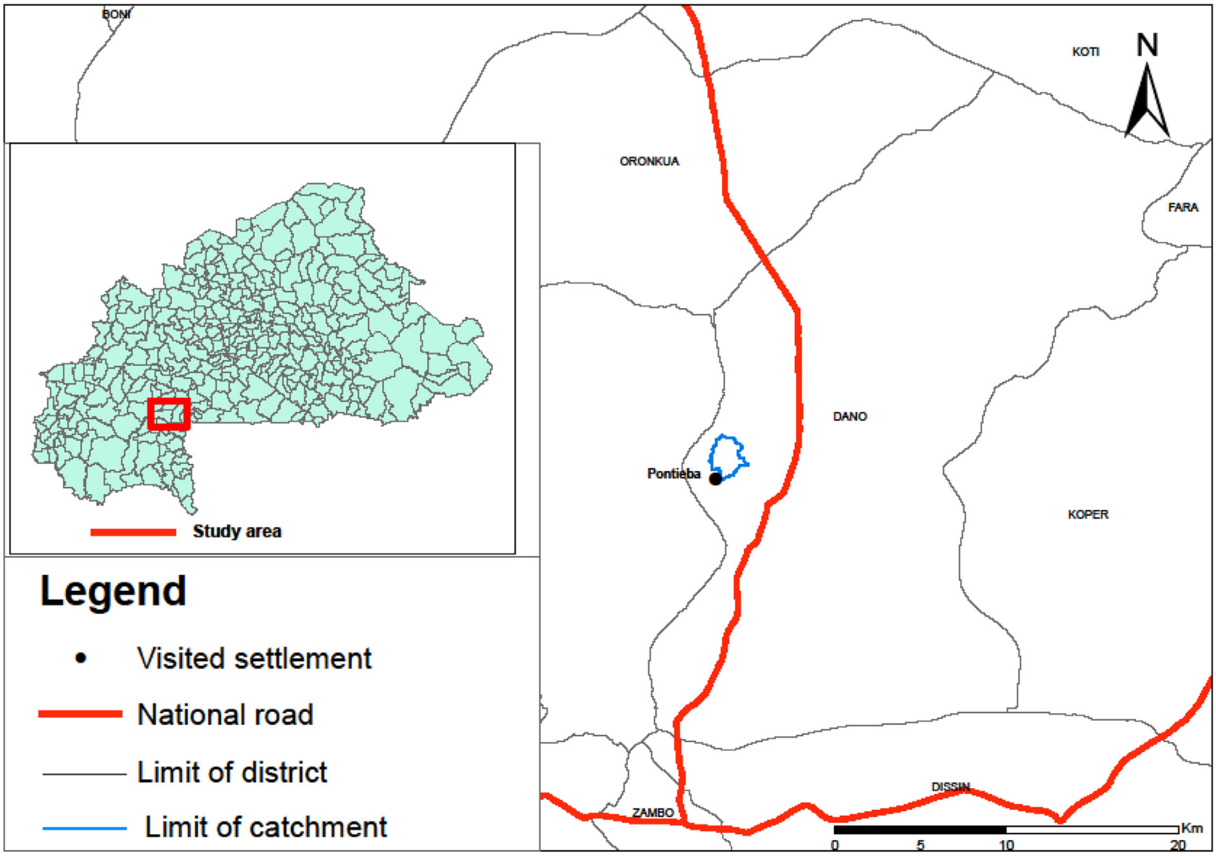


**Fig. 1.** Location map of the Commune of Dano.

The land uses in the model are maize, sorghum, millet, cotton, rice, tomatoes and fallow. For maize, the model has distinguished between extensive maize referred to as 'traditional' without SWC techniques nor fertilizer and fertilized maize under supplemental irrigation.

The model distinguishes between good land with deep soil used for rainfed crops, marginal land with more shallow soils used for rainfed crops, irrigated land in the rainy season, irrigated land in the dry and cold season, and irrigated land in the dry and hot season. In addition, there are two types of lowland: slightly flooded lowland which is more favourable for maize and regularly flooded lowland which is more favourable for rice or sorghum.

The cropping season has been divided into six periods to better reflect labour-related constraints: the planting of rain-fed crops, the harvesting of rain-fed crops, the planting of irrigated crops in the dry and cold season, the harvesting of irrigated crops in the dry and cold season, the planting of irrigated crops in the dry and hot season and, finally, the harvesting of irrigated crops in the dry and hot season.

The model also distinguishes between three types of rainy seasons: a dry season, a normal season and a wet season. We defined the distributions of these types of seasons by combining two types of approaches: that taken by the Burkina Faso Meteorological Services Department and the approach taken by farmers. The first classifies seasons according to whether or not they are above or below normal. It classifies any season receiving <90% of the long-term mean (over 30 years, 1981–2010) as a dry or poor season. Seasons ranging from 90% of the long-term mean to 110% are classified as normal. Seasons ranging from 111% of the long-term mean to 150% are classified as wet or good seasons. Finally, seasons with >150% of the long-term mean rainfall are classified as very wet or very good seasons. This classification is a simplification and does not take into account dry spells within the rainy season. Consequently, in order to verify farmers' assertions, the study looked at dry spells within the rainy season that can negatively impact crop yields.

Each type of rainy season is associated with a probability of occurrence referred to as *proba (h)*. In the baseline scenario there is no forecast and the model is considered myopic. We assign identical probabilities (33%) for the distribution of each of the three types of rainy seasons (wet, normal and dry), which is the approach used by the African Centre of Meteorological Applications to Development (ACMAD) to present seasonal forecasts in West Africa.

For each type of rainy season, the model associates yields and prices. Yields are estimated according to a Cobb-Douglass production function (Tables 1, 2 and 3). The results on crop yields for each type of rainy season from the Cobb-Douglas production function are used to derive technical coefficients to parameterize the mathematical programming model. During the survey and focus groups discussions, farmers were asked the following questions: Among the agricultural seasons in the past 10 years, which was the best (in term of good yields)? Which was the worst? What are crop yields in good and bad seasons? How were the prices after a good or a bad season? From this information, we cross checked with statistics data from the Ministry of Agriculture and were able to construct confidence intervals for yields and prices for each crop. Considering prices to follow a law of uniform probability, we estimated the random coefficients. Subsequently, the real prices were obtained by multiplying the average by the estimated random coefficients. The prices of food crops vary, usually in the opposite direction of yields. Thus, a dry rainy season is associated with low yields and high prices and the opposite is true for a wet rainy season. The exception is cotton, for which prices are set.

The model includes several constraints: land, water, labour, capital and cereal consumption. We added a water constraint related to the irrigated scheme. For supplemental irrigation, we assume that small ponds have been built. Following the government initiative, we assumed that these ponds have an average capacity of 300 $m^3$. We added the labour requirement to dig a 300 $m^3$ farm pond. Farm ponds

**Table 1**
Expected sign of the Cobb Douglas (Solow growth) model variables.
The theoretical specification of the model is as follow:
$LnYC_{i,t} = \alpha_{0_{i,t}} + \alpha_1 LANDC_{i,t} + \alpha_2 LABOURC_{i,t} + \alpha_3 NPKC_{i,t} + \alpha_4 UREC_{i,t} + \alpha_5 PPC$
$+\alpha_6 PLC_{i,t} + \alpha_7 OMC_{i,t} + \alpha_8 dumyHR + \alpha_9 dumyLR + e_{i,t} + \mu_{i,t}$

| Variables | Description | Expected sign |
|---|---|---|
| $LnYC_{i,t}$ | The logarithm of the yield of crop 《c》 of household i at year 《t》 (kg/ha). | |
| $LANDC_{i,t}$ | Area of the crop 《c》 of the household 《i》 at year 《t》 (ha) | positive |
| $LABOURC_{i,t}$ | Effective work force for the crop 《c》 of the household 《i》 at year 《t》 (man/day). | positive |
| $NPKC_{i,t}$ | Amount of NPK used by household 《i》 for crop 《c》 at year 《t》 (g/ha) | positive |
| $UREC_{i,t}$ | Amount of urea used by household 《i》 for crop 《c》 at year 《t》 (g/ha) | positive |
| $PPC_{i,t}$ | Solid herbicide used by household 《i》 for crop 《c》 at year 《t》 (g/ha). | positive |
| $PLC_{i,c}$ | Liquid herbicide used by household 《i》 for crop 《c》 at year 《t》 (ml/ha). | positive |
| $OMC_{i,c}$ | Binary variable describing the use of organic manure by household 《i》 for crop 《c》 at year 《t》. | positive |
| dumyHR | 《Dummy》 variable with multiple character characterizing rainfall of the year said to be high than the normal. | Positive |
| dumyLR | 《Dummy》 variable with multiple character characterizing rainfall of the year said to be less than the normal. | negative |
| $e_{i,t}$ | Random error term with regard to the time. | |
| $\mu_{i,t}$ | Random error term with regard to the household. | |

are dug during the dry season when labour is abundant and the model takes into account the cost of digging a farm pond. The characteristics of the soil in the catchment allow the model to consider a self-sealing option (Fox et al., 2005). The farm ponds are built without waterproofing in clayish soils where filtration is limited.

Farm ponds are filled by direct runoff. The small 300 $m^3$ pond is usually filled by a few rainfall events. In the Sudanian zone, the runoff coefficients range from 10% to 25% depending on surface features (Bagayoko, 2006; Kasei, 2009; Ibrahim et al., 2015). Thus, with a mean rainfall intensity of 14 mm/day and from an impluvium of one to two hectares, the ponds are supplied with water from the first large rainfalls. Since the ponds contain water from the first cropping stage onwards, farmers can practice supplemental irrigation of maize from the beginning of the rainy season. A bucket-based splashing irrigation technique (hand irrigation) is used in the model.

We selected only maize in the model because it is a well-marketed food crop in the sub-region. We added a cereal consumption constraint because farmers consume much of their produced grain. We also added a risk constraint because of the tendency of farmers to be risk averse. To ease understanding of the model's equations, vectors are written in lower case letters, and variables are in capitals.

The land constraint is represented as follows:

$$\sum_c \sum_s X(c,s) \le land(s) \tag{1}$$

The land parameter “land(s)” distinguishes the surface areas of the various types of land, with “s” being the type of land. The cultivated land variable is represented by “X(c, s)”. The total cultivated area must be less than or equal to the surface area available throughout the catchment area per type of land.

The cropping season was divided into six periods to identify work peaks in the agricultural calendar. Cropping activities require labour which varies in some periods. Several farming system studies in Burkina Faso have attempted to calculate labour requirements for typical farms using the number of active workers in the household and the number of available working days (Broekhuyse, 1983; Prudencio, 1996; Dugué, 1987; Matlon and Fafchamps, 1988; INERA, 1994). Based on these studies, some authors consider that household members over the age of 15 provide almost the entire workforce (Roth, 1986; Maatman et al., 1996). People <15 years of age are not considered active although they contribute to some farm activities. Roth and Maatman observed that an active man works 7 h a day while a woman works 6 h a day. In our study, the work force is adult-equivalent and men and women achieve the same work with the same efficiency.

The Eq. (2) expresses the labour constraint at the catchment level and takes into account the fact that labour can be hired. The total labour requirement (Table 4) takes into account the labour requirement for each crop for each of the six agricultural periods “lrc (c, p)”, the number of available working days “awd” per person, the number of people in the catchment area “pop”, the proportion of the working population “wp” and the labour to be hired for each period “LH (p)”:

$$\sum_c \sum_s X(c,s) \times lrc(c,p) \le awd \times pop \times wp + LH(p) \tag{2}$$

The parameter “cap(c, s)” represents the capital requirement per hectare per crop and per soil type for the purchase of seeds and other inputs. The parameters “cseed(c, s)” and “cinp(c, s)” represent the cost of

**Table 2**
Results of the Cobb Douglas (Solow growth) model and the derived technical coefficients of key variables.

| Crops (type of model) | Variables | Correlation (%) | Coefficients (%) | Standard errors | A 95% confidence interval | Derived technical coefficients |
|---|---|---|---|---|---|---|
| Cotton (random) | *DUMYHR* | 32.52 | 56.6683*** | 0.1546996 | [0.2584627; 0.864874] | 1.57 |
| | *DUMYLR* | −7.14 | −25.95908* | 0.1071021 | [−0.5732961; 0.0541145] | 0.74 |
| Cowpea (homogenous) | *DUMYHR* | 53. 01 | 99.02486*** | 0.2987906 | [0.3894898; 1.591007] | 1.9 |
| | *DUMYLR* | −33. 39 | −26.67062** | 0.11020917 | [−0.7907365; 0.257324] | 0.73 |
| Maize (random) | *DUMYHR* | 38.55 | 37.91985** | 0.1823822 | [0.0217361; 0.736661] | 1.38 |
| | *DUMYLR* | −24.88 | −12.96973*** | 0.04785878 | [−0.357787; 0.0983927] | 0.87 |
| Millet (random) | *DUMYHR* | 5 | −10.93378* | −0.0451106 | [−0.3629938; 0.144318] | 0.89 |
| | *DUMYLR* | −19.33 | −36.30121*** | 0.1243693 | [−0.6067715; −0.119252] | 0.64 |
| Sorghum (random) | *DUMYHR* | 43.29 | 51,47674** | 0.2451846 | [0.0342143; 0.9953204] | 1.51 |
| | *DUMYLR* | −40.09 | −50,63665*** | 0.1868915 | [−0.872667; −0.1400658] | 0.49 |
| Rice (random) | *DUMYHR* | 68.02 | 142.1224*** | 0.2131245 | [1.003507; 1.83894] | 2.42 |
| | *DUMYLR* | −43.1 | −2.35319*** | 0.00805887 | [−0.526778; 0.4797142] | 0.98 |

*** Significant at 1%.
** Significant at 5%.
* Significant at 10%.

**Table 3**
Results of the Cobb Douglas (Solow growth) model of the other variables.

| Crops (type of model) | Variables | Correlation (%) | Coefficients (%) | Standard errors | A 95% confidence interval |
|---|---|---|---|---|---|
| Cotton (Random) | $LANDC_{i,t}$ | 0.4168 | 22.39011*** | 0.0672523 | [0.0920891; 0.3557131] |
| | $LABOURC_{i,t}$ | 26. 75 | 0.73928 | 0.0407374 | [−0.072451; 0.0872367] |
| | $NPKC_{i,t}$ | 33.16 | 8.31e−05** | 3.43E−07 | [−0.071E−05; 0.237E−05] |
| | $UREC_{i,t}$ | 23.00 | 3.97e−05*** | 1.46E−07 | [−0.0758E−05; 0.155E−05] |
| | $PLC_{i,t}$ | 15.71 | −0.03214 | 4.48E−04 | [−0.0758E−05; 55.74E−05] |
| | $PPC_{i,t}$ | 8.43 | 0.07372 | 1.71E−03 | [−2.617E−03; 4.0918E−03] |
| | $OMC_{i,t}$ | 14.27 | 23.34217 | 0.2536728 | [−0.263768; 0.7306113] |
| Cowpea (Homogenous) | $LANDC_{i,t}$ | 25.54 | 67.3826 | 0.6670281 | [−0.667324; 0.02014976] |
| | $LABOURC_{i,t}$ | 32.56 | 9.20636* | 0.0527422 | [−0.0139817; 0.1981089] |
| | $NPKC_{i,t}$ | 13.12 | 2.71e−05 | 2.67E−06 | [−0.51E−05; 0.564E−05] |
| | $UREC_{i,t}$ | 19.29 | 3.97e−04 | 1.32E−05 | [−2.26E−05; 3.05E−05] |
| | $PLC_{i,t}$ | 16.40 | −0.23746 | 4.35E−03 | [−11.11E−03; 6.3704E−03] |
| | $PPC_{i,t}$ | 4.98 | 0.06753*** | 1.36E−04 | [0.402E−03; 0.9477E−03] |
| | $OMC_{i,t}$ | 18. 00 | −43.83726 | 0.377949 | [−1.19829; 0.3215447] |
| Maize (Random) | $LANDC_{i,t}$ | 22.48 | 42.09896*** | 0.1246502 | [−0.103549; 0.105707] |
| | $LABOURC_{i,t}$ | 23.04 | 4.40973 | 0.0285344 | [−7.09e−06; 0.263E−04] |
| | $NPKC_{i,t}$ | 12.27 | −1.94e−04 | 3.10e−06 | [−0.544E−04; 0.349E−04] |
| | $UREC_{i,t}$ | 11.38 | 5.14e−04 | 5.17e−06 | [−0.588E−02; 0.154E−02] |
| | $PLC_{i,t}$ | −4.02 | −00.08536 | 0.080E−02 | [−4.721E−02; 1.285E−02] |
| | $PPC_{i,t}$ | 3,55 | 1.31933 | 1.1446E−02 | [−0.80326; 0.174690] |
| | $OMC_{i,t}$ | 37,92 | 41.66618* | 0.1719065 | [−0.103549; 0.105707] |
| Millet (Random) | $LANDC_{i,t}$ | 25.52 | 22.50895** | 0.0770841 | [7.40074E−02; 0.376171] |
| | $LABOURC_{i,t}$ | 18.67 | 03.45181 | 0.0282378 | [−2.08E−02; 8.986E−02] |
| | $NPKC_{i,t}$ | −7.21 | −1.27e−04 | 3.60e−06 | [−8.32e−06; 5.78e−06] |
| | $UREC_{i,t}$ | −6.55 | −9.31e−04 | 0.13E−04 | [−0.348E−04; 0.161E−04] |
| | $PLC_{i,t}$ | −2.10 | 0.00172 | 0.6651E−04 | [−1.13E−04; 1.475E−04] |
| | $PPC_{i,t}$ | 1.89 | 0.95622*** | 0.3660E−02 | [0.238E−02; 1.673E−02] |
| | $OMC_{i,t}$ | 15.37 | 22.15881 | 0.2339473 | [−0.23694; 0.68011] |
| Sorghum (Random) | $LANDC_{i,t}$ | 28.61 | 10,8956 | 0.0825545 | [−0.05284; 0.27075] |
| | $LABOURC_{i,t}$ | 27.60 | 8,65954* | 0.0460801 | [−0.37213E−02; 0.17691] |
| | $NPKC_{i,t}$ | 10.72 | 3.98e−04 | 4.34e−06 | [−4.53e−06; 0.125E−04] |
| | $UREC_{i,t}$ | 6.95 | −0.00128 | 0.1641E−04 | [−0.45E−04; 0.194E−04] |
| | $PLC_{i,t}$ | 2.46 | 0.08442 | 8.2351E−04 | [−7.69E−04; 0.245E−02] |
| | $PPC_{i,t}$ | −0.97 | −0.81391 | 0.0253305 | [−5.778E−02; 4.150E−02] |
| | $OMC_{i,t}$ | 25.73 | 50.56557 | 0.337992 | [−0.1567964; 1.168108] |
| Rice (Random) | $LANDC_{i,t}$ | 25.33 | 182.6514* | 0.7765023 | [0.304598; 3.348431] |
| | $LABOURC_{i,t}$ | 7.01 | 0.10787 | 0.053383 | [−0.10354; 0.10570] |
| | $NPKC_{i,t}$ | 7.37 | 9.59e−04 | 8.51e−06 | [−7.09E−06; 0.263E−04] |
| | $UREC_{i,t}$ | 5.35 | −9.77e−04 | 0.2281E−04 | [−0.544E−04; 0.349E−04] |
| | $PLC_{i,t}$ | −6.93 | −0.21686 | 0.1896E−02 | [−0.588E−02; 0.154E−02] |
| | $PPC_{i,t}$ | −1.60 | −1.71797 | 0.0153249 | [−4.721E−02; 1.285E−02] |
| | $OMC_{i,t}$ | 11.21 | −31.42886 | 0.2494838 | [−0.80326; 0.17469] |

*** Significant at 1%.
** Significant at 5%.
* Significant at 10%.

**Table 4**
Crop water, labour requirement and average yields.

| Crops | Water requirement ($m^3$/ha) | Labour requirement (persons-day ) | | | | | | Crops yields (kg/ha) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Periods | | | | | | Type of soil | | | | | | |
| | | Planting of rainfed crops[a] | Harvesting of rainfed crops | Planting of irrigated crops (dry and cold season)[a] | Harvesting of irrigated crops (dry and cold season) | Planting of irrigated crops (dry and hot season)[a] | Harvesting of irrigated crops (dry and hot season) | Marginal lands | Good lands | Rainy season irrigated lands | Cold dry season irrigated lands | Hot dry season irrigated lands | slightly flooded low-lands | Highly flooded low-lands |
| Cotton | | 74 | 92 | | | | | 900 | 1200 | | | | | |
| Cowpea | | 45 | 18 | | | | | 500 | 700 | | | | | |
| Maize T | | 52 | 10 | | | | | 700 | 1300 | | | | 1300 | 900 |
| Maize F | 3520 | 60 | 20 | | | | | 1300 | 3500 | 3900 | 3900 | 3900 | 1800 | 1000 |
| Millet | | 41 | 13 | | | | | 645 | 800 | | | | | |
| Sorghum | | 51 | 13 | | | | | 750 | 900 | | | | | |
| Rice | 10,000 | 100 | 60 | | | | | | | 5000 | 4000 | 3000 | 1500 | 2500 |
| Tomatoe | 6000 | | | 150 | 110 | 150 | 110 | | | | 12,000 | 11,000 | | |

Maize T = 'traditional' maize.
Maize F = fertilized maize.
[a] Sowing + weeding.

crop seed and the other inputs respectively with:

$$\text{tcinp}\ (c,s) = \text{cseed}\ (c,s) + \text{cinp}(c,s) \tag{3}$$

where "tcinp(c, s)" is a parameter indicating the total cost of all inputs.

The model offers the possibility of using seasonal credit "CRED", and "cap" is a parameter indicating the farm capital available at the beginning of the agricultural season:

$$\sum_c \sum_s X(c,s) \times \text{tcinp}(c,s) \le \text{cap} + \text{CRED} \tag{4}$$

The credit for input is related to the cotton surface area "cot" and corresponds to the input needed for a standard area of cotton:

$$\sum_c \sum_s X(\ \text{cot}, s) \times \text{cap}(\ \text{cot}, s) \ge \text{CRED} \tag{5}$$

The cereal consumption constraint specifies that each household has to cover its cereal needs. This is the product of the annual need for grain per person "cons" multiplied by the population of the catchment "pop". The variable "SELF(c)" is the optimal amount of self-consumed cereals. The variable "BC(c)" is the optimal amount of grain possibly bought to meet the needs of the households and "fp(c)" is a food preference coefficient for each type of cereal. It is assumed that farmers display an optimisation behaviour that determines their consumption decisions based on their economic environment (changes in product prices and incomes). Therefore, the food constraint is written as follows:

$$\sum_c (\text{SELF}(c) + \text{BC}(c)) \times \text{fp}(c) \ge \text{cons} \times \text{pop} \tag{6}$$

To take into account the water constraint in the irrigated area, we incorporated the parameters "wat (h, s)" which indicates the amount of water available in the reservoir and "watn(c, h, s)" which indicates the need for water in cubic metres per hectare per crop (Table 4). The various constraints related to the construction of farm ponds "BAS(s)" and water retention facilities are also introduced. The following equations summarise the water constraints for the two types of irrigation that is from the reservoir and from farm ponds:

$$\sum_c X(c,s) \times \text{watn}(c,h,s) + O(h,s) \le \text{wat}(h,s) + O(h,s-1) + \text{BAS}(s) \tag{7}$$

The water requirement by hectare of crops "watn(c, h, s)" has to be met by the amount of water available in the reservoir "wat (h, s)", or "BAS(s)" (for supplemented irrigated and fertilized maize). The water available from the dam at the beginning of the optimisation period "wat (h, s)" can be transferred from one season to the other "O (h, s)". Farm ponds created by the model are filled with water runoff, "ROFF(s)". Eq. (8) below calculates the optimal number of farm ponds "NBAS (s, p)" created depending on the period "p":

$$\text{BAS}(s) = \text{BAS1}(s) + \sum_P \text{NBAS}(s,p) \tag{8}$$

Eq. (9) assumes that the farm ponds are filled many times "fill" during the rainy season.

$$\text{BAS}(s) \times \text{fill} = \text{ROFF}(s) \tag{9}$$

Finally, the risk-related constraint states that the income of an adverse year should not be less than a minimum income "MINC (h)". The limited-risk models are intended to impose additional constraints on the model which state that the likelihood of occurrence of all other model requirements should be greater than a given threshold (Diarra et al., 2013).

$$\text{INC}(h) \ge \text{MINC}(h) \tag{10}$$

The net cash income of the catchment to be maximised is calculated as follows: the quantities of products sold per crop "c" are added, "SELL(c, h)" multiplied by the unit sale price "sp(c, h)" of each crop, and minus the total cost of inputs "tcinp (c, s)" per unit of land cultivated multiplied by the crop area "X(c, s)", minus cereal purchases "cp(c, h)" for consumption multiplied by their purchase price "cpp(c,h)", minus financial costs "rate" related to seasonal credits multiplied by the amount of credit taken out "cred", minus taxes "tax" per unit of irrigated area "land(irr)", minus the amount of labour to be hired "LH (p)" multiplied by the price of agricultural labour "cl", minus the cost required to dig farm ponds "costfp(p)".

$$\begin{aligned} &\sum_c \text{SELL}(c) \times \text{sp}(c) - \sum_{c,s} X(c,s) \times \text{tcinp}(c) \\ &- \sum_c \text{CP}(c,h) \times \text{cpp}(c,h) - [\text{rate} \times \text{CRED}] - [\text{tax} \times \text{land(irr)}] \\ &- \sum_p \text{cl} \times \text{LH}(p) - \sum_p \text{costfp}(p) = \text{INC}(h) \end{aligned} \tag{11}$$

To ascertain that the model does indeed replicate land allocation to crops, calibration and validation processes are required. The calibration consists of adjusting some model parameters (and/or coefficients), and ensuring its internal logic and consistency in order to reproduce farmers' actual observed situations (Boussard, 1987). This is a way to find the best parameters (and/or coefficients) that strengthen the model's capacity to reproduce reality (Santillana and Serrano, 2005). We used a manual calibration process which accepts a residual deviation of the model's results. The variable "MINC" is used to calibrate the model by adjusting it exogenously until the model approximately reflects the allocation of land to crops in the study area.

However, while calibration is necessary, it is not sufficient to assess a model, and so the model also needs to be validated. Ignizio (1982) identifies four criteria to validate models: logical consistency in its construction, the reliability of the data on which the model is based, the consistency of the model for simple simulations and its ability to reproduce current trends. The observed cropped areas were used as data to validate the model. We compared the simulated land allocation to the various crops to the actual observed allocation (Table 5). The difference is small enough to indicate that the model mimics farmers' behaviour quite well.

### 2.4. Scenarios tested

The proposed scenarios were designed to test the impact of supplemental irrigation. The first scenario reflects the baseline situation where farmers have no farm ponds. In the second scenario, farmers can dig farm ponds for use during the rainy season. We assume that farmers can build farm ponds in clayish soils, in other words soils which do not need waterproofing with cement coatings or tarpaulins. We also

**Table 5**
Compared crop areas (observed and simulated).

| Crops | Observed crops areas (ha) | Percentage of the total area | Simulated crops areas (ha) | Percentage of the total area | Different (%) between observed and simulated crops areas |
|---|---|---|---|---|---|
| Sorghum | 440 | 37% | 434 | 36% | −1% |
| Millet | 225 | 19% | 240 | 20% | 6% |
| Maize | 324 | 27% | 343 | 29% | 6% |
| Rice | 67 | 5% | 65 | 5% | −3% |
| Cotton | 49 | 4% | 47 | 4% | −4% |
| Cowpea | 23 | 2% | 0 | 0 | – |
| Tomatoes | 50 | 4% | 50 | 4% | – |
| Fallow | 27 | 2% | 26 | 2% | −3% |
| Total | 1205 | 100% | 1205 | 100% | – |

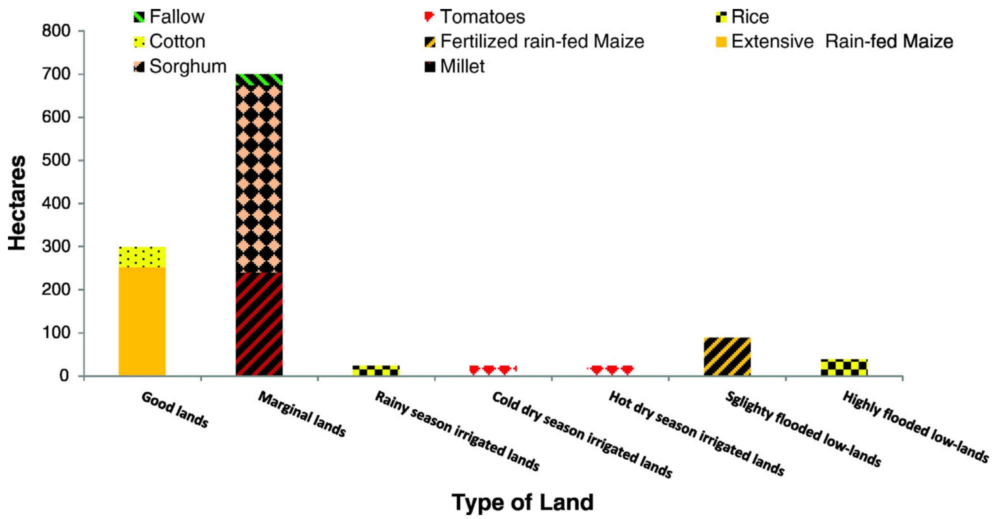


**Fig. 2.** Land allocation to the various crops in the baseline scenario.

assume that water will be lifted by hand and that irrigation is done with watering cans.

For a given scenario, the model calculates the crop allocation and the whole catchment revenue associated with each type of rainy season multiplied by its respective coefficient.

## 3. Results and discussion

### 3.1. Baseline scenario

The baseline simulation estimates land allocation between the various crops, agricultural production, several cropping patterns, techniques, consumption, labour, capital allocation between activities and net cash income for the whole catchment.

#### 3.1.1. Land allocation to crops

Land allocation without the ponds is similar to farmers' practices in the catchment. Millet and sorghum occupy most of the marginal land where soils are shallow (Fig. 2). Extensive rain-fed maize and cotton are grown on the deeper soils. Intensive rain-fed maize and rice are planted in the slightly flooded lowland and the regularly and highly flooded lowland respectively. During the dry season, the model adopts, as indeed farmers do, irrigated rice and tomatoes. Around 2% of the land is left fallow because labour is a constraint. However, with population growth all arable land will soon be cropped. Irrigated plots are allocated to rice production during the rainy season and tomato production during the dry and cold season and the dry and hot season. Millet occupies 20% of the available land, sorghum 36%, extensive rain-fed maize 21%, intensive rain-fed maize 8%, cotton 4%, rice 5%, and tomatoes 4%.

#### 3.1.2. Catchment income

The optimal baseline cash net income in normal years is US$ 347,005 for the whole catchment area (Fig. 3). During dry years, the catchment cash net income (US$ 265,680) is 23% less than for a normal year due to lower yields. The consequences of dry years are lower crop yields and higher prices. Crop yields tend to fall in proportions greater than price gains (especially for maize and rice). This increase in price does not compensate for lower yields because farmers have little to sell during dry years and have to buy more food at higher prices. On average, in dry years, millet, sorghum, maize and rice yields can drop by 24%, 43%, 60% and 29% respectively (DPASA, Ioba, 2013). In the model, product prices are exogenous but linked to yields. Millet and sorghum prices can rise by 40% and 45%, while maize and rice prices can rise by 42% and 13%.

Moreover, in the model, because farmers have to meet household cereal needs, they sell only the surplus, especially after a dry rainy season when they consume their own millet and maize. After a wet season, the catchment income (US$ 395,136) is 14% higher than a normal year when yields are higher but prices are lower.

The irrigated area is fully used and a small fraction of the so-called marginal land is not cultivated because village labour is not sufficient to crop the whole area. The marginal value of 1 ha of good land is about US$ 61. The marginal value of irrigated land in the rainy season, irrigated land in the dry and cold season, irrigated land in the dry and

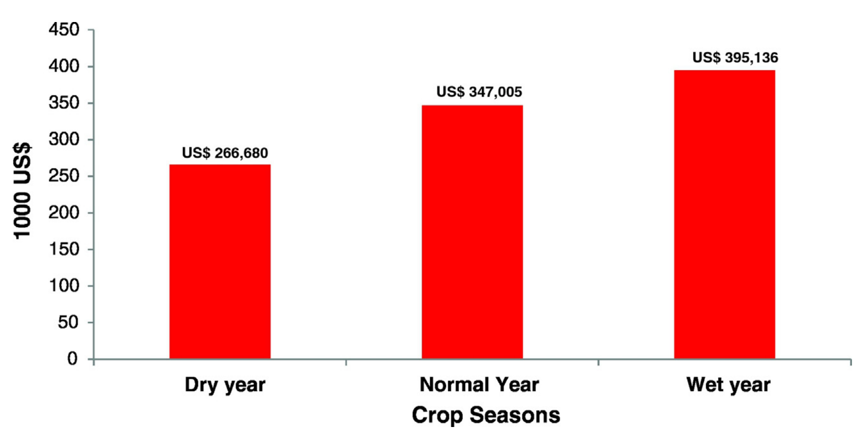


**Fig. 3.** Income of the whole watershed per type of rainy season in the baseline scenario.

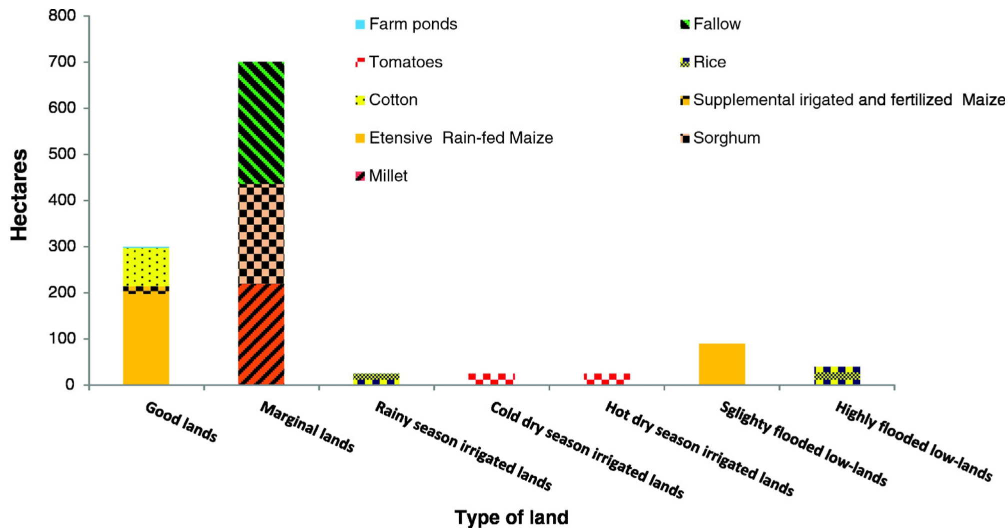


**Fig. 4.** Allocation of land to crops in the scenario with farm ponds.

hot season, slightly flooded lowland, and regularly and highly flooded lowland is US$ 1324, US$ 3935, US$ 3605, US$ 269 and US$ 382 respectively. This means, for example, that an additional hectare of irrigated land used in the dry and cold season would increase the catchment income by US$ 3935.

Labour is a limiting factor during planting periods and, to a lesser extent, at harvest. Although the model allows labour to be hired, the constraints on capital limit the hiring of workers. It also means that farmers in the catchment area could benefit from hiring external labour during the planting season, provided its cost is lower than the marginal value, which is about US$ 3. During the dry season, labour is not a constraint because only the small irrigated section (4%) of the area is cultivated. The available cash and credit are fully utilised by farms. The model adopts the planting of cotton in order to gain access to credit and inputs. The cotton company provides credit to finance cotton production but not for the other crops.

Water is also a limiting factor because the actual reservoir is small and all the water is used. The marginal value is US$ 0.10, meaning that one cubic metre of water would increase the overall income by this amount. This is very little.

Risk is also a limiting factor because farmers cannot afford to have too low an income after a dry season. To reduce risk they still grow millet to avoid the impact of droughts, thus pulling down the average income.

### *3.2. The supplemental irrigation scenario*

#### *3.2.1. Land allocation to crops*

The model adopts 192 farm ponds of 300 $m^3$ each to irrigate 16 ha of fertilized maize during dry spells in the rainy season. Farm ponds occupy about 3 ha of good land, which is about 17% of the land under supplemental irrigation. Introducing farm ponds for supplemental irrigation during the rainy season will change the allocation of crops slightly (Fig. 4) compared to the baseline scenario. Fertilized maize under supplemental irrigation appears on good land with deeper soils (about 2% of the total cropped area). On marginal soils, the model reduces the surface area of millet from 20% to 18% and that of sorghum from 36% to 18%. Fallow land increases significantly, from 26 to 265 ha which is an increase of 919% (Table 6). On slightly flooded lowland, the model proposes extensive rain-fed maize, accounting for 7% of the total cropped area, at the expense of intensive rain-fed maize. On good land, extensive rain-fed maize decreases from 21% to 16%, while the acreage allocated to cotton increases from 4% to 7%. The results show that labour is increasingly allocated to supplemental irrigation and more profitable crops. Indeed, cotton and supplemental irrigated and fertilized maize cultivation is more labour-intensive but more profitable than extensive rain-fed maize, millet or sorghum. The surface area allocated to irrigated rice and tomatoes remains almost unchanged.

**Table 6**
Compared crops harvested areas (baseline scenario and scenario with farm ponds).

| | Baseline scenario | | Scenario with farm ponds | | Variation |
|---|---|---|---|---|---|
| | Harvested area (hectares) | Percentage of the total harvested area (%) | Harvested area (hectares) | Percentage of the total harvested area (%) | (%) |
| Marginal lands | | | | | |
| Millet | 240 | 20 | 220 | 18 | −8 |
| Sorghum | 434 | 36 | 215 | 18 | −50 |
| Fallow | 26 | 2 | 265 | 22 | +919 |
| Good lands | | | | | |
| Cotton | 47 | 4 | 83 | 7 | +75 |
| Extensive rain-fed maize | 253 | 21 | 198 | 16.4 | −22 |
| Supplemental irrigated and fertilized maize | – | – | 16 | 2 | – |
| Farm ponds | – | – | 3 | 0.2 | – |
| Rainy season irrigated land | | | | | |
| Rice | 25 | 2 | 25 | 2 | No change |
| Cold dry season irrigated land | | | | | |
| Tomatoes | 25 | 2 | 25 | 2 | No change |
| Hot dry season irrigated land | | | | | |
| Tomatoes | 25 | 2 | 25 | 2 | No change |
| Slightly flooded low-land | | | | | |
| Extensive rain-fed maize | 0 | 0 | 90 | 7.4 | – |
| Fertilized rain-fed maize | 90 | 8 | 0 | 0 | −100 |
| Highly flooded low-land | | | | | |
| Rice | 40 | 3 | 40 | 3 | No change |
| Total harvested area of the watershed | 1205 | 100 | 1205 | 100 | – |

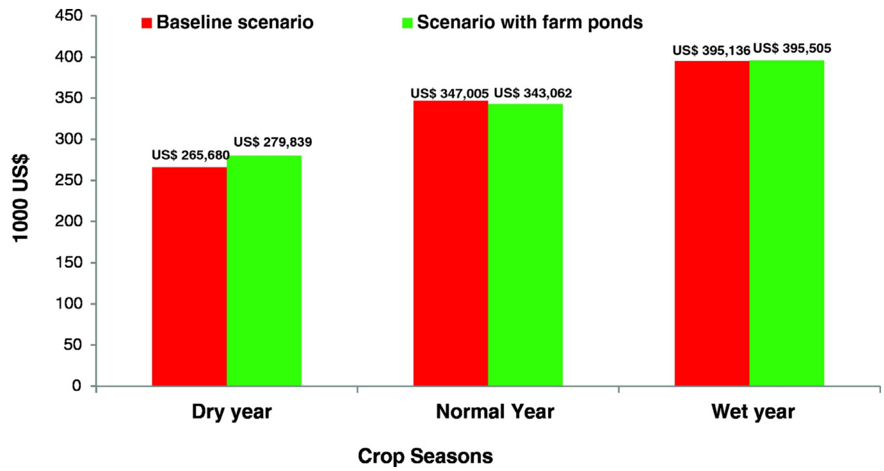


**Fig. 5.** Compared watershed income of the two scenarios (Baseline scenario (without farm ponds) and Scenario with farm ponds).

*3.2.2. Catchment income*

Gains are higher during dry years with a net catchment income increase of 5% over the baseline situation. This is an increase of US$ 14,159 compared to the catchment income in the baseline scenario (Fig. 5). In wet and normal years, gains of the ponds are negligible. With supplemental irrigation, fertilized maize yield gains are higher during drier years than they are in normal or wet years. The profitability of irrigated and fertilized maize under supplemental irrigation helps offset the loss of land to the pond and the reduction in amount of land devoted to rain-fed crops.

Labour is likely to be a limiting factor because digging farm ponds is time consuming. Given the high demand for labour during the field preparation for rain-fed cropping and at harvest time, the model chooses to build the farm ponds during the dry season when the labour opportunity cost is lower. During the dry season, only 4% of the total farmland is under cultivation and labour is still abundant.

Capital remains a limiting factor. This finding is corroborated by Kumar and Dam (2008), who reports that capital is likely to be one of the main constraints in the water harvesting systems needed for supplemental irrigation.

## 4. Conclusion

This study evaluated the relative advantage of farm ponds and supplemental irrigation as an adaptation strategy to rainfall variability compared to existing practices in a small catchment in south-western Burkina Faso. A bio-economic model based on mathematical programming was used to mimic the local economy under various scenarios. The model takes into account the complexity of farmers' decisions in a severe agro-climatic environment.

The baseline simulation produces a crop allocation similar to the one practiced by farmers in the catchment on the different types of soils in the catchment. If given the possibility, the model adopts 192 farm ponds of 300 $m^3$ to irrigate 16 ha of intensive maize during dry spells in the rainy season, which means that supplemental irrigation is profitable. However, overall gains remain modest. They are higher during dry years when incomes increase by 5%. Supplemental irrigation makes intensive maize production possible over a small area but would reduce the area of rain-fed crops, such as maize, millet and sorghum, and more land would be left fallow. The increase in intensive maize would also trigger the expansion of cotton because cotton production increases access to credit and inputs.

The model proposes the building of more ponds but constraints on labour, water and capital restrict its expansion beyond the 16 ha. Supplemental irrigation secures only part of production. It could become an important technology for agriculture in semi-arid regions such as Burkina Faso, but we also need to consider the capital constraints of Burkinabe farmers.

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