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Smallholder Shallow Groundwater Irrigation Development in the Upper East Region of Ghana

Regassa E. Namara, Joseph A. Awuni, Boubacar Barry, Mark Giordano, Lesley Hope, Eric S. Owusu and Gerald Forkuor

International Water Management Institute

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International Water Management Institute
P O Box 2075, Colombo, Sri Lanka

The authors: Regassa E. Namara is a Senior Economist at the Regional Office for Africa of the International Water Management Institute (IWMI) in Accra, Ghana; Joseph A. Awuni is a lecturer at the University for Development Studies, Tamale, Ghana; Boubacar Barry is Coordinator of the West African Science Service Center on Climate Change and Adapted Land Use (WASCAL) project at the satellite office of IWMI in Ouagadougou, Burkina Faso; Mark Giordano is Theme Leader – Water and Society at the headquarters of the International Water Management Institute (IWMI) in Colombo, Sri Lanka; Lesley Hope is a Research Officer at the Regional Office for Africa of IWMI in Accra, Ghana; Eric S. Owusu was Research Officer at the Regional Office for Africa of IWMI in Accra, Ghana, and is currently Research Scientist at the Food Research Institute of the Council for Scientific and Industrial Research (CSIR), Accra, Ghana; and Gerald Forkuor was a Research Officer at the Regional Office for Africa of IWMI in Accra, Ghana, and is currently a PhD student at University of Würzburg, Germany.

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Cover photograph shows smallholder shallow groundwater irrigation in the Dangme East District of Ghana (*photo credit*: Regassa Namara, IWMI).

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Contents

Summary

In sub-Saharan Africa (SSA), in general, and in Ghana, in particular, there is a paucity of information on the potential of groundwater resources. The limited information that is available, based on data from specific aquifers, paints a pessimistic view about groundwater resources. Due to its perceived inadequate availability, groundwater is largely associated with domestic use and the potential of using groundwater for agriculture are not well reflected in the country's water and irrigation policies. However, contrary to the official statistics and priorities, farmers do use shallow groundwater to produce horticultural crops in many parts of Ghana. In the Upper East Region, which is the most populous of the three poorer Northern regions of Ghana, groundwater infrastructure is developed using rudimentary technologies banking on the relative abundance of human labor during the long dry season. This paper analyzes: (1) the extent of shallow groundwater irrigation in the region, (2) the economics of smallholder groundwater irrigation, (3) the food security and poverty impacts of access to groundwater resources, and (4) constraints and opportunities of smallholder groundwater irrigation systems. This paper is based on data generated from 420 farmers that were randomly selected from three micro-watersheds of the White Volta Basin in Upper East Region of Ghana.

Of the total 4,576 households found in the area, about 61% practice irrigation. Of those 61%, about 90% use shallow groundwater. The total estimated shallow groundwater irrigated area in the White Volta Basin during the 2008/2009 dry season was about 916 hectares (ha), of which 597 ha of land was developed using in-field seasonal shallow wells, 213 ha was developed using riverine seasonal shallow wells, and 106 ha was developed using permanent shallow wells. The farmers have developed complex but water-efficient and labor-intensive on-farm water management and agronomic practices. This reflects the relative resource scarcities during the long dry season. During the dry season, land and labor are relatively abundant but water is the limiting factor for production.

Tomato and pepper are the two main crops produced. Cultivation of these crops under shallow groundwater irrigation is generally profitable, particularly when the value of family labor involved in the cultivation process is not considered. If the opportunity cost of labor increased substantially, groundwater irrigation under current technologies would no longer be profitable.

The three to four months of dry-season irrigation using shallow groundwater have created additional demands for labor estimated at 359,511 man-days (or approximately 214 full-time equivalent (FTE[1]) per year) during a season of near-zero alternative employment. The total contribution of shallow groundwater irrigation to the economy of the 35 communities in the White Volta Basin is about GHS 1.62 million (or about USD 1.1 million). In conclusion, these irrigation systems have: (1) created jobs during the dry season with a likely effect on rural-urban and north-south distress migration in Ghana, (2) significantly contributed to the economy of the communities, (3) reduced poverty, and (4) enhanced the food security status of the practitioners.

[1] One FTE per year is equivalent to 1,680 hours of work per year or 35 hours per week.

The practices and outcomes found here are believed to also occur in the Upper West, Brong-Ahafo, Ashanti, Volta, Eastern (especially in the Afram Plains District) and Greater Accra regions. However, the extent of groundwater irrigated area has not been well examined. Other recent studies of hydrology in the region have shown that there is sufficient groundwater for further expansion, but that there is the risk of overdraft. Thus, while additional study is needed, there is room for cautious optimism that the regions hydrogeology will support expansion of groundwater use. However, to get the full livelihood benefits from existing and expanded use of groundwater resources, farmers indicated a number of constraints. These included complex land tenure issues, lack of access to efficient drilling technology, marketing challenges, and the general lack of official support services such as extension and micro-credits.

Smallholder Shallow Groundwater Irrigation Development in the Upper East Region of Ghana

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Introduction

Ghana's agriculture is predominantly rain-fed. However, the government and donors are now once again placing increased attention on irrigation as a way to increase output, address food and nutrition security, and alleviate poverty. Within irrigation discussions, groundwater gets relatively little attention, for example, receiving almost no mention in the recent national water and irrigation policies. This is likely, in part, because in most of SSA there is a general view that groundwater yields are simply not sufficient for agricultural development. This view is furthered by evidence that where many boreholes have been drilled, groundwater tables have fallen (e.g., Gyau-Boakye and Tumbulto 2000).

Most commentators suggest that the available groundwater resources in Ghana should primarily be used for domestic purposes. According to Kortatsi (1994), 84% of groundwater extracted is used in the domestic sector and less than 5% is applied in agriculture. However, as has been found in many other parts of the world, groundwater use for agriculture and its potential may be underreported and unappreciated (Giordano 2005; Shah 2009). While information on groundwater availability and storage is in fact scarce (Yidana 2008), some recent assessments have suggested a positive view of the possibilities for groundwater use in agriculture in Ghana. Yidana (2008) and Yidana et al. (2008a) find that groundwater in the Afram Plains has the potential to meet localized current and future community irrigation needs. According to Akudago et al. (2009), there is enough groundwater in Northern Ghana to support irrigation provided that careful management practices of the aquifer system are adhered to.

The authors of this report have also found that agricultural groundwater use in Ghana may be greater than generally believed. Informal surveys found shallow wells that have been dug extensively for irrigation along river banks, and coastal and low-lying areas of Upper East, Volta, Upper West, and the Greater Accra regions (Namara et al. 2011). There is also documentation on groundwater-based irrigation in coastal areas of Volta and Greater Accra regions (Kortatsi 1994). This study takes an in-depth look at agricultural groundwater use in one of these areas - the Upper East region, which is an inland area away from major population centers. This study uses a survey that was carried out amongst 420 farmers to provide insights into the following questions:

- What is the nature and extent of agricultural use of shallow groundwater in the Upper East region?
- What are the economic and socioeconomic impacts of shallow groundwater irrigation as practiced in the study locations?
- What are the prospects, constraints and opportunities for further expansion of shallow groundwater irrigation?

Data and Methods

This study was carried out in three watersheds in the Upper East region of Ghana, namely the Atankwidi (270 square kilometers (km^2)), Anayere (200 km^2) and Yariga-tanga watersheds (Figure 1). The Upper East region covers 8,842 km^2 (or about 7%) of the total land area of Ghana. The total population is about 1 million. With a population density of approximately 113 people per square kilometer, it is the most densely populated area in northern Ghana.

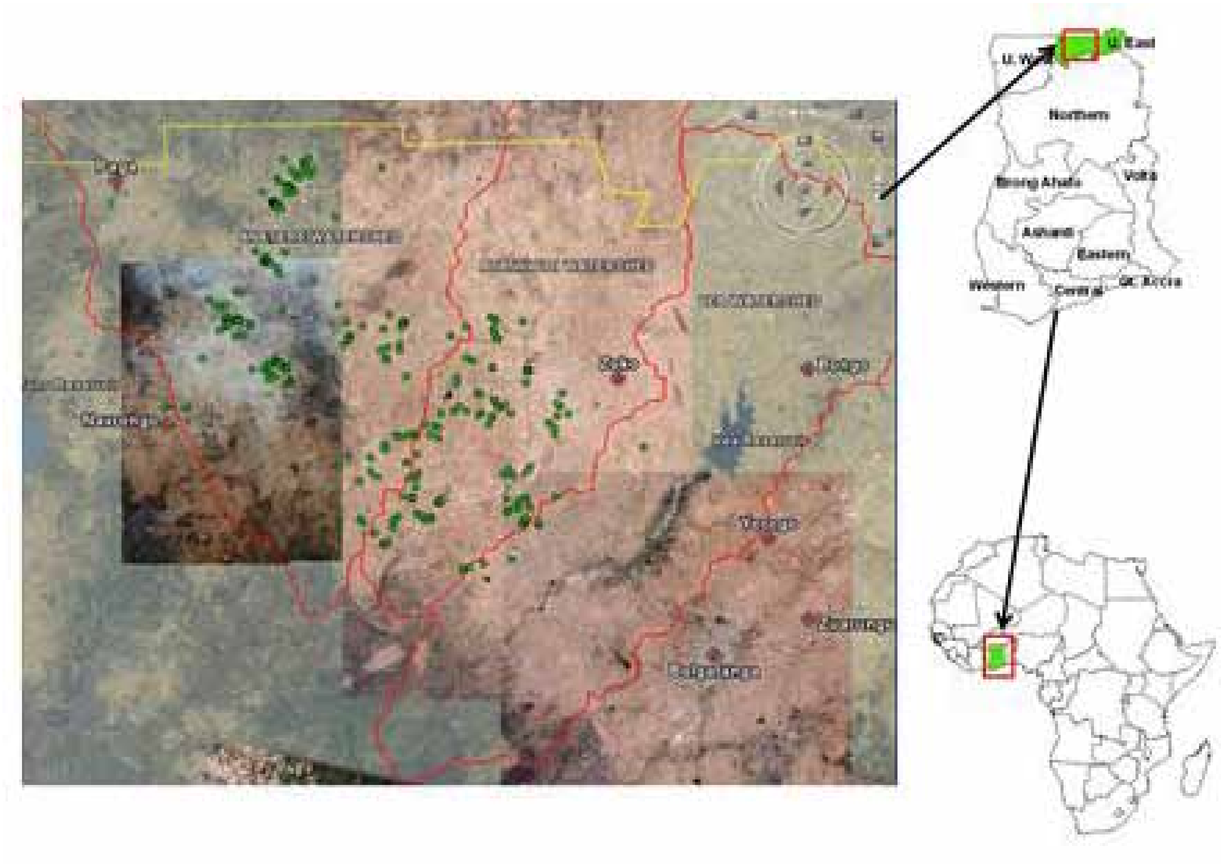

FIGURE 1. Map of the study areas.

Relatively limited productive land, an increasing population and difficult climatic conditions pose a problem of perennial food deficits in the Upper East region. Subsistence agriculture is the main occupation of the people. Most farms are of two types: (a) ‘compound farms’ which lie immediately around the house; and (b) ‘bush farms’ which may border on the compound farm or be located several kilometers away from the main village. Some households keep cattle as well as sheep, goats, chickens and guinea fowl. The cattle are kept for security reasons or as a capital investment. The main food crops are cereals (rice, sorghum, millet) and pulses (groundnuts, cowpea and Bambara beans). Vegetables, particularly onions and tomatoes, are produced in the dry season with the bulk being sold for cash to supplement household needs. Women and youth manage most of the dry-season vegetable production.

Two types of groundwater systems are used in the region, seasonal shallow well irrigation and permanent shallow well irrigation. Seasonal shallow wells are used primarily by farmers in low-lying areas with high water tables, often along river banks, on riverbeds, in swampy areas or close to poorly functioning formal irrigation schemes. When in a river bed, seasonal shallow wells are referred to as riverine shallow wells and when they are in fields they are referred to as in-field seasonal shallow wells (Figure 2). The wells are unlined and irregularly shaped, but are usually near-cylindrical. The depth of seasonal shallow wells depends on the level of the water table and also the water-lifting technologies used.

Simple tools like bars, axes and hoes are used for digging the wells. A rope is tied to a bucket and the soil is collected and pulled out of the well. The number of wells to be constructed per unit of cultivated area depends on the depth and availability of water, planned size of irrigated area, the type of technology involved in lifting and distributing water, and the seepage rates from the surrounding grounds into the well.

Seasonal shallow wells tend to be used for vegetable farming in the dry season and for the cultivation of staple crops such as maize, sorghum and millet in the wet season. Farmers fill in the wells at the end of the dry season and re-dig them the following year.

Permanent shallow wells tend to be closer to the homestead or even in the living compound. They can be (cement) lined or unlined (Figure 3). Farmers prefer the lined wells but some do not have the financial means to acquire the requisite materials for lining. The unlined wells are irregularly shaped. The depth of the wells ranges from 1 to 14 meters (m) depending on the prevailing groundwater level. The diameter ranges between 1 to 2 m. Similar to the case of seasonal shallow wells, simple manual tools are used for the construction of permanent wells. Thus, the major cost components in the construction of wells are human labor and cement for lining.

FIGURE 2. Riverine and in-field seasonal shallow wells (*photo credits:* Eric Ofosu, PhD student, UNESCO-IHE Institute for Water Education).

FIGURE 3. Permanent shallow wells (*photo credits*: Regassa E. Namara, IWMI).

Sampling Design and Procedure

The basic sampling unit for the study was households within the three watersheds. A stratified random sampling approach was used. The specific procedures followed in the selection of samples are as follows. First, 35 communities distributed in the three sub-watersheds of the White Volta Basin with potential[2] access to shallow groundwater were identified. Second, a household census was conducted in each of the 35 communities to develop a sampling frame. These communities comprised 2,085 compounds with 4,576 households. Third, the identified households were stratified into purely rain-fed farming households and households using irrigation. The households using irrigation were further stratified into those using seasonal shallow wells, permanent shallow wells and surface water sources (mainly small reservoirs). Finally, a sample consisting of a total of 420 farmers was selected using probability-proportional-to-size sampling, in which the selection probability for each strata is set proportional to the size of the stratum relative to the total population. The final samples included 141 farmers who relied purely on rain-fed farming, and 212, 23 and 40 farmers who used seasonal shallow wells, permanent shallow wells and small reservoirs, respectively, for irrigation.

The survey instrument included three modules. The topics covered under module 1 included household demographic and socioeconomic characteristics, resource endowments (e.g., farm size, size of livestock holding), shallow groundwater construction process and costs if relevant, detailed agronomic and on-farm water management practices, crops grown and level of institutional support (e.g., credit, extension). Module 2 covered farm households' access to food. Module 3 dealt with consumption expenditure.

[2]The potential here is assessed based on the distance of the communities from the riverbed. Only alluvial aquifers are used in the region.

Results

Nature and Extent of Agricultural Use of Shallow Groundwater

Our survey identified 35 communities (with a total of 20,962 residents) with potential access to shallow groundwater and other forms of irrigation in the entire three micro-watersheds of the White Volta Basin. A synopsis of households by their irrigation choices is given in Table 1. Interestingly, there was no overlap found in irrigation choices. However, some farmers using water from small reservoirs also make use of the drainage water by digging shallow wells in the command areas or in the premises of the reservoirs.

Overall, approximately 60% of households had at least one of the nearly 7,000 wells in the study area, irrigating a total land area of approximately 907 ha. Approximately 85.2% of the farmers who practiced riverine shallow well irrigation dug three riverine shallow wells or less during a season, and about 72.1% of these wells had a depth of 6 m or less. On the other hand, 96.1% of the farmers using in-field shallow wells owned six or less of these wells, and about 68.5% of these had a depth of 6 m or less. The maximum number of riverine shallow wells owned by farmers is five while the corresponding figure for in-field shallow wells was 11. Details of farmer characteristics are given in Appendix 1, Tables A1.1 to A1.3.

TABLE 1. Extent of irrigated area and irrigation types.

	Number of households	Number of wells	Average number of people per household	Area	Area/well
Total households	4,576	NA	NA	NA	NA
Non-irrigating	1,795	NA	NA	NA	NA
Irrigating	2,781	NA	NA	NA	NA
Seasonal shallow wells	1,987	6,212	3.13	810	0.13
In-field	1,603	5,290	3.30	597	0.11
Riverine	384	922	2.40	213	0.23
Permanent shallow wells	512	666	1.30	106	0.16
Small reservoirs*	282	NA	NA	69.7	NA

Source: Authors' survey

Note: *Some farmers reuse drainage water from reservoirs for irrigation; NA – not applicable.

To put these numbers in context, the total irrigated area in Ghana has been officially estimated at around 30,000 ha. No groundwater irrigation has been officially reported and no informal irrigation such as that has been identified in these figures. Inclusion of groundwater use found only in this study, increases the total official figure by 3%.

Is the Practice of Shallow Groundwater Irrigation Profitable?

One of the critical objectives of this study is to examine the economics of shallow groundwater irrigation. Of particular importance is the cost structure of shallow groundwater irrigation so as to identify possible constraints to expansion, the profitability under current conditions, and how those conditions may change as the opportunity cost of labor changes. Here, we first describe the fixed costs involved in the development of wells. We then examine the agro-economic and on-farm water management practices and their associated costs. Finally, we combine the information to estimate overall profitability.

Investment Costs of Shallow Groundwater Development

The main elements of the investment costs of shallow groundwater development are well drilling and well lining (both functions of well depth), and procurement of water-lifting devices. Water is lifted using a variety of technologies including motorized pumps, rope and bucket, hand pumps and treadle pumps. However, the use of motorized pumps is limited to riverine shallow wells where yield is sufficiently high[3]. Water is primarily lifted from infield shallow wells by rope and bucket. The service life of motorized pumps has been estimated to be about 5.5 years while rope and buckets provide a service of about 4.5 years. Field watering is also carried out manually, mainly using the same buckets by literally pouring water on to the field crops or using a water hose and pipes.

Motorized pumps are the single largest cost in the development of shallow groundwater wells. However, they can be used on multiple wells, and so it is important to consider total costs per household and per well when considering investment costs. Labor also forms a substantial part of costs in the development of wells and, as shown in the next section, of overall variable costs. As most labor is self-supplied, assumptions on the opportunity cost of labor rates are critical. Here we used USD 1.4/day, the observed farm wage rate in the study area.

The investment costs of shallow groundwater irrigation are detailed in Table 2. It is interesting to note that riverine shallow wells, while being the most expensive to develop in terms of capital costs, are actually the second cheapest in terms of costs per hectare. It is also worth noting the comparison in the costs of informal groundwater development versus formal surface irrigation schemes. Estimates of the costs of formal irrigation development in Ghana are often given in the range of USD 10,000-15,000 per hectare (Kyei-Baffour and Ofori 2006), which is vastly more than farmers' self-developed groundwater. While the comparison is not entirely fair because of differences in purpose and overall water control, the difference is still striking.

There are a few other reliable estimates of drilling costs in Ghana, which can be used to compare these figures. Obuobie and Barry (2004) estimated the average cost of drilling a 40-m deep borehole to be approximately USD 3,920, which is approximately USD 98 per meter. Local drillers in the Keta District report charging about USD 36 for drilling a 6-m deep shallow well. Farmers in the study area also reported that costs for the development of permanent wells could be highly variable depending on whether rock was encountered during drilling.

[3] 82.6% of farmers that use shallow groundwater for irrigation used manual water-lifting technologies while 17.4% used motorized pumps.

TABLE 2. Technical characteristics of shallow well irrigation.

	Riverine shallow well	In-field shallow well	Permanent shallow well	
			Lined	Unlined
(1) Mean depth (m)	5.6	5.9	12.2	10.4
(2) Labor rates (USD/day)	1.4	1.4	1.4	1.4
Drilling costs				
(3) Labor (man-days/m)	0.94	0.94	3.6	4.3
(4) Other costs (USD/m)	2.4	1.4	1.4	1.6
(5) Total drilling costs (1*[(2*3)+4])	20.8	16.02	78.6	79.2
Lining cost				
(6) Labor (in USD)	NA	NA	10.5	NA
(7) Material cost (in USD)	NA	NA	11.8	NA
(8) Total lining costs (6+7)	NA	NA	22.3	NA
(9) Total construction costs per well (5+8)	20.8	16.2	101.0	79.2
(10) Cost of water-lifting device (USD)	222.1	6.9	5.8	5.8
(11) Wells per household	2.4	3.3	1.5	1.2
(12) Investment cost per household ((9*11)+10)	**272.0**	**60.4**	**157.3**	**101.0**
(13) Average investment costs per well (12/11)	**113.3**	**18.3**	**104.9**	**84.2**
(14)Average irrigated area/well (ha)	0.23	0.11	0.16	0.16
Average investment costs per hectare (13/14)	**492.6**	**166.4**	**655.6**	**526.3**

Source: Authors' survey

Note: *NA = not applicable

Agronomic and On-farm Water Management Practices and Associated Costs

There were 171, 41 and 23 farmers in the sample representing in-field, riverine and permanent shallow wells, respectively. These farmers operated 247 fields with a total cultivated area of 92.0 ha. Three farmers who initially reported only owning a riverine shallow well indicated that they also had an in-field shallow well, which they used to irrigate a few beds. The major crops grown during the 2008/2009 dry season include tomato (87%), pepper (9.5%) and other crops (3.5%). The other crops grown include onion, rice, okra, leafy vegetables and maize (Table 3). Tomato is the single most important crop grown under shallow groundwater irrigation, and pepper dominates irrigation using permanent shallow wells. Staple crops such as maize are also grown under permanent shallow well irrigation, usually for subsistence purposes.

TABLE 3. Cropping patterns.

Irrigation method	Tomato		Pepper		Others		Number of fields
	Area	%	Area	%	Area	%	
In-field shallow wells	55.8	89.1	4.1	6.5	2.4	3.9	176
Riverine shallow wells	23.6	94.3	1.0	4.0	0.4	1.6	48
Permanent shallow wells	0.7	14.9	3.7	76.6	0.4	8.5	23
Total	80.1	87.0	8.8	9.5	3.2	3.5	247

Source: Authors' survey

Farmers grow many crops on very small plots in complex associations and sequences. Some of these are intercropped. Many problems associated with aphids and nematodes affect production of respondent's crops. Crops such as onions are particularly preferred because they can be stored for several months without significant quantitative and qualitative losses, which ensures that farmers can still get high prices for their goods.

The cropping calendar for tomatoes and pepper (the two major crops) cultivated during the 2008/2009 season is depicted in Figure 4 and Figure 5, respectively. The bars of each graph show the actual number of fields/plots on which a particular agronomic operation (planting, start of harvest and completion of harvest) was carried out during the months indicated. For tomatoes, planting starts in July and extends to January, but about 81% of the fields are planted in the months of October and November. January, February and March are the peak harvesting period for tomatoes. The practice of teamwork is frequently carried out during harvesting. Farmers assist each other in turn. For pepper, August, September and October are busy planting months. The major harvesting operations are performed from December through to April.

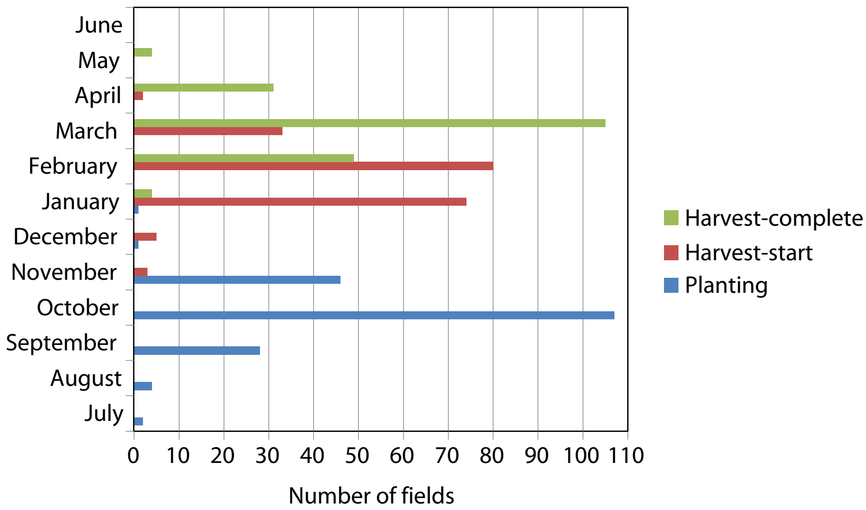

FIGURE 4. Cropping calendar for tomatoes during the 2008/2009 season.

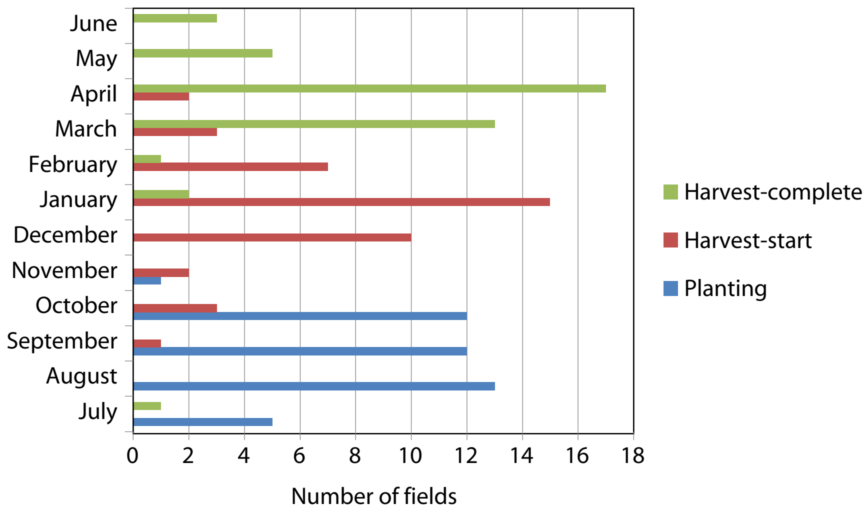

FIGURE 5. Cropping calendar for pepper during the 2008/2009 season.

Agronomic practices

Land preparation: The main mode (85.7% of fields) of land preparation is manual using a hoe/cutlass. Bullocks (own and/or rented) were used on about 11.7% of the fields and tractors were used only on two fields belonging to the farmers using riverine shallow wells. The two fields rented tractors at a rate of USD 92.7 per hectare for plowing and USD 40.5 per hectare for harrowing. The labor associated with tractor operation was estimated at 6.7 man-days. The rental cost for bullocks is about USD 28.3 per hectare, and the human labor associated with bullock plowing is estimated at 8.2 man-days per hectare. Other than tractor use, there is no significant difference in the mode of land preparation among the three types of shallow groundwater irrigation systems.

A hoe can be acquired at a price of USD 1.6 per unit while a cutlass can be obtained at approximately USD 3.4 per unit. Both instruments can be used for two years. One person from the sample of farmers using permanent wells used 4.9 liters per hectare (l/ha) of roundup for land clearing. The cost of the roundup was USD 5.6 per liter and 2 hours of labor used for application.

Fencing: Fencing is often necessary to protect irrigated fields from the damage caused by livestock and wildlife. Consequently, approximately 26.3% of farmers using in-field seasonal shallow wells fenced their fields, while only 4.9% of the farmers using riverine shallow wells fenced their fields. Almost all of the farmers using permanent shallow wells fenced their fields. Labor for fencing is about 33.3 man-days per hectare and cost of fencing material is about USD 43.5 per hectare.

Planting: For all crops and types of shallow groundwater irrigation, transplanting is the dominant mode of planting. Approximately 96.7% of the fields were transplanted as compared to a mere 3.3% of the fields which were planted by broadcasting or dibbling methods. The mean seed rates were 4.4 and 2.7 kilograms (kg) per hectare for tomatoes and pepper, respectively. The cost of tomato seeds was approximately USD 13.1 per kilogram, and for pepper it was approximately USD 9.1 per kilogram. The mean labor required for nursery preparation and transplanting was 32.1 and 29.1 man-days per hectare for tomatoes and pepper, respectively.

Weed control: Hand-weeding is the dominant weed control strategy for both tomato and pepper crops. Weeding is carried out by direct hand-pulling or by the use of tools such as the hoe (93%). The tools used for hand-weeding are mainly the same tools used for land preparation. Tomato weeding required about 26.7, 21.2 and 66.7 man-days per hectare for in-field, riverine and permanent shallow well irrigation, respectively; whereas pepper needed 78.5, 9.6 and 69.4 man-days per hectare, respectively. It appears that fields belonging to the category of farmers using permanent shallow well irrigation demand more labor input for weeding and a few farmers have used herbicides (5.2%).

Diseases and other pest control: Out of the total of 213 fields that were reportedly treated with pesticides (other than herbicides), 13 were wrong prescriptions - 12 fields were treated with herbicides (even though the farmers intention was insect control) and 1 field was treated with liquid fertilizer. Out of a total of 200 fields that were treated with pesticides, about 95% were sprayed with DDT (Dichloro-diphenyl-trichloroethane) while the remaining 5% were treated with different kinds of insecticides and fungicides, namely Diazole 50 EW, Lambda Super, Karate, Diethyene M 45, Funguran-OH, Kocide 101, and Cocobrain.

The pesticide rates applied depend on the type of chemical and also the prevalence and severity of the pest as observed by the farmers. For instance, the rate of insecticide (i.e., DDT) applied ranged between 3.95 to 11.6 l/ha. Of the farmers using shallow well irrigation, 13.6% own knapsack sprayers. Those farmers who do not own sprayers obtain it from neighbors and relatives or rent it. The rental cost of a sprayer ranges from USD 8.2 to USD 20.3 per hectare, depending on whether the labor costs for application was part of the deal or not. About 35.3% of the farmers reported that the rental cost of the sprayer was inclusive of the labor costs for spraying.

Soil fertility management: The main types of inorganic fertilizer applied were NPK (15-15-15), ammonia, urea and NPK (20-20-20). The use of NPK (20-20-20) was rare. Farmers use a single fertilizer or a combination of fertilizers as detailed below:

- Of the 238 fields that received fertilizer, 71.4% were treated with a combination of ammonia and NPK (mainly 15-15-15).
- Only NPK (15-15-15) and NPK (20-20-20) fertilizer were applied to 11.3% of the fields.
- A combination of urea and NPK (15-15-15) and NPK (20-20-20) were applied to 7.6% of the fields.
- A combination of urea and ammonia were applied to 3.8% of the fields.
- A combination of urea, ammonia and NPK (15-15-15) and NPK (20-20-20) were applied to 3.4% of the fields.
- Only urea was applied to 1.7% of the fields.
- Only ammonia was applied to 0.8% of the fields.

The reported fertilizer application rates are summarized in Table 4. On average, pepper received more doses of fertilizer than tomatoes. Mean fertilizer prices per bag are USD 24.4 (urea), USD 24.6 (ammonia), USD 27.2 (NPK (15-15-15)) and USD 28.2 (NPK (20-20-20)) for farmers using in-field and riverine shallow well irrigation. Application rates reported by farmers using permanent shallow well irrigation were somewhat lower than that reported by the rest.

Labor costs for the application of inorganic fertilizer ranged from 41.5 to 81.5 man-hours per hectare for tomatoes and 48.6 to 76.5 man-hours per hectare for pepper. In addition to inorganic fertilizers, farmers also applied organic fertilizers. Labor costs for the application of organic fertilizer ranged from 12.4 to 29.3 man-days for tomatoes and 24.4 to 34.8 man-days for pepper. Thus, the level of labor costs for fertilizer application is quite variable depending on the method used and frequency of application.

TABLE 4. Fertilizer application rates (in bags per hectare).

Fertilizer	Tomatoes			Pepper	
	In-field	Riverine	Permanent	In-field	Permanent
Urea	4.0	2.5	3.7	5.4	5.4
Ammonia	3.5	5.4	0.6	4.9	4.9
NPK (15-15-15)	4.0	8.9	0.9	6.4	6.4
NPK (20-20-20)	4.9	0.0	0.0	0.0	0.0

Source: Authors' survey

Harvesting: The main method used for harvesting is handpicking without the use of any tools. The number of harvests during the season ranges from 0 to 10 for tomatoes and 1 to 20 for pepper. A zero harvest implies a crop failure. However, most fields of tomatoes (about 88.7%) were harvested 1 to 5 times during a season. Contrarily, most pepper fields were harvested 6 to 10 times in a season (about 70.7%). The labor required for harvesting is a reflection of the number of times a farmer harvests in a season. This ranges from 12.8 to 77.8 man-days per hectare for tomatoes and 12.4 to 171.9 man-days per ha for pepper. Farmers report outputs in local units such as crates for tomatoes and *basins* for pepper. For this reason, the farmers used in the sample were asked to report the value of their harvests as well.

The estimated yield of tomatoes ranged from 53.8-104.4 crates per hectare. The corresponding gross value ranged from USD 605.1-USD 2,587.4 per hectare. Mean higher yield and value were recorded for farmers using riverine shallow well irrigation, which may be due to differences in water availability and planting density. For pepper, the yields ranged from 40.3-133.8 *basins* per hectare with the corresponding value ranging from USD 1,255.4-USD 1,719.0 per hectare. The lowest pepper yield was recorded for farmers using riverine shallow well irrigation. One can conclude that, even though the farmers can achieve an overall mean higher value from the cultivation of tomatoes, the variance is also high indicating the riskiness of tomato cultivation. It was also recognized that these crops are produced mainly for sale. Surprisingly, all outputs were sold on the farm.

On-farm water management practices

The on-farm water distribution or management methods employed by farmers are ridging (51%), basin/holing (39%), bed and furrow (6.8%) and others (3.2%). The majority of fields irrigated with water from riverine shallow wells adopted the ridging method (on about 95.7% of the fields) whereas about 92.9% of the fields under in-field seasonal shallow well irrigation employed the basin/hole and ridging methods. All of the farmers using water from permanent shallow wells for irrigation constructed basin/hole and bed and furrow structures.

The system of on-farm water management employed is dictated partly by the quantity of available water in the well and partly by the nature of the crop. The basin/hole system is the most water-efficient system, and is practiced on 46.2% and 56.5% of the fields irrigated with water from in-field shallow wells and permanent shallow wells, respectively. It has to be noted that the water yield of in-field shallow wells is inferior to that of riverine shallow wells, and that water from permanent shallow wells is used for multiple purposes. The major instruments used for preparing on-farm water management structures are the hoe and shovel. These instruments can be purchased at a price of USD 1.4-USD 2.1 per unit. The labor required for bed and furrow preparation is 20.0 man-days per hectare. The labor required for basin/hole preparation is 35.3 man-days per hectare.

Most farmers did not irrigate their fields during plowing. Of the fields that were under permanent, riverine and in-field shallow well irrigation, 43.5%, 55% and 56%, respectively, did not receive irrigation during plowing. For fields under in-field and riverine shallow well irrigation, one to three rounds of irrigation takes place during plowing with one round of irrigation being the most common practice. Farmers using permanent shallow wells tend to provide more rounds of irrigation during plowing as compared to the other groups. Labor required for irrigation during plowing was about 2.5, 6.4, and 7.7 man-days per hectare for fields under riverine, in-field and permanent shallow well irrigation, respectively.

On average, farmers practice irrigation for about 12 weeks, each week providing about three rounds of irrigation, except in week 6 when most farmers did not water their crops during the 2008/2009 season perhaps due to receiving adequate rainfall during that time. Some fields receive irrigation more than eleven times a week. Irrigation requires substantial labor input. The total labor demand for irrigation operations during the 2008/2009 season was about 10,668 man-days (or about 45.4 man-days per household). The level of irrigation labor required per unit area depends on the type of on-farm water management adopted, the type of technology used for lifting water and the crop type. For instance, mean irrigation labor per hectare for tomatoes was about 125.7 man-days while the corresponding value for pepper was 314.8 man-days. Obviously, farmers using motorized pumps to lift water need lower labor per unit area of land.

All of the farmers using water from riverine shallow wells for irrigation used motorized pumps to lift water. The total fuel consumed was about 1,513.0 liters, which translates into 84.9 liters per hectare. The price of fuel per liter as reported by farmers ranged between USD 0.5 and USD 1.1 per liter, with USD 0.9 per liter being the most common price faced by farmers. Thus, the total value of fuel consumed for pumping water for irrigation was about USD 1,280.7.

Economics of Shallow Groundwater Irrigation

The profitability of irrigated tomato and pepper cultivation under the three shallow groundwater irrigation systems is summarized in Table 5. Labor constitutes a significant proportion of total costs.

Fixed cost constitutes a very small part of the total cost of production, and ranges from 1.3% to 11%. For farmers using water from in-field shallow wells for irrigation, the fixed cost is especially low because of the fact that the farmer performs the drilling jobs every season and uses only rudimentary technologies for land preparation, land levelling and water lifting. The fixed costs are higher for farmers who use riverine shallow wells, because they use motorized pumps for lifting water. The fixed costs are also high for farmers who use permanent wells because the drilled wells are deeper and are used for several years.

Gross margin (or income above variable costs) was negative for pepper cultivation under in-field shallow well irrigation and also for tomato cultivation under permanent shallow well irrigation. However, this may be due to an overestimation of the opportunity cost of labor, since, in fact, there is substantial unemployment or underemployment as already mentioned. Assuming zero opportunity cost for labor, the gross margins obtained from all irrigation systems are positive (Table 5). As shown in Table 5, the fixed costs of well construction are a minor part of the overall costs. The consideration of fixed costs has little bearing on the expected benefit values. The single most important cost would be labor if market wages were applied.

Table 5. Profitability analysis (USD/ha).

Items	In-field seasonal shallow wells		Riverine seasonal shallow wells		Permanent shallow wells	
	Tomato	Pepper	Tomato	Pepper	Tomato	Pepper
Gross income	1,493.7	1,719.7	2,570	1,255.4	605.1	1,611.9
Variable costs						
Fertilizer	192.5	362.4	375.2	0	41.9	295.3
Other material costs	203.6	214.4	295.8	228	54.6	60.5
Capital cost	132.9	172.1	217.2	71.3	31.2	93.9
Labor cost	517.3	981.9	333.2	376.6	784.6	923.3
Total variable cost	1,046.3	1,730.8	1,221.4	675.9	912.3	1,373
Gross margin	**447.4**	**-11.1**	**1,348.6**	**579.5**	**-307.2**	**238.9**
Gross margin at zero opportunity cost of labor	**964.7**	**970.8**	**1,681.8**	**956.1**	**477.4**	**1,162.2**
Fixed cost	13.7	13.7	83.8	83.8	84.7	84.7
Total cost	**1,060**	**1,744.5**	**1,305.2**	**759.7**	**997**	**1,457.7**
Net returns (returns to land and management)	**433.7**	**-24.8**	**1,264.8**	**495.7**	**-391.9**	**154.2**
Total labor per hectare (man-days)	367.3	697.2	236.6	267.4	557	655.6
Irrigation cost	278.4	482.5	283.6	384.1	437.3	512.8
Labor cost (%)	48.8	56.3	25.7	49.6	78.7	63.3
Fixed cost (%)	1.3	0.8	6.4	11	8.5	5.8

Source: Authors' survey

Note: Fixed costs calculated using straight-line amortization.

Welfare Impacts of Shallow Groundwater Development

We now shift attention to the impact that groundwater irrigation has on the welfare of the people in the study region. We first examine the overall impact on income and employment. We then look at the impacts on food security and diet diversity. Finally, we examine the impact on poverty and equity.

Employment and Value Addition

The three months of dry-season irrigation using shallow groundwater have created additional demands for labor estimated at 359,511 man-days, which is approximately 214 FTE jobs per year (Table 6). This increased demand for labor is significant, since during the dry season there is substantial unemployment or underemployment, and migration to the cities of Kumasi and Accra. The total annual contribution of shallow groundwater irrigation to the economy of the 35 communities in the White Volta Basin is approximately USD 1.1 million. This is about USD 455/groundwater irrigating compound/year or about USD 54 per capita for the entire 35-village study area. In context, the poverty line for Ghana is USD 540.

Food Security

Food insecurity is a major issue in the study region. The vast majority of the farmers (98.8%), irrespective of whether they had access to irrigation, reported food shortages during the 12 months prior to the date of the interview. As shown in Figure 6, farmers using groundwater irrigation had reduced periods of food deprivation than purely rain-fed farmers. As shown in Figure 7, the same pattern prevailed almost without exception throughout the year. Figures for owners of small reservoirs are included for comparative purposes.

TABLE 6. Demand for labor and economic contribution of shallow groundwater irrigation.

Irrigation typology	Labor (man-days)	Value added (in USD)
In-field seasonal shallow wells	240,889	636,066
Riverine seasonal shallow wells	50,800	382,506
Permanent shallow wells	67,822	119,857
Total	359,511	1,138,429

Source: Authors' survey.

Note: Value added calculated as mean gross margin per hectare x estimated area.

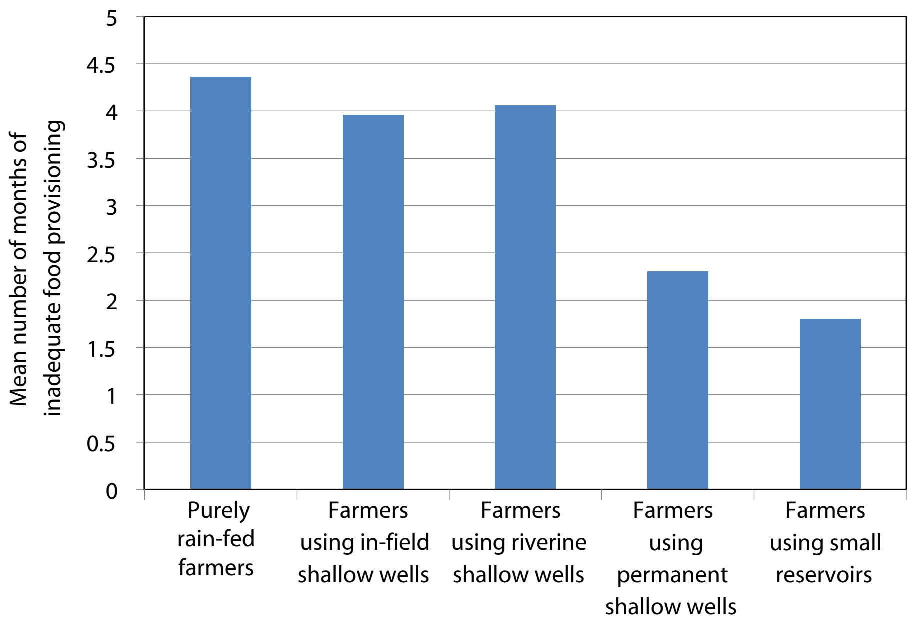

FIGURE 6. Relationship between irrigation typology and food security.

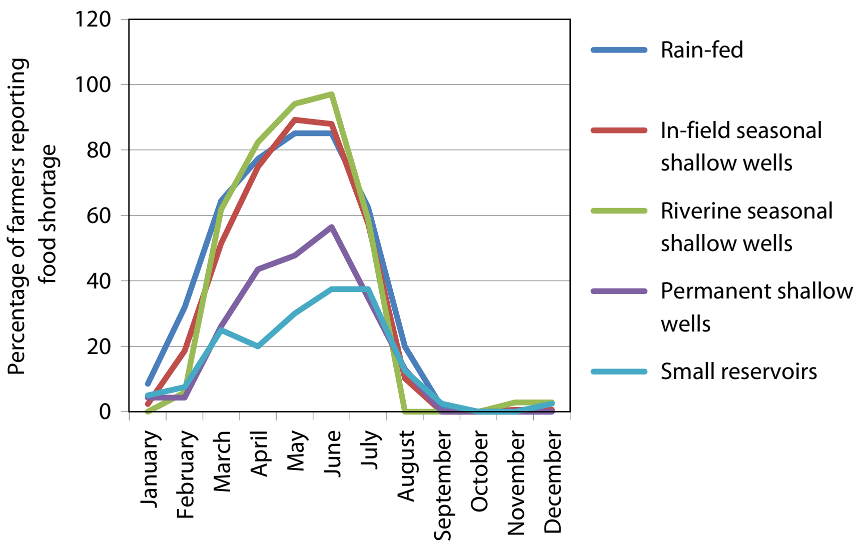

FIGURE 7. Monthly food security status for different categories of farmers.

Household dietary diversity

A more diversified diet is associated with a number of improved outcomes in areas such as birth weight, child anthropometric status, improved hemoglobin concentrations, caloric and protein adequacy, percentage of protein from animal sources (high quality protein) and household income. Following the Household Dietary Diversity Score (HDDS) measurement guideline stated in Swindale and Bilinsky (2006), we examined the relationship between groundwater irrigation and dietary diversity. The farmers used in the sample were asked whether a set of 12 food groups[4] were consumed by anyone in the household

[4] These food groups are: cereals, roots and tubers, vegetables, fruits, meat (poultry, offal), eggs, fish and seafood, pulses/legumes/nuts, milk and milk products, oil/fats, sugar/honey and miscellaneous.

during the 24 hours prior to the time the interview was conducted. Questions were asked in terms of food groups, since groups differ more in macronutrients and micronutrients than, say, different items from the same group. Scores range from 0 to 12.

There was no significant difference between the scores for rain-fed (6.3) and irrigated (6.5) farmers overall. However, there are significant differences in HDDS between different categories of farmers which are defined by their access to irrigation (Figure 8). Interestingly, farmers using permanent shallow well irrigation had the lowest HDDS.

Poverty and Inequality

To compare the poverty status of the different categories of farmers, we employ the poverty gap approach of measuring poverty (Coudouel et al. 2002). Specifically, we used the popular class of poverty gap indices known as the Foster-Greer-Thorbecke (FGT) indices. To compare the income inequality, we used the Lorenz Curve, which gives a more comprehensive description of relative income or consumption than the traditional summary inequality indices.

Poverty and inequality indices were calculated from consumption expenditure data. On average, about 57% of the farmers in the sample are poor,[5] a ratio above national averages for Ghana, confirming the general understanding that poverty is severe in the Northern Ghana regions. In the sample selected, poverty incidence is lower among farmers that have access to shallow groundwater irrigation (or irrigation) compared to purely rain-fed farmers.

The poverty gap, which is a measure of the depth of poverty or the mean consumption shortfall from the poverty line, is lower among farming households who have access to irrigation but the difference is not significant. The overall mean poverty gap value is 0.15, which means that to lift the poor out of poverty their current consumption level has to be increased by 15%. Income disparity among farmers in the sample does not seem to be that serious as indicated by the S-Gini values (Table 7). It is lowest among the farmers that

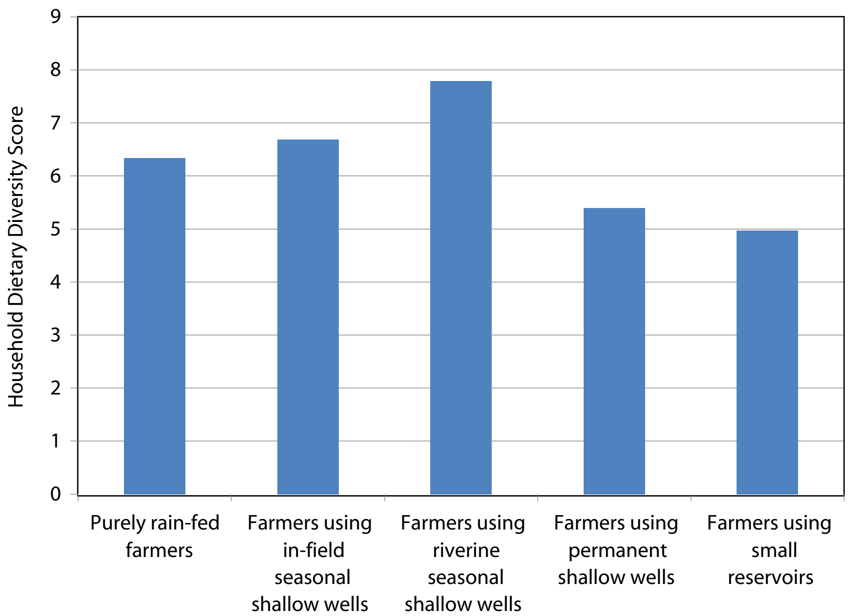

FIGURE 8. Comparison of mean Household Dietary Diversity Scores.

[5] In calculating poverty incidence, a national poverty line of USD 540 per capita per year was used.

TABLE 7. Situation of income, poverty and inequality among farmers in the sample.

Categories	S-Gini coefficient	Poverty incidence	Poverty gap
Non-irrigators	0.24	0.62	0.16
In-field shallow wells	0.18	0.55	0.14
Permanent shallow wells	0.24	0.46	0.13
Riverine shallow wells	0.27	0.58	0.19
Small reservoirs	0.33	0.50	0.15
Overall	0.24	0.57	0.15

Source: Authors' survey

use in-field seasonal shallow wells and higher among farmers that use riverine shallow wells and small reservoirs.

The Causal Link between Shallow Groundwater Irrigation and Welfare

Are the observed differences in the welfare indicators, described in the previous section, attributed to (caused by) shallow groundwater irrigation? To estimate the effect of access to shallow groundwater irrigation on household welfare, we employed the Propensity Score Matching (PSM) method, which is a non-parametric method that is widely used in impact evaluation (Dehejia and Wahba 2002). The method creates a counterfactual from a control group.

The method attempts to solve the problem of causal inference in observational or non-experimental studies such as this one, and corrects for sample selection bias due to observable differences between irrigation practitioners (the treatment group) and rain-fed farmers (the control group). Matching involves pairing treatment and control units that are similar in terms of their observable characteristics or propensity scores. The propensity score is the probability of receiving treatment (in the present case, becoming a user of shallow groundwater for irrigation) being conditional on observable characteristics. The first step in estimating the treatment effect is to estimate propensity score, which is carried out here using a logit model. Once the scores are created, an algorithm is used to match treated units (to the extent possible) with control units which have propensity scores that are sufficiently close. In the present study, households with and without access to irrigation were matched based on their propensity scores using the nearest neighbor, kernel and stratification matching methods[6]. These methods identify the closest match for each irrigating household based on propensity score among households that have no access to irrigation, and then compute the effect of shallow groundwater irrigation as the mean difference in the selected welfare indicators between the two groups of households.

The results, summarized in Table 8, largely confirm the relationships described above. Additional details are given in Appendix 2, Tables A2.1 to A2.5. Overall, the results largely confirm the relationships reported above. Farmers using groundwater had either lower poverty or fewer months of food inadequacy than those that did not use groundwater. Dietary diversity actually decreased for farmers that owned permanent shallow wells. Literature on the subject of the impact of irrigation on nutritional diversity is not unanimous (Castillo et al. 2007). For example, irrigation development may adversely affect the nutritional intake of the poor when it leads to monocropping of cereals as carried out in parts of Bangladesh (Hossain et al. 2005). This appears to also be the case in our study area, with farmers using small reservoirs where monocropping of rice is common.

[6] For the detailed exposition of this matching algorithms, see Becker and Ichino (2002).

TABLE 8. Contribution of groundwater to poverty measures, non-irrigators versus categories listed.

	Significant reduction in poverty*	Significant reduction in months of food inadequacy*	Significant increase in dietary diversity*
In-field shallow wells	No	Yes	Yes
Permanent shallow wells	No	Yes	No (reduction)
Riverine shallow wells	Yes	No	Yes
Small reservoirs	Yes	Yes	No (reduction)

Source: Authors' survey
Note: * The statistical significance level can be inferred from the t-values provided in Appendix 2.

Constraints, Opportunities and Prospects for Further Expansion

While being relatively unknown, the practice of agricultural groundwater use appears to have begun in the study region in the 1890s with the colonial agricultural service (Barry et al. 2010). While post-colonial governments did not continue to support groundwater use, it has increased in recent years as a result of droughts and floods and has led farmers to innovate their own adaptive strategies; population pressure induced the adoption of intensification strategies; the expansion of improved infrastructure opened up vegetable markets of the south to northern Ghana; and the Burkina Faso-Ghana cross-border tomato trade motivated farmers to engage in tomato cultivation using shallow groundwater during the off-season. As we have shown, groundwater irrigation provides employment opportunities and substantial income, particularly during the long dry season in the northern savannah zones of Ghana. The question is whether groundwater use can be further expanded. The first issue in addressing this question is - availability of the resource itself.

Groundwater resources are poorly understood in many parts of SSA, including Ghana and the region selected for this study. In Ghana, those studies that do exist are dominated by the analysis of hydrochemistry. These studies have evaluated the suitability of groundwater for irrigation based on the level of salinity, sodicity, acidity and alkalinity of the water samples collected from selected localities in the Volta, Eastern, Northern and Upper East regions (Banoeng-Yakubo et al. 2009; Ganyaglo et al. 2011; Yidana 2010; Anku et al. 2009; Yidana et al. 2008b; Yidana et al. 2007). Most of the samples analyzed were regarded as being in good or excellent condition for irrigation.[7]

In terms of quantity, Barry and Forkuor (2010) provide the only study available. They estimated the aquifer storage volume under a 387-ha shallow groundwater irrigated area of the Atankwidi Basin and determined annual storage to be 370 million cubic meters (MCM), which is about 4 times more than the current annual

[7] However, in some areas such as the Keta Basin, Birimiam Basin and Kulpawn Subbasin of the White Volta Basin, aquifers do not supply groundwater of acceptable quality for irrigation due to high salinity, high permeability, medium to high sodicity and significant magnesium hazard (Kortatsi et al. 2009).

groundwater use (89,000 cubic meters (m^3)). This indicates that groundwater resources in the underlying aquifer are capable of sustaining shallow groundwater irrigation. It also indicated that groundwater irrigation could be expanded if appropriate drilling technologies were used (Barry et al. 2010: 19). Since the geological conditions and irrigation practices in the Atankwidi Basin are similar to those in parts of the White Volta Basin, it seems that there is possible room for expansion of shallow groundwater irrigation there (Barry et al. 2010).

However, groundwater flow modeling and sustainability analysis by Barry et al. 2010 for the 2006/2007 cropping season showed that caution was needed. Increasing the irrigated area by 50% would require a total of 396,000 m^3 of groundwater, and a drop in the hydraulic head by 8.6 m from the beginning to the end of the 2006/2007 cropping season compared to a drop of 6.2 m for same period under existing practices. Increasing abstraction by 100% would drop the hydraulic head by 12.7 m. Thus, further abstraction could have a significant effect on the groundwater level in the alluvial aquifer and could lead to local overextraction (Barry and Forkuor 2010).

While there is cautious optimism for some expansion based on resource availability, interviews with farmers, both individually and in groups and with key informants including extension agents, women traders and transporters, highlighted a number of other constraints. These are listed below in the perceived order of priority.

(1) Technical knowledge: Lack of adequate knowledge of the potential of the resource, and affordable and efficient technology and/or methods for drilling wells are considered as major limiting factors. Currently, farmers rely on their own experience-based judgement and methods of trial and error for locating wells.

(2) Institutional issues: land tenure security is a major concern for practitioners. Because of land tenure insecurity, many farmers have to endure the drudgery of digging and refilling wells every season. Many farmers work on plots leased, given to them for free or at a small cost. Therefore, they do not enjoy the assurance that they will be using the same plot of land the following season.

(3) Marketing: Groundwater irrigators are necessarily market-oriented by virtue of the nature of crops they cultivate. They consume a smaller share of what is produced. On the other hand, most of the outputs are perishable requiring special storage and transportation facilities. Temporal and spatial price variability is too high, and there are limited marketing channels or market participants. The paucity of alternative marketing channels and market participants allows few buyers (e.g., market women) to bid the price down. Consequently, crops are sold directly on the field, as farmers have no storage facilities to keep freshly harvested vegetables. Purchases are also usually made on a credit basis. The transportation cost is too high due to a poor road network. The ratio between the high price per unit received from the sale of vegetable crops and the corresponding low price received for the quantity within a season is as high as 700%.

(4) Limited access to inputs and technologies: high cost of essential inputs such as fertilizers, pesticides, herbicides and improved seeds contributes either to outright financial loss or significant reduction in the profit margin of farmers, thus reducing farmers' incentives. Most of the groundwater irrigated crops do not qualify for the Ghanaian government's current fertilizer subsidy policy. For instance, certified shallot seeds are not easily available in Ghana. There is also paucity of affordable land preparation technologies. Most Ghanaian farmers have little experience in cheaper alternative plowing techniques such as bullock traction.

The availability of modern and efficient water-lifting technologies and affordable well-drilling technologies or services is also a constraint to the development of groundwater irrigation. For those that are in use, farmers lack the skill for maintenance and proper operation. Energy for lifting and distributing water is also a problem. The price of petrol and diesel are considered too high.

(5) Biophysical factors: Dry-season vegetable production is also severely constrained by the occurrence of pests and diseases, which cause

significant yield loss or force farmers to purchase expensive chemicals to protect their crops. The notable crop pest and diseases observed are nematodes, root rot, leaf curl, aphids, etc. Birds and fowls also destroy crops, since the dry-season crops are the main food items available during this time.

(6) Limited availability of credit facilities: Credit services for developing wells, acquiring water-lifting devices and financing expenses for crop production inputs are limited. In instances when credit facilities are available, the terms of credit are too high.

(7) Extension support: Extension services in the irrigation sector, in general, and in the groundwater irrigation sector, in particular, are poor. Farmers require agronomic advice to find appropriate seed and agrochemicals. Farmers claim that extension services are not regularly available. There is, at present, no advice available to farmers on the amount of water or irrigation schedule that they should use for a particular crop.

(8) Livestock/dry-season crop cultivation interface: A major problem in the dry season is the presence of livestock who frequently destroy crops. Farmers would like to fence their plots. Fencing can be a major production cost item, particularly in the Northern Ghana regions, where livestock rearing is one of the important livelihoods of farming households.

(9) Labor availability or drudgery: In situations where water is manually lifted and distributed, farming becomes labor-intensive. High frequency of irrigation in sandy areas also contributes to the demand for labor.

Conclusions and Recommendations

Knowledge about Ghana's groundwater resources is scarce, and much of the limited available information paints a pessimistic view about the potential use of groundwater in agriculture. Consequently, agricultural use of groundwater is not sufficiently addressed in Ghana's water and irrigation policies. This is largely true for most SSA countries. Despite the official pessimism, some studies have shown potential and as we show here smallholders have developed shallow groundwater-based irrigation systems in many regions of Ghana including the Upper East region.

The total estimated shallow groundwater irrigated area in the White Volta Basin during 2008/2009 dry season was about 916 ha, of which 597 ha of land was developed using in-field seasonal shallow wells, 213 ha was developed using riverine seasonal shallow wells and 106 ha was developed using permanent shallow wells. Tomatoes and pepper are the two major crops grown. Many other crops are also cultivated including onion, okra, leafy vegetables, rice and maize often in complex patterns and sequences.

The investment cost of developing shallow groundwater for irrigation is low. Labor constitutes the majority of the total investment cost while the fixed cost is minimal except for constructing riverine shallow wells, which involves procuring motorized pumps. Labor also constitutes a significant proportion of the costs of production. The farmers largely employ rudimentary technologies that are available at low prices or that can be made by themselves. The high demand for labor and low initial capital requirement of the current shallow groundwater development technology is compatible with the socioeconomic circumstances of the farming communities in the study area, particularly during the dry season.

Farmers have developed complex but water- and nutrient-efficient, labor-intensive on-farm water management and agronomic practices and infrastructures, which reflects the relative resource scarcities during the long dry season. During the dry season land and labor are relatively abundant but water is the limiting factor for production. Thus, farmers have adopted on-farm water management and agronomic techniques that allows the application of water and nutrients directly to the root zone.

Crops irrigated using shallow groundwater are generally profitable, even when considering market wage rates that may not apply during the labor-abundant dry season. When the opportunity cost of labor is zero (or when we assume that the required labor is supplied entirely by family members), cropping is highly profitable. Thus, the opportunity cost of labor is the key for the sustainability of current shallow groundwater irrigation in the White Volta Basin.

Shallow groundwater-based irrigation systems have significantly contributed to the economy of the communities, poverty reduction and food access, particularly during months of extreme food shortages. The total value addition of shallow groundwater irrigation was estimated to be about USD 1.1 million in just 3 to 4 months. It created jobs, particularly for the young people, during the dry season with the likely effect on rural-urban and north-south distress migration in Ghana.

The question is how much further potential is there for further expansion of shallow groundwater irrigation. Clearly, there is a need for more research on this aspect in Ghana and SSA at large. The recent information available shows that groundwater resources in the underlying aquifer are capable of sustaining shallow groundwater irrigation in the Atankwidi Basin and that more land can be irrigated if appropriate technologies are introduced. Moreover, there are many areas in Ghana with similar hydrogeological conditions where the practice of shallow groundwater irrigation can cautiously be scaled out.

However, the full realization of the economic potential of shallow groundwater irrigation is faced with many challenges, including land tenure insecurity, lack of access to appropriate low-cost drilling technologies, lack of decision support for precise sitting of the wells, inefficiencies in output marketing, crop pests and diseases, and absence of explicit government support services (i.e., extension, credit, etc.). For instance, the type, rate and combination of chemical fertilizers applied by farmers are not based on sound experimental research results or research-based extension advice. It is usually based on farmers' own judgments or extrapolations of extension recommendations for rain-fed crops. Similarly, farmers lack proper advice on type, rate of application, and the safety precautions required in calibrating and applying pesticides.

To get the maximum benefit from groundwater, the findings from this study suggest the following:

1) Better understanding of the nature and extent of the existing use of groundwater, so that it is considered more in national planning and policy.

2) Better understanding of the hydrogeology, so that expansion can be profitably planned.

3) Reducing some of the other constraints identified here, including:

    - provision of land tenure security through innovative institutional arrangements;
    - provision of decision support tools, such as easy to comprehend groundwater maps for assessing the precise sitting of wells;
    - improving access to appropriate and affordable drilling technologies;
    - introducing tube-well technology, where applicable;
    - provision of research-based (or founded) extension advise on agronomic practices (i.e., soil fertility management, crop protection, etc.) and water management systems;
    - training farmers in safety precautions regarding the handling of agro-chemicals;
    - improving the supply chain of complementary inputs (e.g., improved seeds, fertilizer, herbicides, etc.); and
    - improving output marketing systems by, for example, organizing farmers using shallow groundwater irrigation into commodity value chains.

References

Akudago, J.A.; Chegbeleh, L.P.; Nishigaki, M.; Nanedo, N.A. 2009. Estimating the storage and maximum annual yield of the aquifer system in northern Ghana and the potential for irrigation. *Journal of Environmental Hydrology* 17: 1-13.

Anku, Y.S.; Banoeng-Yakubo, B.; Asiedu, D.K.; Yidana, S.M. 2009. Water quality analysis of groundwater in crystalline basement rocks, Northern Ghana. *Environmental Geology* 58(5): 989-997.

Banoeng-Yakubo, B.; Yidana, S.M.; Nti, E. 2009. An evaluation of the genesis and suitability of groundwater for irrigation in the Volta Region, Ghana. *Environmental Geology* 57(5):1005-1010.

Barry, B.; Forkuor, G. 2010. *Contribution of informal shallow groundwater irrigation to livelihoods security and poverty reduction in the White Volta Basin (WVB): Current status and future sustainability*. CPWF Project Report. Colombo, Sri Lanka: CGIAR Challenge Program on Water and Food (CPWF). www.waterandfood.org

Barry, B.; Kortatsi, B.; Forkuor, G.; Gumma, M.K.; Namara, R.E.; Rebelo, L-M.; van den Berg, J.; Laube, W. 2010. *Shallow groundwater in the Atankwidi Catchment of the White Volta Basin: Current status and future sustainability*. Colombo, Sri Lanka: International Water Management Institute. 30p. (IWMI Research Report 139).

Becker, O.S.; Ichino, A. 2002. Estimation of average treatment effects based on propensity scores. *The STATA Journal* 2(4): 358-377.

Castillo, G.E.; Namara, R.E.; Ravnborg, H.M.; Hanjra, M.A.; Smith, L.; Hussein, M.H. 2007. Reversing the flow: Agricultural water management pathways for poverty reduction. Chapter 4 in: Molden, D. (ed.), *Water for food, water for life: A comprehensive Assessment of Water Management in Agriculture*. London: Earthscan; Colombo: International Water Management Institute.

Coudouel, A.; Hentschel, J.S.; Wodon, Q.T. 2002. Poverty measurement and analysis. In: Poverty Reduction Strategies Paper (PRSP) Sourcebook. Washington, DC, USA: World Bank. Pp. 27-74.

Dehejia, R.H.; Wahba, S. 2002. Propensity score-matching methods for nonexperimental causal studies. *The Review of Economics and Statistics* 84(1): 151-161.

Ganyaglo, S.Y.; Banoeng-Yakubo, B.; Osae, S.; Dampare, S.B.; Fianko, J.R. 2011. Water quality assessment of groundwater in some rock types in parts of the eastern region of Ghana. *Environmental Earth Sciences* 62(5):1055-1069.

Giordano, M. 2005. Agricultural groundwater use in sub-Saharan Africa: What do we know and where should we go? *Water Policy* 7: 613-626.

Gyau-Boakye P. and J.W. Tumbulto. 2000. The Volta Lake and declining rainfall and streamflows in the Volta River Basin. *Environment Development and Sustainability* 2: 1-10.

Hossain, M.; Naher, F.; Shahabuddin, Q. 2005. Food security and nutrition in Bangladesh: Progress and determinants. *Electronic Journal of Agricultural and Development Economics* 2(2): 103-132.

Kortatsi, B.K. 1994. Groundwater utilization in Ghana. In: Future Groundwater Resources at Risk (Proceedings of the Helsinki Conference, June 1994). IAHS Publ. No. 222. Available at http://iahs.info/redbooks/a222/iahs_222_0149.pdf (accessed on November 21, 2011).

Kortatsi, B.K.; Anku, Y.S.A.; Anornu, G.K. 2009. Characterization and appraisal of facets influencing geochemistry of groundwater in the Kulpawn sub-basin of the White Volta Basin, Ghana. *Environmental Geology* 58(6):1349-1359.

Kyei-Baffour, N.; Ofori, E. 2006. Irrigation development and management in Ghana: prospects and challenges. *Journal of Science and Technology (Ghana)* 26(2): 148-159.

Namara, R.E.; Horowitz, L.; Nyamadi, B.; Barry, B. 2011. Irrigation Development in Ghana: Past experiences, emerging opportunities, and future directions. Ghana Strategy Support Program (GSSP) Working Paper No. 0026. Accra, Ghana: International Food Policy Research Institute (IFPRI).

Obuobie, E.; Barry, B. 2004. Groundwater Socio-Ecology of Ghana. IWMI-OPEC funded groundwater project studies in selected sub-Sahara African countries. Ghana Country Report. 41p. Project report for Organization of the Petroleum Exporting Countries (OPEC).

Shah, T. 2009. *Taming the anarchy: Groundwater governance in South Asia*. Washington, DC, USA: Resources for the Future (RFF); Colombo, Sri Lanka: International Water Management Institute (IWMI).

Swindale, A.; Bilinsky, P. 2006. *Household Dietary Diversity Score (HDDS) for measurement of household food access: Indicator guide. Version 2*. Washington, DC: Food and Nutrition Technical Assistance (FANTA) Project, Academy for Educational Development (AED). Available at http://www/fantaproject.org/downloads/pdfs/HDDS_v2_Sep06.pdf (accessed on November 21, 2011).

Yidana, S.M. 2008. A simulation/optimization model for groundwater resources management in the Afram Plains area, Ghana. *Journal of Environmental Hydrology* 16: 1-14.

Yidana, S.M. 2010. Groundwater classification using multivariate statistical methods: Birimian Basin, Ghana. *Journal of Environmental Engineering* 136(12): 1379-1388.

Yidana, S.M.; Ophori, D.; Banoeng-Yakubo, B. 2008a. Groundwater availability in the shallow aquifers of the southern voltaian system: A simulation and chemical analysis. *Environmental Geology* 55(8):1647-1657.

Yidana, S.M.; Ophori, D.; Banoeng-Yakubo, B. 2008b. Groundwater quality evaluation for productive uses - The Afram Plains area, Ghana. *Journal of Irrigation and Drainage Engineering* 134(2): 222-227.

Yidana, S.M.; Ophori, D.; Obeng, B. 2007. Hydrochemical analysis of groundwater from the Keta Basin, Ghana. *Journal of Environmental Hydrology* 15: 1-11.

Appendix 1. Occupational Profiles

Arable farming is the major livelihood strategy for all categories of farmers (Table A1.1). However, there is a slight decrease in the significance of arable farming among farmers using small reservoirs for irrigation. A relatively higher percentage of household heads (about threefold more) reported non-farm/off-farm activities as being their major livelihood strategy among farmers using small reservoirs for irrigation compared to other categories of farmers. The reason for this may be that those with access to small reservoirs have accumulated enough assets to diversify their livelihood portfolios. None of the farmers have reported tree crop farming as being their major occupation.

TABLE A1.1. Percentage of family members engaged in different livelihood activities.

Livelihood strategies	Purely rain-fed farmers		Farmers using seasonal shallow wells for irrigation		Farmers using permanent shallow wells for irrigation		Farmers using small reservoirs for irrigation	
Major	House-hold head (%)	Other members (%)	House-hold head (%)	Other members (%)	House-hold head (%)	Other members (%)	House-hold head (%)	Other members (%)
Arable farming	91.5	46.1	92.9	42.7	87.0	36.7	75	28.1
Livestock	0.0	0.2	0.0	0.1	0.0	0.0	0.0	0.0
Non-farm/off-farm activities	5.7	15.5	5.7	12.7	4.3	15.5	15.0	16.4
Minor								
Arable farming	14.9	12.8	13.7	12.1	73.9	31.1	65	29.7
Livestock	72.3	26.8	74.1	22.7	4.3	2.2	5.0	1.0
Tree crop farming	0.0	0.04	0.5	0.1	0.0	0.0	0.0	0.0
Non-farm/off-farm activities	7.8	21.1	10.3	19.5	17.3	19.0	15.0	13.3
Fishing	0.7	0.1	0.5	0.2	0.0	0.0	5.0	1.3

Source: Authors' survey

Despite the prevalence of livestock in the study area, a very low proportion of farmers in the sample regarded livestock rearing as being a major livelihood strategy. No household from the categories of farmers using permanent shallow wells and small reservoirs for irrigation reported livestock as being a major livelihood strategy. Livestock keeping is a significant minor occupation for rain-fed farmers and farmers using seasonal shallow well irrigation, whereas non-farm/off-farm activities and fishing are considered as important minor livelihood strategies for farmers using permanent and small reservoirs for irrigation.

Education and Household Demographic Structures

The proportion of female-headed households in the category of purely rain-fed farming is significantly higher than the households using permanent shallow wells and small reservoirs, indicating the bias in access to irrigation towards male farmers (Table A1.2). The farmers using small reservoirs for irrigation have a better level of education. Moreover, households using permanent shallow wells and small reservoirs for irrigation have slightly less dependents and more working-age members.

TABLE A1.2. Demographic structure of sample households.

Items	Non-irrigators	Households using seasonal shallow wells for irrigation	Households using permanent shallow wells for irrigation	Households using small reservoirs for irrigation
Mean years of schooling of household heads	2.0	2.0	2.4	4.4
Maximum years of schooling attained in the household	7.2	7.4	7.0	8.4
Percentage of household members < 15 years	35.2	40.2	27.2	31.9
Percentage of household members between 15 and 65 years	55.3	53.7	67.4	60.8
Percentage of household members 65 years and above	9.5	6.2	5.5	7.3
Percentage of female-headed households	7.8	5.2	2.5	2.5

Source: Authors' survey

Asset Endowments

Land and Land Tenure

All the categories of sample households, including farmers previously considered as purely rain-fed, have potential irrigable areas (Table A1.3). However, not all of the potential rain-fed and irrigable area is put under cultivation, implying that land is not a constraining factor for production. However, access to water constrains production in this region of Ghana. Interestingly, farmers with access to small reservoirs also practice shallow groundwater irrigation.

Table A1.3. Land ownership (ha) by household categories during the 2008/2009 season.

Items	Non-irrigators	Farmers using seasonal shallow wells for irrigation	Farmers using permanent shallow wells for irrigation	Farmers using small reservoirs	F-statistics
Own rain-fed land	2.1	2.1	1.3	1.5	5.916***
Own potential irrigable land	0.4	0.6	0.2	0.3	6.308***
Cultivated area: rain-fed	1.9	1.9	1.1	1.4	5.366***
Cultivated area: irrigated	0.06	0.5	0.2	0.3	39.173***
Irrigable area: groundwater	0.3	0.6	0.3	0.5	10.097***
Irrigated area: groundwater	0.0	0.5	0.2	0.3	73.862***
Irrigated area: small reservoir	0.0	0.01	0.01	0.3	194***
Pump-irrigated area	0.0	0.01	0.01	0.01	NS

Source: Authors' survey

Note: *** denotes that the differences are statistically significant at 1% significance level. NS means that the differences are statistically not significant.

The observed land tenure regime is very complex. There are numerous modes of land transactions including inheritance; gift from friends, relatives and the land priest; rentals on both cash and sharecropping basis; and in rare cases purchases, particularly for irrigated farming. The major source of land for both irrigated and rain-fed farming is inheritance. Rentals on a sharecropping basis are prevalent in rain-fed farming, while rental on a cash basis is more prevalent in irrigated farming. In the case of land rental arrangements, the duration of the contract ranges from a season (approximately half a year) to 10 years. However, the majority of farmers (90.2%) said the contract only lasts for a year. The mean annual rental rate for land is about USD 56.3 per hectare, ranging from USD 3.5 to USD 347.8 per hectare.

Livestock

Farmers using shallow groundwater irrigation tend to have more livestock holding than the other categories of farmers even though the difference is not that significant. The mean livestock holding size in Tropical Livestock Unit (TLU) is 3.5, 4.0, 4.2 and 3.6 for purely rain-fed farmers, farmers using seasonal shallow wells, farmers using permanent shallow wells and farmers using small reservoirs. However, farmers using shallow wells for irrigation have a significantly higher number of poultry, goats and pigs.

Appendix 2. Propensity Score Matching (PSM) Results

TABLE A2. 1. The effects of access to irrigation on the welfare of farm households.

Outcome variable	Matching technique	Number of treated	Number of controls	Average Treatment effect on the Treated	Std. Err	t-value
Total expenditure per capita (in USD)	Stratification	278	141	25.6	39.992	0.911
	Nearest neighbor	278	111	42.6	48.870	1.239
	Kernel	278	141	25.9	41.699	0.883
Household food diversification index	Stratification	278	141	0.18	0.210	0.859
	Nearest neighbor	278	111	0.15	0.245	0.593
	Kernel	278	141	0.17	0.192	0.897
Household food inadequacy (month)	Stratification	278	141	-0.69	0.209	3.353
	Nearest neighbor	278	111	-0.94	0.239	3.947
	Kernel	278	141	-0.72	0.177	4.076

Source: Authors' survey

TABLE A2.2. The effects of in-field seasonal shallow well irrigation on the welfare of farm households.

Outcome variable	Matching technique	Number of treated	Number of controls	Average Treatment effect on the Treated	Std. Err	t-value
Total expenditure per capita (in USD)	Stratification	165	142	-13.3	36.717	0.516
	Nearest neighbor	166	68	4.2	59.485	0.099
	Kernel	166	141	-13.9	35.658	0.554
Household food diversification index	Stratification	165	142	0.33	0.306	1.078
	Nearest neighbor	166	68	0.22	0.342	0.634
	Kernel	166	141	0.36	0.345	1.056
Household food inadequacy (month)	Stratification	165	142	-0.40	0.198	2.024
	Nearest neighbor	166	68	-0.55	0.333	1.665
	Kernel	166	141	-0.41	0.211	1.954

Source: Authors' survey

TABLE A2.3. The effects of permanent shallow well irrigation on the welfare of farm households.

Outcome variable	Matching technique	Number of treated	Number of controls	Average Treatment effect on the Treated	Std. Err	t-value
Total expenditure per capita (in USD)	Stratification	21	136	-50.9	56.752	1.274
	Nearest neighbor	23	18	-16.0	113.109	0.200
	Kernel	23	134	-1.7	62.499	0.038
Household food diversification index	Stratification	21	136	-0.77	0.250	3.079
	Nearest neighbor	23	18	-0.87	0.467	1.862
	Kernel	23	134	-0.89	0.310	2.874
Household food inadequacy (month)	Stratification	21	136	-2.00	0.417	4.762
	Nearest neighbor	23	18	-2.20	0.548	3.964
	Kernel	23	134	-2.00	0.348	5.732

Source: Authors' survey

TABLE A2.4. The effects of riverine seasonal shallow well irrigation on the welfare of farm households.

Outcome variable	Matching technique	Number of treated	Number of controls	Average Treatment effect on the Treated	Std. Err	t-value
Total expenditure per capita (in USD)	Stratification	44	124	63.2	65.378	1.373
	Nearest neighbor	45	29	89.0	80.360	1.573
	Kernel	45	123	52.2	64.589	1.147
Household food diversification index	Stratification	44	124	0.97	0.414	2.346
	Nearest neighbor	45	29	0.80	0.522	1.533
	Kernel	45	123	1.07	0.464	2.312
Household food inadequacy (month)	Stratification	44	124	-0.03	0.319	0.077
	Nearest neighbor	45	29	0.13	0.477	0.280
	Kernel	45	123	0.04	0.310	0.134

Source: Authors' survey

TABLE A2.5. The effects of access to small reservoir irrigation on the welfare of farm households.

Outcome variable	Matching technique	Number of treated	Number of controls	Average Treatment effect on the Treated	Std. Err	t-value
Total expenditure per capita (in USD)	Stratification	39	131	175.9	152.732	1.636
	Nearest neighbor	40	27	307.0	191.243	2.280
	Kernel	40	130	247.6	196.467	1.790
Household food diversification index	Stratification	39	131	-1.24	0.281	4.395
	Nearest neighbor	40	27	-1.30	0.412	3.155
	Kernel	40	130	-1.09	0.313	3.490
Household food inadequacy (month)	Stratification	39	131	-2.47	0.336	7.346
	Nearest neighbor	40	27	-2.78	0.511	5.426
	Kernel	40	130	-2.43	0.280	8.693

Source: Authors' survey

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Barry, B.; Kortatsi, B.; Forkuor, G.; Gumma, M. K.; Namara, R. E.; Rebelo, L-M.; van den Berg, J.; Laube, W. 2010. ***Shallow groundwater in the Atankwidi Catchment of the White Volta Basin: Current status and future sustainability***. Colombo, Sri Lanka: International Water Management Institute (IWMI). 23p. (IWMI Research Report 139)

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Namara, R. E.; Horowitz, L.; Kolavalli, S.; Kranjac-Berisavljevic, G.; Dawuni, B. N.; Barry, B.; Giordano, M. 2010. ***Typology of irrigation systems in Ghana***. Colombo, Sri Lanka: International Water Management Institute (IWMI). 27p. (IWMI Working Paper 142)

www.iwmi.org/Publications/Working_Papers/working/WOR142.pdf

Purkey, D. R.; Vermillion, D. 1995. ***Lift irrigation in West Africa: Challenges for sustainable local management.*** Colombo, Sri Lanka: International Irrigation Management Institute (IIMI). 60p. (IIMI Working Paper 033)

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Postal Address
P O Box 2075
Colombo
Sri Lanka

Location
127 Sunil Mawatha
Pelawatta
Battaramulla
Sri Lanka

Telephone
+94-11-2880000

Fax
+94-11-2786854

E-mail
iwmi@cgiar.org

Website
www.iwmi.org

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