CPWF Project Report

Shallow Groundwater Irrigation in the White Volta Basin

Project Number 65

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Project participants

“To dig or not to dig”

Program Preface:

The Challenge Program on Water and Food (CPWF) contributes to efforts of the international community to ensure global diversions of water to agriculture are maintained at the level of the year 2000. It is a multi-institutional research initiative that aims to increase the resilience of social and ecological systems through better water management for food production. Through its broad partnerships, it conducts research that leads to impact on the poor and to policy change.

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Project Preface:

Contribution of informal shallow groundwater irrigation to livelihoods security and poverty reduction in the White Volta Basin (WVB): current status and future sustainability

Shallow groundwater irrigation (SGI) using hand-dug shallow wells and dugouts is expanding, in the WVB, and is becoming attractive to farmers throughout. SGI is farmer-driven and has developed without any government or donor involvement. The production of vegetables and cash crops during the dry season utilizing SGI has provided farmers with a supplemental source of income and an alternative to seasonal urban migration. Although SGI has been increasing substantially, the extent of this practice is not documented.This project has help assess, the impacts of intensive SGI on sub-basin hydrology, net groundwater recharge farmers' livelihoods and on rural poverty reduction in the Atankuidi catchment a tributary of the WVB with the highest per capita groundwater use.

CPWF Project Report series:

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

RESEARCH HIGHLIGHTS

Shallow groundwater irrigation (SGI) in the White Volta Basin (WVB) is practised on many independent small areas ranging from 1 to 20 ha stretches along dry tributaries. Farmers identify suitable areas for irrigation based on their local experience of the groundwater availability in the area for dry season farming. They derive this experience (of knowing where there's enough water) from their fathers, brothers or friends, or by learning from other farmers who already apply Shallow Groundwater Irrigation (SGI).

This study assesses the extent, potential and socio-economics of SGI in the Atankuidi catchment located in the Upper East Region. The Atankuidi catchment is a tributary of the WVB with the highest per capita groundwater use due mainly to the fast expansion of SGI activities. It is also widely accepted that the Atankuidi basin is very representative of the regolith aquifer which is dominant in the WVB.

The extent and potential of SGI in the Atankuidi catchment was determined using high resolution satellite imagery to delineate irrigated areas, and geophysical surveys to determine the size of the aquifer. A simple numerical model of groundwater flow was developed to analyze the sustainability of SGI in the study area. Results from this study show that current use of groundwater is very low compared to the total water that is annually available, and that the practice of "gutter/furrow irrigation" as done by farmers, and which consists of planting crops in gutters, is water efficient. However, the hard labour associated with the digging of wells and their deepening during the cropping season as well as the refilling of these same wells after harvesting remain the major constraint for SGI expansion.

The cultivation of vegetable crops especially tomatoes under shallow groundwater irrigation is generally profitable, particularly when the value of labour involved in the cultivation process is not considered. The economics of crop cultivation using shallow groundwater is influenced by the extreme volatility of vegetable crop prices particularly that of tomatoes, and by the various production risks farmers face (e.g., crop pests and diseases). The incidence of poverty among households with access to shallow groundwater irrigation is lower as compared to purely rain-fed farmers.

Organizations such as the International Development Enterprises (IDE) are benefiting from the awareness and knowledge generated by this study. IDE's purpose is to introduce affordable well drilling technologies in northern Ghana that will assist small and medium scale farmers easily access shallow groundwater for all year round irrigation.

EXECUTIVE SUMMARY

Over the past years, recurrent droughts /spells or frequent floods have led to food insecurity and increasing poverty in most of northern Ghana where formal irrigation benefits only a limited number of farmers. Thus, in the White Volta basin and particularly in the Upper East Region (UER), hundreds of rainfed smallholder farmers began developing their own irrigation systems abstracting shallow groundwater in the lowlands and from the dry river beds of two tributaries of the White Volta River - Atankuidi and Anyere. This type of informal irrigation system is referred to as Shallow Groundwater Irrigation (SGI) and has become an increasing phenomenon in the White Volta Basin. Water is abstracted from shallow wells or dugouts by means of buckets or pumps to irrigate small pieces of cultivated land. SGI is mainly carried out in inland valleys where water is retained in the alluvial material close to the river where farmers can cultivate vegetables, especially tomatoes, from November to April. Since the late 1990s, plots in the Atankuidi catchment have been cropped only during the dry-season every year, contrary to practice in other sites where plots are constantly cultivated throughout the whole year.

The development of shallow groundwater irrigation (SGI) hinged on a number of preconditions. Since the early 1990s, due to the enhancement of road access to northern Ghana, the medium-scale irrigation schemes have attracted traders, who come to buy vegetables from the area to cater for the high demand in southern Ghana (Kumasi and Accra). Since 2007 the rehabilitation of the tomato factory at Pwalugu located near the production sites in UER has motivated more young farmers to invest in SGI rather than migrating South. Small-scale farmers show a large degree of aptness to respond to the newly developing market opportunities when they see how profitable the tomato production can be.

Research on groundwater spatial distribution, production and potential in some parts the Volta Basin showed that only a limited amount of groundwater is being used mainly for rural domestic supply. Martin and Van de Giesen (2005) estimate that the groundwater production is approximately 5% of the average groundwater recharge, the rest mainly evaporates or runs off through the river. Although groundwater production through boreholes, hand-dug wells and piped systems increased substantially in the past decades, Martin and Van de Giesen (2005) state that further development of groundwater resources is desirable. At present, approximately 44% of the Volta Basin inhabitants have access to groundwater for domestic purposes. By increasing the amount of groundwater production, more people will have the opportunity to gain access to safe drinking water. Besides drinking water, more food will be needed for the growing population (2.4% per year). The development of irrigable land by means of groundwater irrigation could contribute significantly to food production.

SGI could mean a significant development in groundwater use in inland valleys where irrigation through surface water is difficult because of the ephemeral nature of the river flows. SGI is mainly located in inland valleys and close to the river where soil conditions retain water in the alluvial material. The water table is often shallow in such locations and with a little investment; farmers can cultivate crops during the long dry season, albeit with hard physical labor. Despite this development, the actual application, current spatial extent of use, the physical and economic efficiency, socio-economic drivers and potential impacts of SGI on the groundwater are largely not documented.

This report presents findings of a detailed study conducted in the Atankuidi catchment aimed at:(1) delineating shallow groundwater irrigated (SGI) areas using high resolution images, (2) determining the volume and quality of water in storage in the underlying shallow aquifer, (3) developing a conceptual model using MODFLOW-3D to assess the availability of the groundwater resource and the extent to which SGI can sustainably be increased, (4) assessing water productivity for tomato production during the dry season, and (5) identifying and analyze the socio-economic drivers of uptake and expansion of shallow groundwater irrigation systems.

Standard methodologies were used to delineate landuse/landcover (LULC) classes including SGI areas using a QuickBird image acquired in May 2008. The image was classified using an unsupervised classification algorithm (ISODATA), after which classes were merged using bi-spectral plots, intensive groundtruthing and Google Earth imagery. Geophysical surveys (electromagnetic profiling and vertical electrical sounding) were conducted to determine the geometry of the underlying aquifer, and subsequently the volume of water stored. Water productivity was assessed by using five plots planted with tomato and irrigated from monitored hand-dug wells and dug-outs. Plot sizes varied from 0.03 to 0.13 ha. Interviews were held with farmers and observations were made of their actions in the field.

Results obtained indicate that SGI is practiced exclusively on low land areas and on fluvisols along the river bed on 387 ha (1.4%), the rainfed cropping area is 15638 ha (54.7%), with the remainder being other LULC types. Comparison of these results with previous work in which a 2005 Quickbird image was analyzed indicate that SGI areas have increased by a factor of six (6) in three years. This suggests a real expansion of SGI in the Atankuidi catchment.

Results of the geophysical surveys revealed that the thickness of the underlying aquifer varies from 2.6 m to 13.7 m. The aquifer has low resistivity in the range 3.2-55.3 ohm-m suggesting high clay content The total volume of water that can be stored annually in the underlying aquifer was estimated to be approximately 3.7×10^{9} m^3, which is far more than what is actually applied for irrigation (2 liters/day/m^2 at planting stage and 5 liters/day/m^2 at flowering stage). The chemical quality of the water was suitable for drinking and irrigation, although microbial analysis was not performed.

Based on the limited data available, a simple conceptual model of groundwater flow in the Atankuidi watershed was developed and a number of simplifying assumptions were also made. It was assumed that (i) the shallow groundwater aquifer is fully located within the downstream portions of the catchment (Ghana portion of the catchment); (ii) the aquifer physical boundaries correspond to the catchment and therefore there is no flow in or from the neighboring basins; (iii) the aquifer is heterogeneous and anisotropic and groundwater flow could be represented as three-dimensional mesh grid.

The model outputs show that indirect recharge is mainly due to extreme events such as high intensity rainfalls and that recurrent flood could be the main source of shallow groundwater renewal. It also indicates that abstractions for irrigation lead to a fast drawdown of the water table in the shallow wells and dugouts requiring SGI-farmers to continuously deepen their wells. With the current irrigation practice, only a small fraction of the total storage volume of the aquifer second layer is abstracted for irrigation. However with a significant increase in the abstraction, some portion of the second layer dry up either because of the small thickness at some specific locations or because of the intensive irrigation due to the sandy nature of the soils in some locations. The third layer remains generally untapped because it is too deep and very hard to reach with the tools used for hand-digging.

To assess water productivity (WP), five irrigated plots planted with tomato were selected within the Atankuidi watershed. Plots were irrigated from monitored hand-dug-well and dug out. Two (2), out of the five, plots use pumps to abstract water from the dugouts and the remaining three plots were irrigated using buckets to fetch water from hand dug shallow wells. Plot size varied from 0.11 to 0.13 ha for pump irrigated plots and from 0.03 to 0.11ha for bucket irrigated plots. Interviews were held with farmers and observations were made of their actions in the field. ROSETTA, a computer program (Schaap et al., 2005) was used to estimate saturated hydraulic conductivity (K_s) and the parameters of van Genuchten's (1980) analytical function. The Soil-Water-Atmosphere-Plant (SWAP) model, (van Dam et al., 1997) was applied to estimate potential and actual crop water use (ET_c and ET_a). Irrigation application as conducted by farmers as well planting in furrow or gutters have proven to be highly water efficient. Water productivity (WP) with respect to ET in Atankuidi was found to be high, mainly influenced by a high crop yield, which, in turn, is caused by high soil fertility.

The basic sampling unit for the socio-economic study was determined to be households within the study area. First, a rapid "census" was conducted by a team of enumerators and using the list of households obtained, a computer aided random sampling was done to select the household to be interviewed in each category (non-irrigators: 137; permanent wells: 50; shallow seasonal wells: 152 (hand dug wells and dugouts). The following two questionnaires were developed, tested and then administered:

(1) General Socio-economic/Agronomic/water Management Module

The questionnaire for this module was very exhaustive and designed to capture the socio-economic characteristics of the respondent's household. In the case of irrigators this module also captured the irrigation practice, agronomic, water /soil fertility management, labour, support services and other key variables essential to the study.

(2) Household Consumption Expenditure Module

Household consumption expenditures consist of two broad categories: food and non-food consumption expenditures. Therefore two separate standard questionnaires were designed to capture the food and non-food expenditures.

Results from the survey show that non-irrigating households have the highest mean area of land put under rain fed cultivation (4.8 acres). It is possible that non-irrigating households tend to put more rain fed land under cultivation to ensure household food security. This strategy further exposes them to the vagaries of the weather. Erratic rainfall has long been a source of concern to many farmers in the Upper East Region.

The profitability estimates suggest that the seasonal shallow well irrigators do make some profit from engaging in vegetable cultivation. However, the profits are very much dependent on prices, which are highly volatile. Interventions that will help address the high volatility of prices could go a long to improve the welfare of the shallow ground water irrigators The seasonal shallow well irrigators have higher per capita household consumption expenditure (GHC 679.1) when compared with the non-irrigating households (GHC618.4). Irrigating households have higher consumption expenditure relative to non-irrigating counterparts.

The gender composition of the households differentiated by irrigation typology cluster does not show any marked difference among the various irrigation typologies. The gender composition of a household is therefore not likely to be a determining factor of a decision to irrigate.

The project findings are being taken up by the NGO International Development Enterprise (IDE) which has recently started a new project on introduction and dissemination of irrigation technologies in Northern Ghana. IDE has trained local entrepreneurs in manual tube-well drilling techniques. The Atankuidi catchment was selected as a one of the training sites and based on the groundwater availability map produced by the project, two tube-wells were successfully drilled.

The project has also successfully supported field work of one PhD and five MSc and two BSc students from Ghana, Germany and the Netherlands.

INTRODUCTION

Livelihood vulnerability, food insecurity and poverty are major problems of the inhabitants of the Volta Basin especially those living in the White Volta Basin. The major activity in the basin is rainfed agriculture, which employs approximately 70% of the inhabitants. Erratic and unreliable precipitation along with the small size of farm holdings (about 90% of farm holdings are less than 2 hectares (ha) in size) and the lack of equipment have resulted over the past years in low food production. Though irrigation has been identified as holding the key to sustained food availability in the face of climate change and population increase (2.4% per year), investments in irrigation development (including research) in the country have been inadequate. Supplemental irrigation is only available for an extremely low percentage of cropland, resulting in a low percentage of irrigated land in the dry season, which is approximately 1% of the total agricultural land (Unofficial report, GVP, 2007).

Government promotion of small and medium-scale irrigation schemes only benefited a minority of farmers in Ghana. Therefore, in the Upper East Region (UER) likewise in many other parts of the White Volta Basin, faced with the decline of rainy season farming due to recurrent droughts and many spells that have led to chronic food insecurity and an increasing poverty, many small-farmers in northern Ghana and more specifically in the UER started to develop their own irrigation facilities. Hundreds of smallholder farmers began developing irrigated vegetable gardens along the dry river beds of the Anayere and Atankuidi rivers in the mid-1990s.

The Atankuidi catchment is a tributary of the White Volta Basin and covers approximately 286 km^2. It is located in the Upper East Region of Ghana between Navrongo and Bolgatanga with its upper reach in Burkina Faso (see figure 1). Climatically, it falls within the Sudan-Savanna zone, which is characterized by high temperatures and a mono-modal rainfall distribution with a distinct rainy season lasting approximately from May to September. The long-term mean annual rainfall in Navrongo is 990 mm as calculated from monthly rainfall data for the years 1961-2001. Temperatures are high throughout the year with an average daily maximum temperature of 35°C and average daily minimum temperature of 23°C.

The Soil Research Institute of Ghana distinguishes three main soil types in the catchment (Environmental Protection Agency / World Bank, 1999). These are: (1) Leptosols, which are predominant along the elevated northern and eastern border; (2) Fluvisols, which are found in the flat terrain to the sides of the main stream, and (3) Lixisols, which covers the rest of the catchment.

The hydrogeology and climate conditions of the catchment are typical for a large part of the Volta River basin Martin and van de Giesen, 2005). This means results of studies conducted in this catchment are transferrable to other areas of the basin. The Atankuidi catchment is one of the areas with the highest groundwater use per km^2 in the Volta River Basin (Martin, 2006). The main aquifer is the regolith aquifer in the weathered zone of granitoids. This hydrogeology is typical for about two thirds of the area of the Volta River basin, which are underlain by Birimian rocks. More than 80 % of all boreholes in the basin target the weathered rock aquifer.

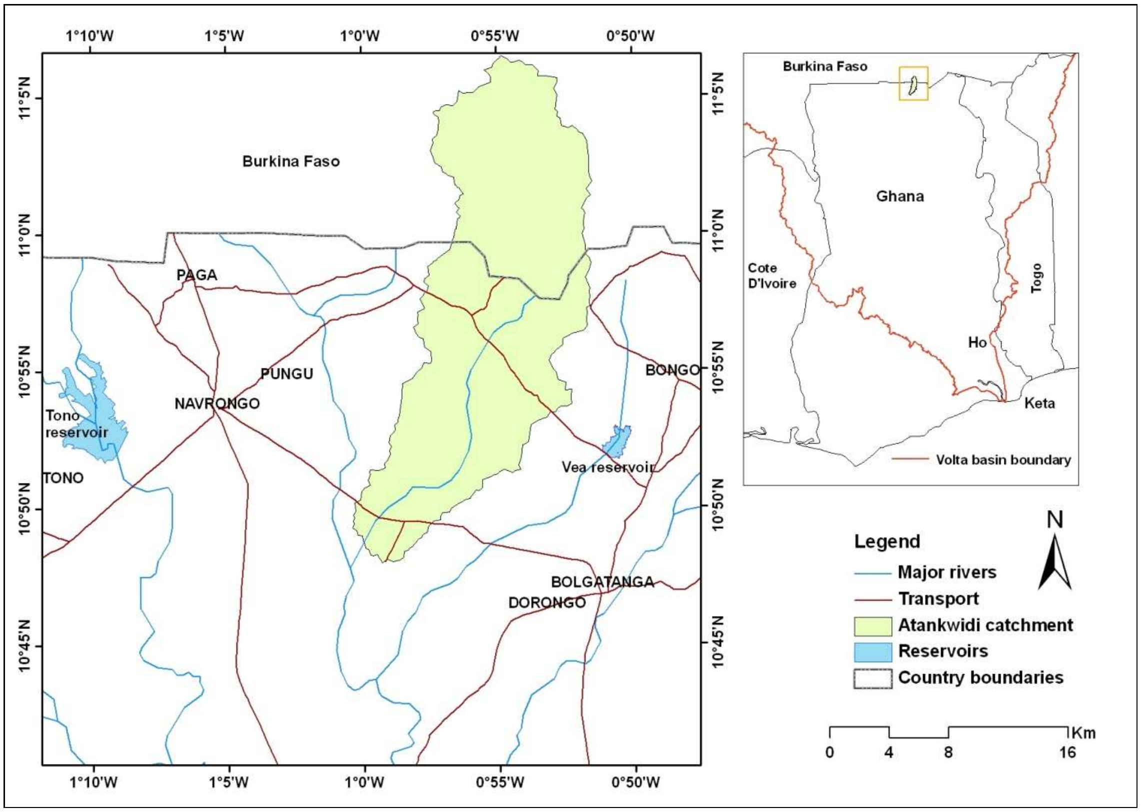


Figure 1. Map of the Study Area

According to Martin and van de Giesen (2005), the Antakwidi watershed is representative of the regolith aquifer found in most of the lowland areas within the Ghana portion of the White Volta Basin. In 2006, more than 80 % of the farmers had less than 10 years of irrigation experience while more than 57 % of the farmers had only practiced irrigation for 5 years.

Farmers take advantage of shallow groundwater which they abstract from wells and dugouts located in lowland areas generally filled with sandy loam soils. Water is mainly abstracted from shallow hand dug wells by manual means using buckets, but a smaller group of farmers also uses motor pumps on dugouts located on river beds. While a quantitative assessment of the area farmed is lacking, results from surveys conducted in 2006/7 in the Atankuidi catchment indicate that small-scale farmers created about 100-200 ha of vegetable gardens. The mean size of farms irrigated by bucket was roughly 600 m² (0.06 ha), while the average size of pump farms about 2000 m² (0.2 ha).

Despite the small size of the farms and the low input levels, farmers involved in SGI are able to reap substantial benefits from their farms. In 2006, bucket farmers gained an average profit of more than 150 GhC (approx. 160 USD) from their farms. Pump farmers earned considerably more (more than 550 GhC/580 USD). Given the fact that more than 80 % of the population of the UER region has an overall income below the official poverty line of 90 GhC (GSS, 2002), the additional income gained through SGI is substantive. Farmers see SGI to be profitable, and the additional income is mainly spent on household. Pump farmers also invest into means of transport and buildings. SGI is the preferred adaptation strategy with regard to poverty and a changing environment of farmers. While migrating, the main alternative adaptation strategy pursued is increasingly perceived to be less attractive and even dangerous. Results of surveys conducted in the Atankuidi catchment showed that 50% of bucket farmers and more than 60 % of pump farmers reported that SGI had changed their migration patterns.

Despite its wide spread practice and immense contribution to food security, information on informal irrigation technologies, their extent and contribution to livelihoods support remains very limited. SGI is practised by many small scale farmers in the informal sector, and contributes immensely to livelihood security and poverty reduction. Although it is increasingly becoming widespread, crucial information such as the spatial extent of use, physical and economic efficiency, socio-economic drivers and potential impacts of SGI on groundwater resources remain largely undocumented. This report examines SGI in detail and discusses its performance in the Atankuidi basin – a representative sub-basin of the White Volta in northern Ghana with the highest per capita use of groundwater. The report aims at answering several interlinked research questions:

1. What is the extent of SGI in the Atankuidi Basin?
2. What are the characteristics of the aquifer in the study area i.e. what is the volume of the shallow groundwater available for use?
3. What is the influence of the application of SGI on the groundwater level in the alluvial aquifer?
4. What is the water productivity in SGI systems?

PROJECT OBJECTIVES

1. Document the current spatial extent and characteristics of shallow groundwater irrigation agro-ecosystems;
2. Generate knowledge on hydrological regimes, bio-physical processes and sustainability of the system
3. Generate knowledge on the crop and water productivity of SGI agro-ecosystems and,
4. Study the Socio-economic drivers of uptake and expansion of shallow groundwater irrigation systems

Objective 1: Document the current spatial extent and characteristics of shallow groundwater irrigation agro-ecosystems

Methods

A very high resolution QuickBird image, acquired in May, 2008 was used as the primary data source for delineating SGI areas in the Atankuidi catchment.

Remotely sensed images are affected by the atmosphere which is the medium through which electromagnetic energy travel. The sun (in the case of passive sensors) sends out electromagnetic radiation, which is reflected off objects on the earth's surface and the response recorded by sensors mounted on satellites. The intensity of the signal from the sun, as well as that from the objects (to be recorded at the sensor) is often attenuated due to atmospheric absorption while its directional properties are altered by scattering (Mather, 2004). Images must, therefore, be preprocessed to correct for any attenuation of the signal recorded at the sensor.

The intensity of the electromagnetic radiation from the earth's surface is recorded by sensors as digital numbers (DNs) for each spectral band (for multispectral images). The use of raw DNs of images in, especially, quantitative image analysis has been described as inappropriate (Lillesand et al. 2004). DNs are image specific - i.e. they are dependent on the viewing geometry of the satellite at the moment the image was taken, the location of the sun, specific weather conditions, etc. It is, therefore, important to convert the DN values to spectral units.
In this study, DNs were converted to spectral units (reflectance) using equations and algorithms presented in Markham and Barker (1986).

Groundtruthing

Groundtruth data was collected during June 3rd -13th, 2008 for 190 sample sites covering major irrigated areas (which includes shallow dug wells and dug outs in riverbed) along the river, rainfed fallows and other land use land cover classes and its percents in the watershed. The purpose of this groundtruthing exercise was to understand the main forms of landuse/landcover (LULC) classes in the area. The intended use of the data was to aid in (1) classification and (2) for accuracy assessment (i.e. posts classification) – verifying that results obtained reflect the real situation on the ground.

The adopted approach was to look for contiguous areas of homogeneous classes within which a sample (GPS location) can be taken. For each LULC class identified, 10 – 40 samples were taken. In addition, two or three photographs of the LULC type at each location sampled were taken. Such photographs prove useful should there be ambiguity about LULC classes during accuracy assessment.

Unique labels were given to each LULC class identified during the groundtruthing exercise. Classes have the flexibility to merge to a higher class or break into a distinct class based on the LULC percentages observed at each location.

Image Classification

The QuckBird image was classified to reveal the various LULC classes using the methodology outlined in Thenkabail et al (2004) and Gumma et al. (2009). Figure 2 below presents the main processes followed.

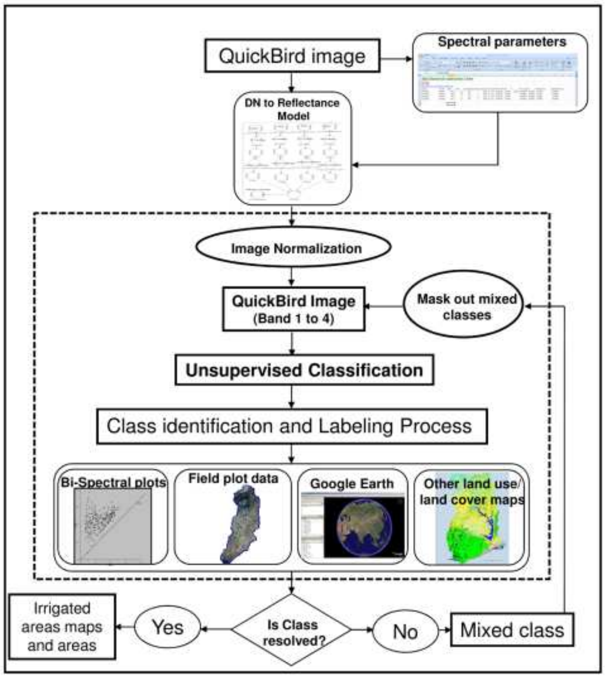


Figure 2. Flow chart of processes

Unsupervised classification using ISOCLASS cluster algorithm (ISODATA in ERDAS Imagine 9.2™) followed by progressive generalization (Cihlar et al., 1998) was, first, used to classify the QuickBird image. With a maximum of 40 iterations and convergence threshold of 0.99, 40 LULC classes were generated. Use of unsupervised techniques is recommended for large areas that cover a wide and unknown range of vegetation types, and where landscape heterogeneity complicates identification of homogeneous training sites (Achard et al., 1995, Cihlar 2000). The 40 classes obtained from the unsupervised classification were merged using bi-spectral plots, intensive ground truth data (described above), and Google Earth imagery (Gumma et al 2009, Thenkabail et al, 2005, Tucker et al, 2005). Older datasets were used for cloud patches.

Bi-spectral plots. The spectral properties of the classes obtained through unsupervised classification were performed on the megafile using ISODATA statistical cluster algorithm for multi dimensional data. The Bi-spectral plot for all the classes is obtained by plotting the spectral reflectance of Band 3, Red(Quickbird), on X Axis and spectral reflectance of Band 4, Near Infrared(Quickbird), on Y Axis. The diagonal line in the graph represents the soil line. The soil line clearly separates the classes with vegetation above the soil line from the classes without vegetation below the Line. The classes with similar spectral reflectance fall nearby as a cluster. Such classes may represent same category with a slight variation in reflection. Classes like water bodies and forest, which have large variation in vegetation, can be easily identified and labeled.

Google Earth data (http://earth.google.com/) contain increasingly comprehensive image coverage of the globe at very high resolution of 0.61-4m, with different seasonal images. These data were used for: i) identification and labeling of classes (especially cloud affected areas), ii) assessing accuracy of irrigated area classes and iii) verification of identified LULC classes.

*Resolving mixed classes: S*ome classes were locally misclassified and intermixed with neighboring classes and such misclassified pixels were normally identifiable using groundtruth data points where land use types were mapped out in their normal context (Fuller et al., 1998). For example, the "fallow" class mixes with rangelands. Such misclassifications were removed by contextual correction methods (Groom et al., 1996: Thenkabail et al., 2005).

Assessing Accuracy of Results

A qualitative accuracy assessment was performed to check if the SGI area is classified as irrigated or not, without checking for crop type or type of irrigation. The accuracy assessment was performed using field-plot groundtruth data (described above), to derive robust understanding of the accuracies of the datasets used in this study.

Accuracy assessment provides realistic class accuracies when land cover is heterogeneous and pixel sizes exceed the size of uniform land cover units (Gopal et al. 1994, Thenkabail et al. 2005 and Gumma et al. 2009). Groups of 3x3 pixels of QuickBird were assigned around each of the field-plot points to one of 6 categories: (1) absolutely correct (100 % correct), (2) mostly correct (75 % or more correct), (3) correct (50 % or more correct), (4) incorrect (50 % or more incorrect), (5) mostly incorrect (75 % or more incorrect), and (6) absolutely incorrect (100 % incorrect). Class areas were tabulated for a 3x3-pixel (9 pixels) window around each field-plot point. Using this, a comprehensive accuracy assessment of all 14 classes was made. For instance, if 14 out of 14 QuickBird classes matched with field-plot data, then it was labeled absolutely correct and so on.

Results

Figure 3 shows the results of the remote sensing analysis to delineate SGI areas. As already noted, other LULC types were also mapped. Overall, 14 LULC classes were identified and mapped in the Atankuidi sub-basin. Results indicate that SGI is practised on a land area of 387 ha (1.4%), rainfed agriculture - on 15,638 ha (54.7%); the remaining being other LULC types. Table 1 gives details of these classes and the area under each. It is clear from the results that the importance and practice of the SGI actually increases along the river in and dryer areas, since in these areas the importance of dry season agriculture for increasing food production leads to agricultural development.

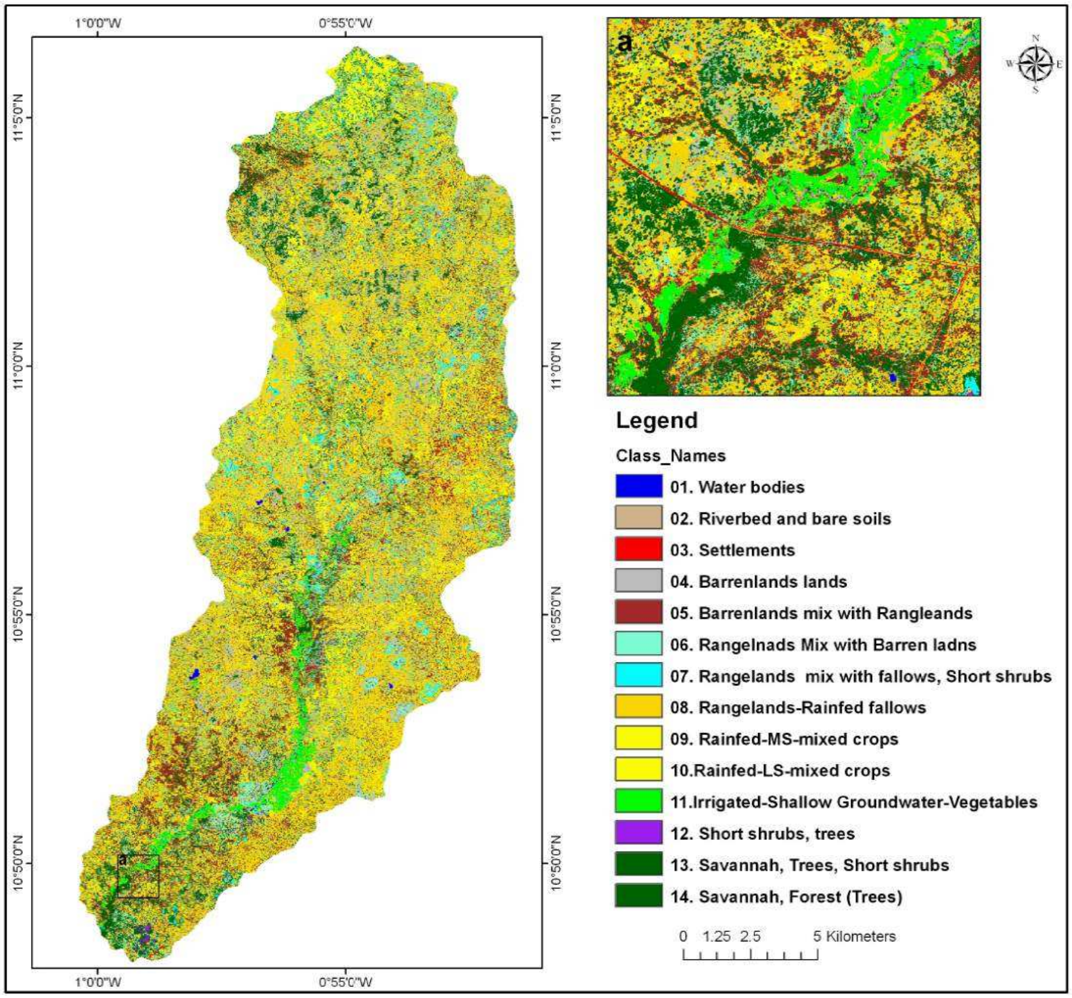


Figure 3. Landuse/ landcover map of Atankuidi catchment (May 2008)

Table 1. Landuse/ landcover areas and their percentage cover

Class No.	Land use/Land cover	Area (Ha)	% area
1	Water bodies	31.82	0.1
2	Riverbed and bare soils	116.58	0.4
3	Settlements	104.96	0.4
4	Barren lands	3014.16	10.5
5	Barren lands mix with Rangelands	2852.02	10.0
6	Rangelands Mix with Barren lands	873.19	3.0
7	Rangelands mix with fallows, Short shrubs	2079.77	7.3
8	Rangelands-Rainfed fallows	11410.77	39.9
9	Rainfed-MS-mixed crops	1712.45	6.0
10	Rainfed-LS-mixed crops	2515.59	8.8
11	Irrigated-Shallow Groundwater-Vegetables	387.23	1.4
12	Short shrubs, trees	64.42	0.2
13	Savannah, Trees, Short shrubs	1578.62	5.5
14	Savannah, Forest (Trees)	1891.07	6.6
		28632.62	100.0

Discussion

The irrigated areas mapped consist of many independent small areas ranging from 1 to 20 ha along the river stretch. Farmers identify suitable areas for irrigation based on their local experience of the availability of water in the area for dry season farming. They derive this experience (of knowing where there's enough water) from their fathers, brothers or friends, or by learning from other farmers who already apply SGI. In a study, Van den Berg (2008) interviewed 30 farmers in the catchment. He found out that the sizes of the irrigated fields vary from 200 to 900 m^2, with three exceptionally large fields of 1045 m^2, 1373 m^2 and 3350 m^2, with an average field size of about 600 m2 (i.e. apart from the exceptionally large fields). Though farmers are willing to cultivate larger areas, they're mostly constrained by lack of finances to purchase agricultural inputs. Other farmers also indicated that the land allotted them by their landowners limit their farm sizes. These farmers are unable to rent land elsewhere because (1) landowners will not rent out lands with good soil and reliable water access (2) in cases that landowners want to rent, farmers cannot afford to pay the rent. These reasons may have accounted for the extremely low percentage of irrigated areas, as compared to rainfed areas.

Although the above results indicate that SGI areas form a small percentage (1.4%) of LULC types in the catchment, previous work, coupled with results obtained in this study indicate that SGI areas increased dramatically between 2005 and 2008. A supervised classification (using the Mahalanobis Distance algorithm) of a QuickBird image of the Atankuidi catchment identified irrigated areas in February 2005. Visual analysis was used to generate training data for five LULC classes – bare soil, savanna vegetation, burned vegetation, trees and irrigated areas. While detailed ground dataset is not available for 2005, data is available for three farms locations which were irrigated at the time of analysis. The location of each of these farms and the irrigated plots within these at the time of image acquisition were compared to the classification results, with all three correctly identified as irrigated land.

Results from the analysis revealed that an area of approximately 60 ha was under SGI in February 2005. Comparing this figure to the 387 ha obtained in the May 2008 suggests a tremendous increase (factor of 6) in SGI in the Atankuidi catchment. It is important to note that February represents the peak of harvesting period in Atankuidi whereas in May, very few crops will still be awaiting harvesting. This means that the actual irrigated area in 2008 may have been much bigger than what was recorded (387 ha), which would have suggested an even much bigger increase in SGI between the two years. The increase between the two years can be mainly attributed to an increased awareness of Northern Ghana residents that migration to the south during the dry season in search of menial jobs is not the solution and that dry season farming could be a real source of livelihood.

Conclusions

Remotely sensed (RS) images were successfully used to determine the current spatial extent of SGI in the Atankuidi catchment. SGI areas were found to have expanded by a factor of six (6) between 2005 and 2008. It is recommended that RS data is used extensively for the study of SGI expansion in the catchment.

Objective 2: Generate knowledge on hydrological regimes, bio-physical processes and sustainability of the system

Three studies were conducted in order to achieve this objective. First is a flood modeling exercise conducted in the study area. Knowledge of the underlying aquifer geometry and the volume of water stored in it are presented. Lastly, the sustainability of the GW resources is addressed through a GW modeling exercise.

Objective 2.1 Mapping floodplains in the Atankuidi

Methods

Flood plains in the Atankuidi catchment were modeled using two main approaches. These are (1) modeling using the SOBEK model, based on a DEM and (2) mapping using Radar images in an image analysis software.

Modeling using SOBEK

A USGS Hydrosheds Digital Elevation Model was used together with the Dutch modeling software SOBEK to simulate flooding over of the study area. The SOBEK model is a physical model made for modeling 2D flood spread. The model is based on the calculation of the momentum equations:

- Momentum:

$$
\begin{aligned}
&\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\frac{\partial \zeta}{\partial x}+g\frac{u|V|}{C^2h}+au|u|=0 \\
&\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+g\frac{\partial \zeta}{\partial y}+g\frac{v|V|}{C^2h}+av|v|=0
\end{aligned}
\qquad (1)
$$

Where:
$$
\begin{cases}
\text{u} & \text{velocity in x-direction [m/s]} \\
\text{v} & \text{velocity in y-direction [m/s]} \\
\text{V} & \text{velocity: V = water level above plane of reference [m]} \\
\text{C} & \text{Chezy coefficient } [\sqrt{\text{m/s}}\ ] \\
\text{d} & \text{depth below the plane of reference [m]} \\
\text{h} & \text{total water depth: + d [m]} \\
\text{a} & \text{wall friction coefficient [1/m]}
\end{cases}
$$

Mapping using Radar Imagery

Satellite radar imagery have in recent times been discovered to be very useful in flood mapping (Giesen, 2001). One advantage of radar sensing as opposed to other remote sensing techniques is the ability of the radar waves to penetrate clouds, and since the weather during floods often is cloudy this is indeed a great advantage (Liebe, 2008). Another advantage of the radar imagery is that the long waves emitted from the satellite are reflected very smoothly even at low water depths.

Satellite images of two different wave-lengths were used for the mapping of the Atankuidi River Basin, namely: L- and C-band radar images, with 12.5 meter resolution. The C-band images were taken from ESA's Envisat ASAR satellite. The L-band images were taken from JAXA's Alos PALSAR satellite. The L- and the C-band images are provided at different wavelengths (15-30 cm and 4-8 cm respectively). Use of the two in mapping flood plains, therefore, provides important information that cannot be derived from either of the two. The peak of the 2007 flood is believed to have come sometime before or after the 27th of August. On the 27th of August 900m3/s water was released fom the Bagré Dam in neighboring Burkina Faso, drastically changing the downstream conditions for the Atankuidi River (IRIN, 2010). The available images of the Atankuidi River Basin taken closest to the assumed flood peak were:

- (C-band) ASAR: 2007-08-26
- (L-band) PALSAR: 2007-09-04

The Idrisi software was used for all image analysis. These include referencing, processing and mapping. Flood maps were made for the year 2007 only due to the fact that no flooding occurred in the Atankuidi in 2009.

Referencing

In order to be able to compare the different images to each other they must have the same reference. First, a Google Earth image was referenced using ground control points (GCPs) gathered during fieldwork in the UER. Next, the referenced Google-Earth image was used to reference the rest of the images used in the analysis.

The blurriness of the satellite images - ASAR and PALSAR made referencing a challenging task. The Google-Earth image was, thus, used to overcome this challenge

Image processing

Both the C- and the L-band images came with what is termed a "salt and pepper" noise. This noise is mainly caused by mechanical or electronic interferences. Eastman (2006) states that "speckle" or "salt and pepper" noise often – especially for radar – occurs due the highly elevated reflection when the signals are reflected of edges or buildings which when frequent has similar effect as the "salt and pepper" noise. In order to remove some of the noise from the images the Idrisi algorithm "Adaptive Box" was used. Eliason (1990) has proven the efficiency of the Adoptive Box in comparison with other spectral noise removing algorithms. The Adaptive Box filter is an extension of the common Lee filter and determines locally, within a specified window (3*3, 5*5, 7*7 meters), the min and max value range based on a user specified standards deviation. If the center window value is outside the user-specified range it will be considered noise and replaced by an average of the surrounding neighbors (Eastman, 2006)

The mapping algorithm

Idrisi Andes provides a multitude of different mapping functions suited for different conditions.
The mapping algorithm chosen here is the Minimum Distance algorithm. MINDIST is the most rigid mapping algorithm and fits perfectly for our case. The MINDIST is mapping the image based on the training site data that is chosen to represent different relative features on the map. The algorithm takes the information from the training sites and uses it for the mapping of the image. The training site data for this project consisted of four categories, namely:

1) Deeper Water
2) Flooded / Very Moist Ground
3) Gallery Forrest
4) Dry land

These categories were thought to be the most relevant for the project and they were also the most prevailing in the basin. Figure 4 explains how this is done. Hence the algorithm works just as its name implies, by finding the shortest distance from the training sites to the unclassified pixel (Eastman, 2006).

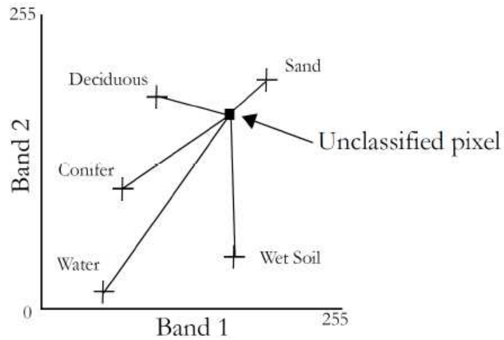


Figure 4. The mapping procedure of MINDIST (Eastman 2006)

Combination of SOBEK and Radar Results

Results from the SOBEK model, together with those obtained from mapping the Radar images, Google-Earth and general knowledge of the area were combined to produce a final map. Areas around the "deeper water" class (in the various results) were digitized as flooded if they are in, for instance, both the C- and L-band images taking general guidance from Google-Earth maps, the SOBEK-modeled map and ground experience.

Results

SOBEK

Result of the SOBEK modeling is shown in the figure 5 below. The modeled floodplains can be The accuracy of the floodplains is very rough due to the rough accuracy of the DEM itself – 95 meters.

It is evident from the results that the areas just on the sides of the river are dryer than the areas a bit farther away. This could be due to the fact that millet which doesn't demand a lot of water is often grown just on the river bank, while the rice – which needs a lot of water – is often grown some distance away from the Atankuidi river. This may serve as an indication that although the resolution is rough it still manages to produce a reasonable result.

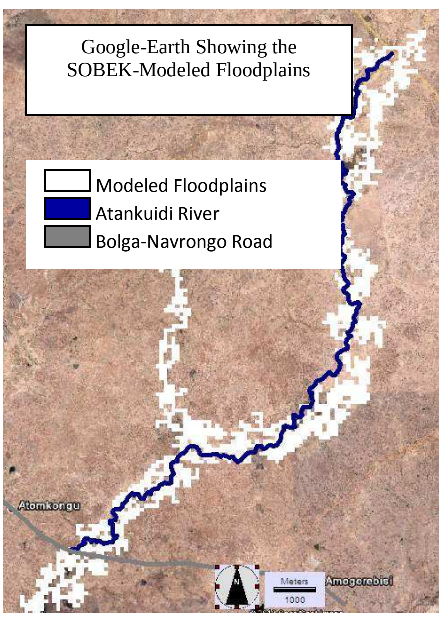


Figure 5. Results of the SOBEK modeling

Radar Mapping

PALSAR [L-band]

The L-band PALSAR radar is quite sensitive in detecting shallow water and even moist ground. This means that the light blue floodplains in figure 6 are not necessarily deep water but very moist. On this MINDIST mapped PALSAR image one can notice the same trend as on the flood map modeled on SOBEK, i.e. the main flooding occurs some distance away from the shores of the main river. The dark green areas are "gallery forest" they show a high reflectance on the satellite images due to the "increased reflection" phenomenon.

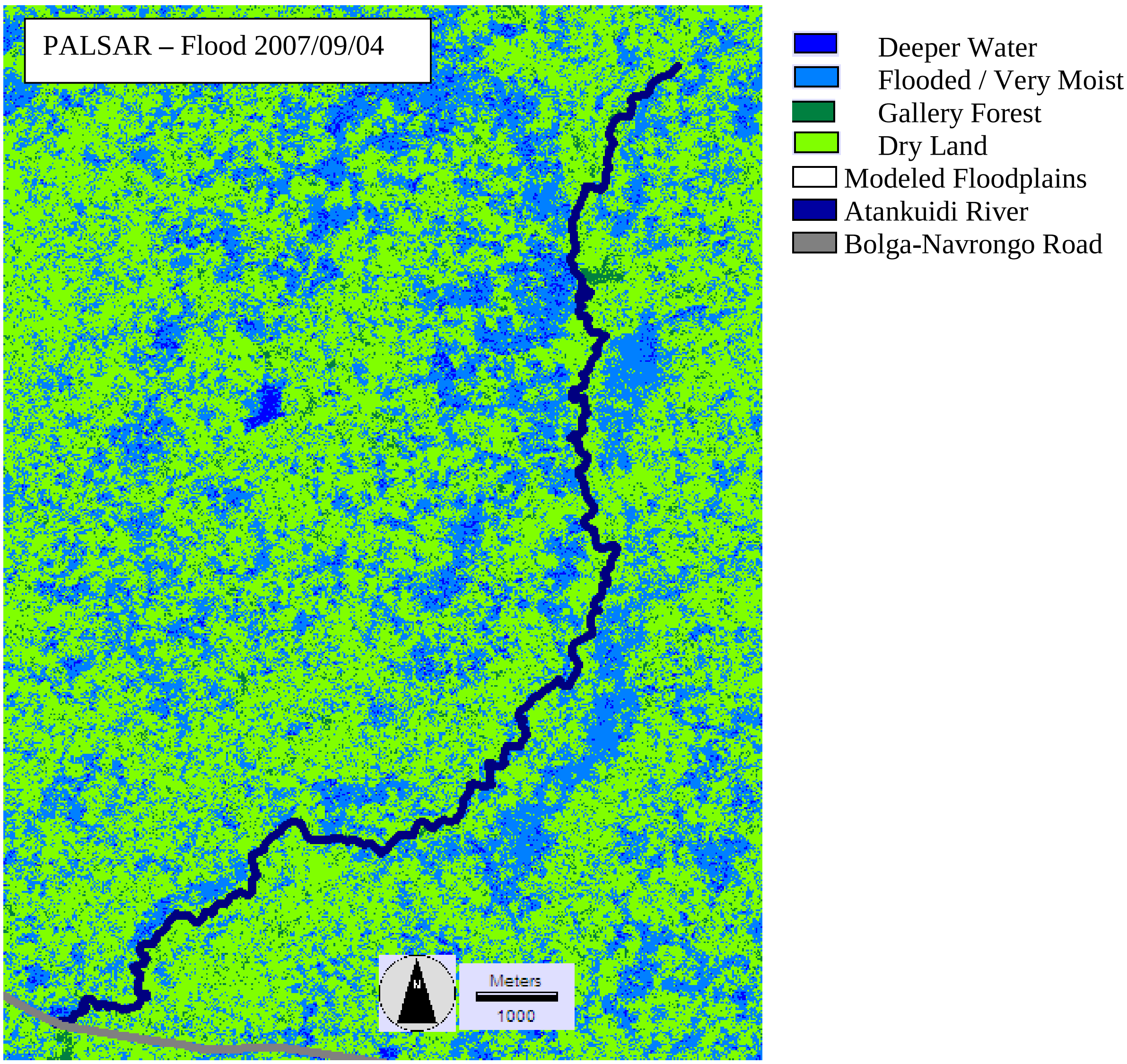


Figure 6. Results of floodplain mapping using PALSAR (L-Band) radar data

ASAR [C-band]

The ASAR image for the 2007 flood period was very noisy in its nature and very difficult to map because of the large spectral noise affecting the image. Even the Adaptive Box procedure, discussed above, was not enough to bring real order to the image and using the Adoptive Box filtering function too much takes away much of the precision of the image. Figure 7 depicts the best try in mapping the image but it can be seen that there is just too much noise to make any sense of it. This noise may be due to the large flood that was over the basin at the time the image was taken. Too much corner reflection may cause a high speckle noise in radar imagery (Eastman, 2006) and given that a large part of the basin was flooded high corner reflection is likely to occur as the radar signal bounces of the water surface and reflecting the surrounding vegetation.

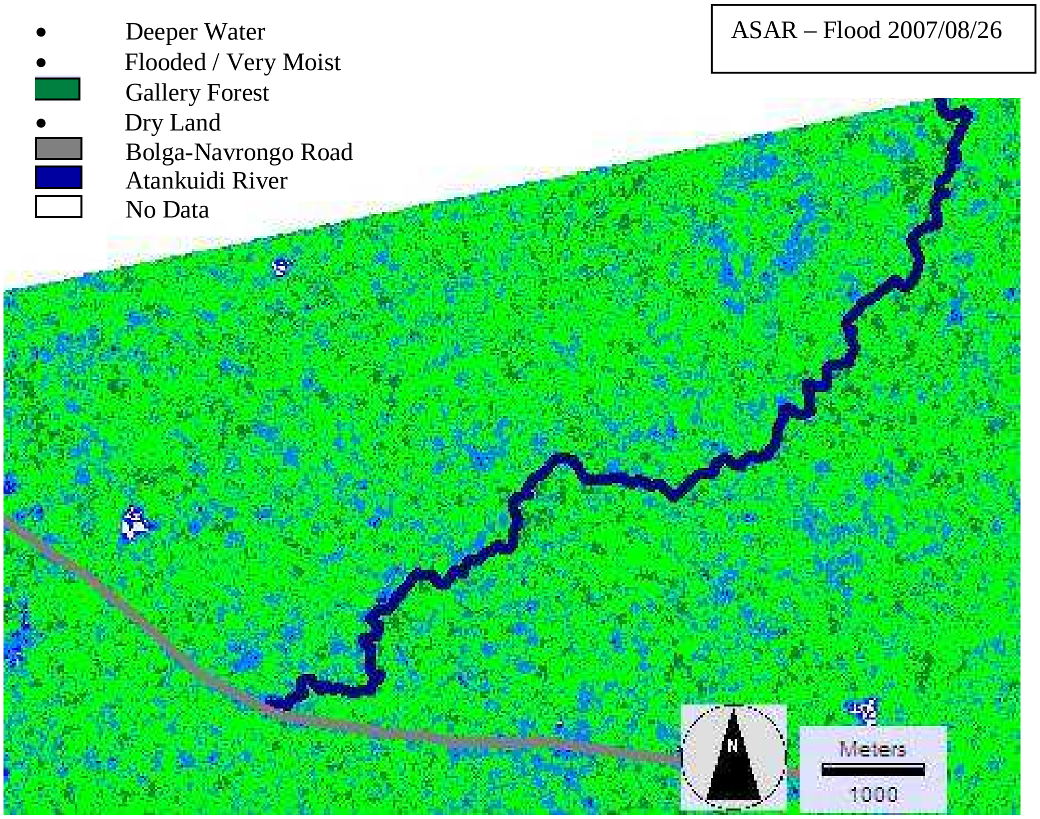


Figure 7. Results of floodplain mapping using ASAR (C-Band) radar data

Idrisi-PALSAR & SOBEK-DEM

Figure 8 shows the Idrisi-mapped PALSAR image next to the SOBEK-modeled map.

The SOBEK model (mapped from a coarse DEM) is very rough in resolution and is only giving a much simplified indication on how the floodplains would look like had the river overflowed. One can see from the image that the two maps follow somewhat each other but the likeliness is far from perfect – this again may be due to the roughness of the DEM-based map.

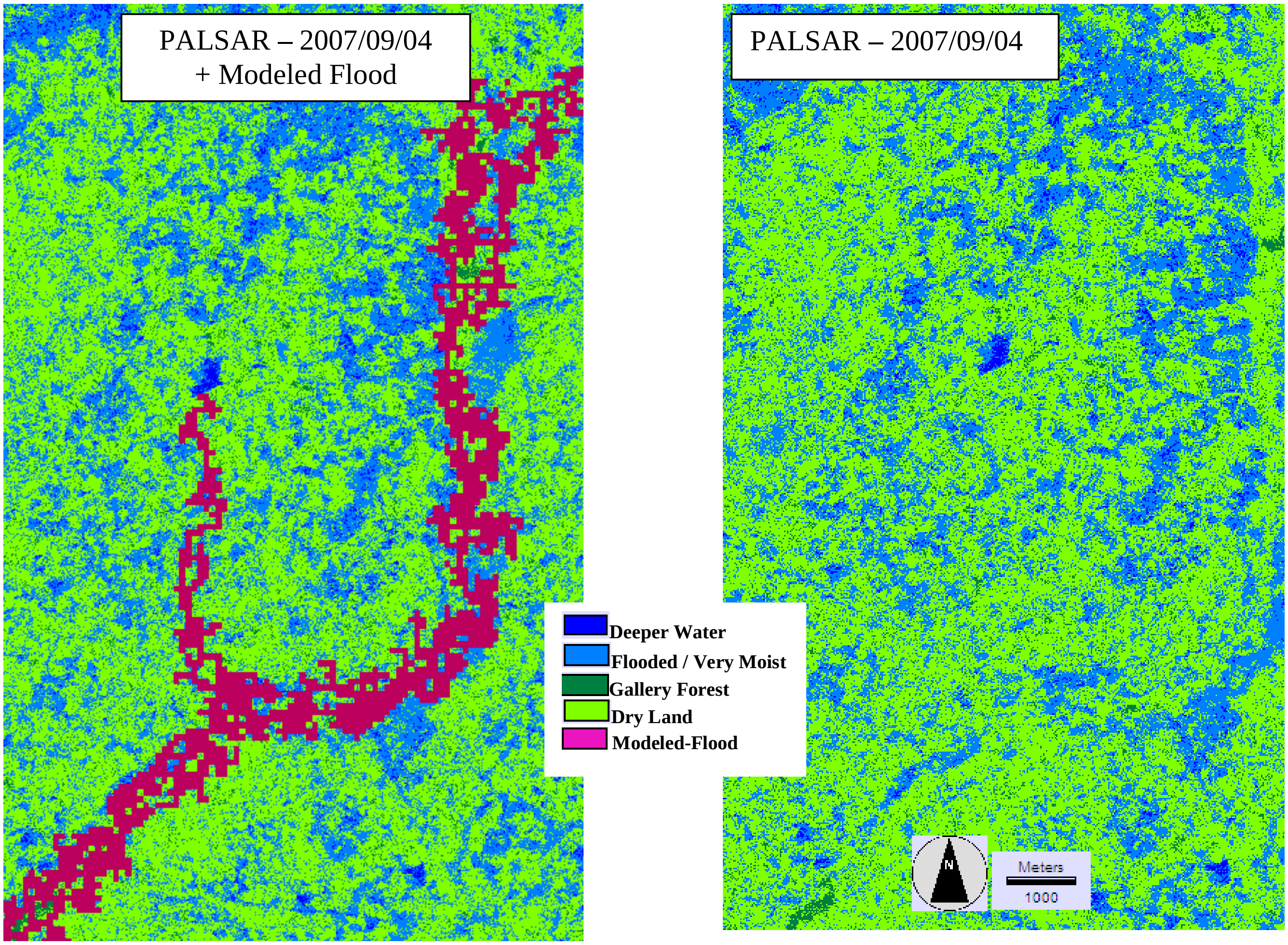
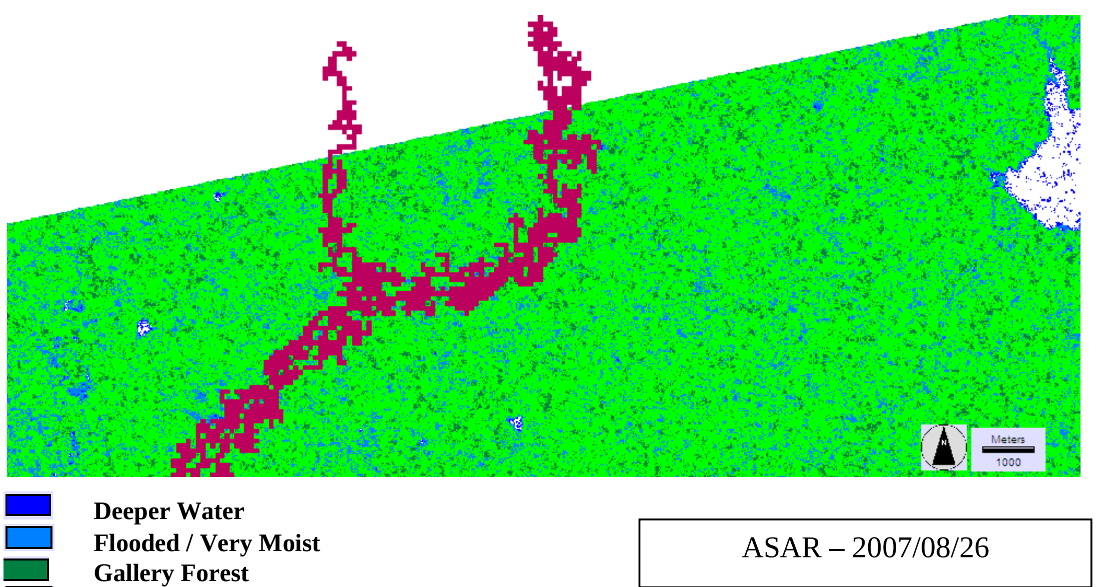


Figure 8. Comparison of Idrisi mapped PALSAR image and SOBEK results

Idrisi-ASAR & SOBEK-DEM

Figure 9 shows the Idrisi mapped ASAR image of the 2007 flood together with the SOBEK-modeled DEM over the Atankuidi. As discussed earlier, the ASAR image was too much affected by spectral noise for it to give good information. The image was however still chosen to be shown here so that the reader can get a better understanding of how bad the map-accuracy was.



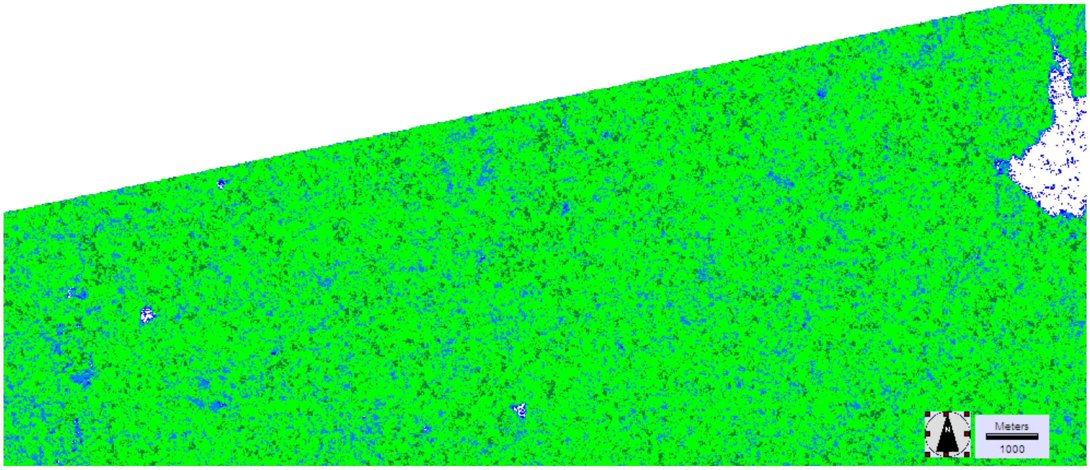


Figure 9. Comparison of Idrisi mapped ASAR image and SOBEK results

The Final Flood Map

The final floodplain map of the area's most prone to flooding in the 2007 flood is shown in the figure below. This map has been obtained with the help of multi-temporal L- and C band radar satellite images and a DEM of the Atankuidi river basin. The images were mapped and processed in Idrisi and the DEM was used to model the floodplains using SOBEK.

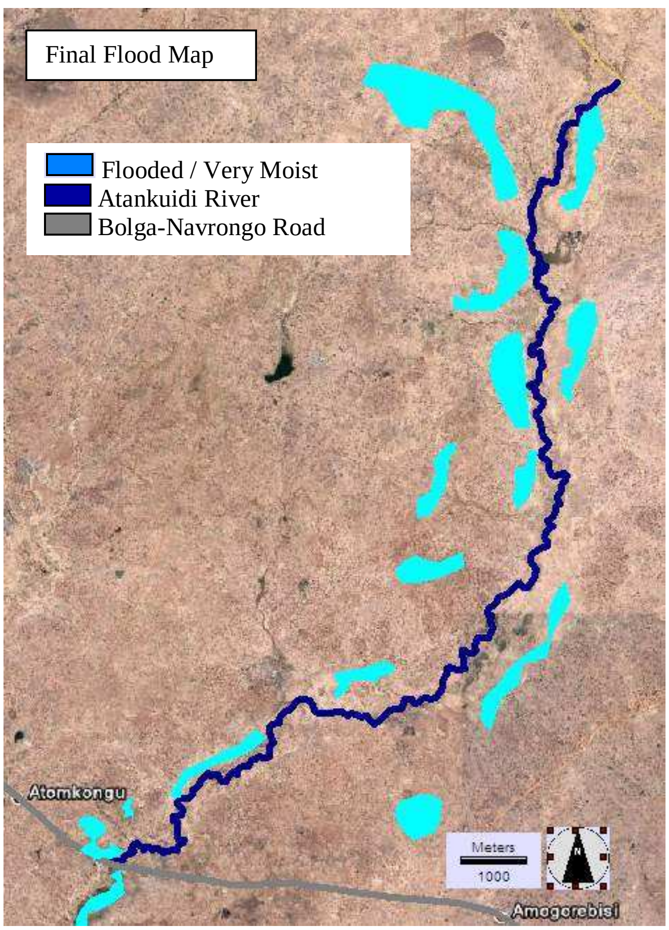


Figure 10. Final map showing an educated guess of Floodplains in the Atankuidi

Discussion
The rough resolution of the DEM is by far the biggest obstacle in obtaining an accurate flood map using SOBEK. Given the fact that the Atankuidi River has a width of around 35 m and the DEM resolution is 96 m no elaborate modeling of the flooding was made with SOBEK but rather a very simplified model to show some general indications of where the floodplains could naturally be formed. Hence, the modeled floodplains do not show an exact map but more an indication of the overall flood trends in the Atankuidi Basin. The floodplains modeled are floodplains which come exclusively from the overflowing of the Atankuidi River. Much of the floodplains, especially farther away from the river, form directly from the ponded rain water.
The SOBEK map, thus, should serve as good complimentary evaluation tool to the Idrisi-mapped satellite images.

The L-band PALSAR image gives a reasonable result, showing some general floodplain areas. The floodplains, similarly to the SOBEK mapped floodplains, are mostly some distance away from the main river. The C-band images were very noisy and it was thus difficult to collect any interesting information from them. The high spectral noise in the ASAR images may be due to the high corner reflection caused by the exceptionally large flood which occurred during the period.
The areas on the map that fall into the category "deep water" are those which most likely were flooded during the period under study, the areas which fall under the category "flooded/very moist" could – just as the name indicates – just be very shallow flood or just very moist ground, the "gallery forest" pixels are due to the double bounce phenomenon which in turn is due to the radar beam being reflected from a smooth surface and bouncing against the surrounding vegetation – this smooth surface is here thought to mostly be made up of flooded areas.

Conclusions
The normal flood spread in the Atankuidi Basin with the usual flooded area is quite well depicted on the mapped PALSAR image in combination with the SOBEK modeled floods on figure 8. However, when the floods become of a more important magnitude, like the ones that occurred in 2007 the entire area gets flooded due to its flatness which is natural to the area but which has also been enhanced by ages of agricultural activities going on in the basin. The large flooding that occurred 2007 can be one of the reasons that the ASAR images of the flooding contained so much noise. This and the small scale of the basin make it very difficult in assessing the flood extent for the Atankuidi. The result of this paper should be looked upon with extreme care as the accuracy of the end product is far from precise but is more to serve as a tool strictly for orientational purposes. This roughness in the results depends on the low resolution of the DEM and the high spectral noise on the ASAR images thus somewhat crippling two of the three legs supporting this project.

Objective 2.2 Characteristics of Aquifer & Volume of water stored

Methods
To estimate groundwater volume, a number of field measurements was made with two different devices. These include electromagnetic profiling and vertical electrical sounding.
Electromagnetic Profiling
Measurements were done to detect fissured zones and thick overburden or weathered zones (regolith), which control shallow groundwater occurrence in the study area. This was carried out using the Geonics EM34-3 ground conductivity meter. This equipment provides a direct reading of apparent conductivity in the region of the measuring coil using electromagnetic induction as described by Mc Neil (1980). A 20 m inter coil separation cable was chosen and the standard 20m station interval was adopted in this study. Ideally, profiling should have been carried out along well defined traverses, but this was impossible because the study area was heavily cropped at the time of survey. Thus measurements were carried out at irregular intervals and sometimes along curved traverses between ridges and along foot paths. Profiling was carried out along 30 traverses in the sub-basin. Conductivity was measured in both horizontal and vertical dipole modes. The measured conductivity values at approximately 7.6 m and 17.4 m i.e. in both horizontal and vertical dipole

modes have been plotted against the station intervals along each traverse to give dipole response curves. Figure 11 shows a sample electromagnetic dipole response curves at location N 10° 49′ 51″ latitude and W 0° 59′ 22″ longitude. The horizontal and vertical dipole responses were compared along each traverse to determine the existence of conductance and hence the presence of structures associated with groundwater occurrence. Typical of the area surveyed, the horizontal dipoles were everywhere higher than the corresponding vertical dipoles, suggesting decreasing conductance with depth and therefore shallow regolith (overburden development). The large variations in apparent conductivity; that is 14-51 μS cm^{-1} for the horizontal dipole and 6.0-36 μS cm^{-1} for the vertical dipole indicate high heterogeneity and therefore, significant variability in permeability and hydraulic conductivity of the aquifer. The clayey portions show higher conductivity values and, hence lower permeability while the more sandy portions show lower conductivity values and thus higher permeability/hydraulic conductivity.

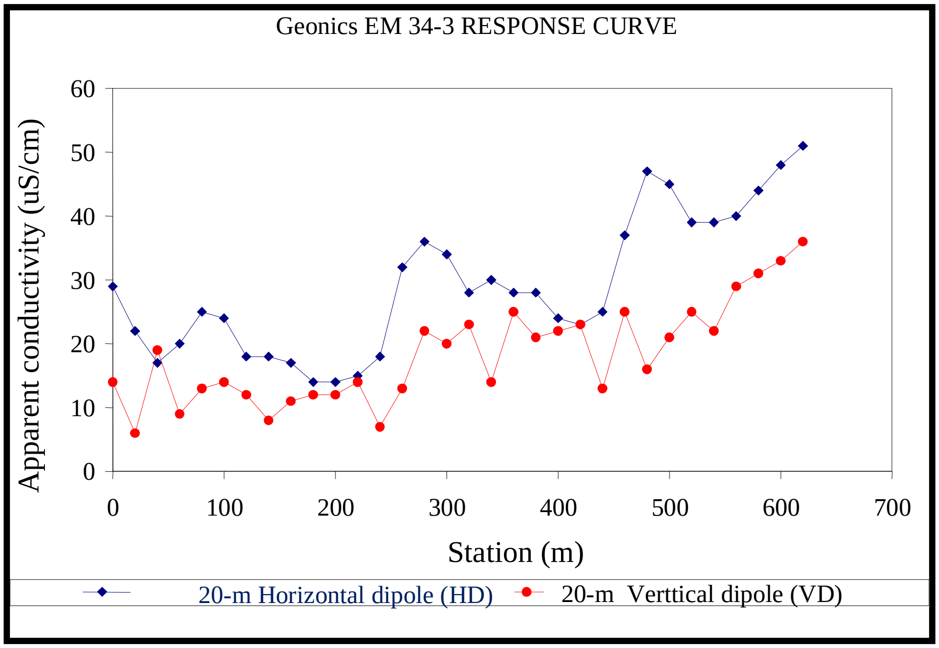


Figure 11: Sample of Geonics EM34-3 Response Curves (20-m horizontal and vertical electromagnetic dipole responses)

Electrical Resistivity Sounding (VES)

VES was conducted at 330 sites in the catchment to determine the depth and thickness of the shallow aquifers. VES points were randomly selected at places where adequate space existed for carrying out the measurement. All points were geo-referenced. Data control was carried out by plotting the VES results as the sounding was in progress. Values, which appeared unreasonable, were rejected and the sounding repeated at the same spot several times as deemed necessary to achieve conformity. Figures 12 and 13 show sample modeled curves created from results of the VES. The results depict a three-layered structure at each VES point. A low resistivity layer sandwiched between a relatively higher resistivity upper and lower layers. In Figure 12, for instance, the soil layer is only 0.6 m thick, the middle layer which is the saprolite and the zone likely to contain groundwater is only 5 m thick and has resistivity as low as 12 ohm-m suggesting high argillite content and thus low permeability/transmissivity. On the contrary, Figure 13 indicates a depth profile of 0.8 m of soil layer, saprolite of 10.5 m with moderate resistivity of 50.2 ohm m suggesting more sandy overburden and higher groundwater potential at location where the b sounding was carried out than where the a sounding was done.

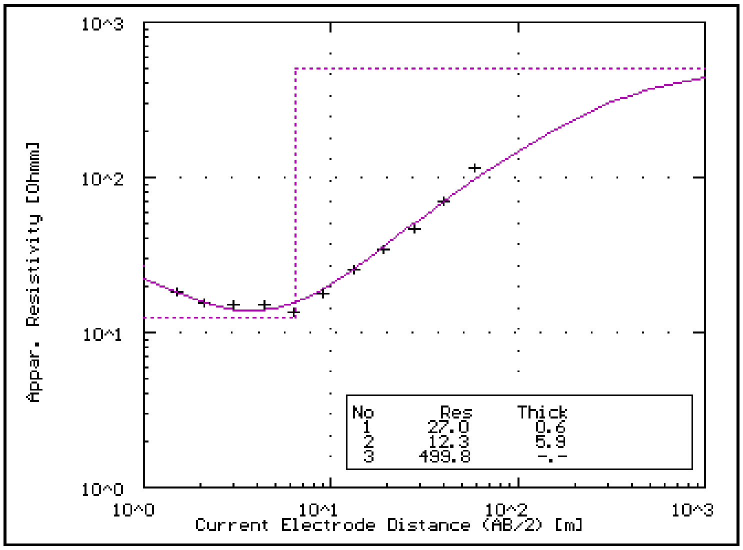


Figure 12. Modelled curve for VES in the edge of the Atankuidi Basin

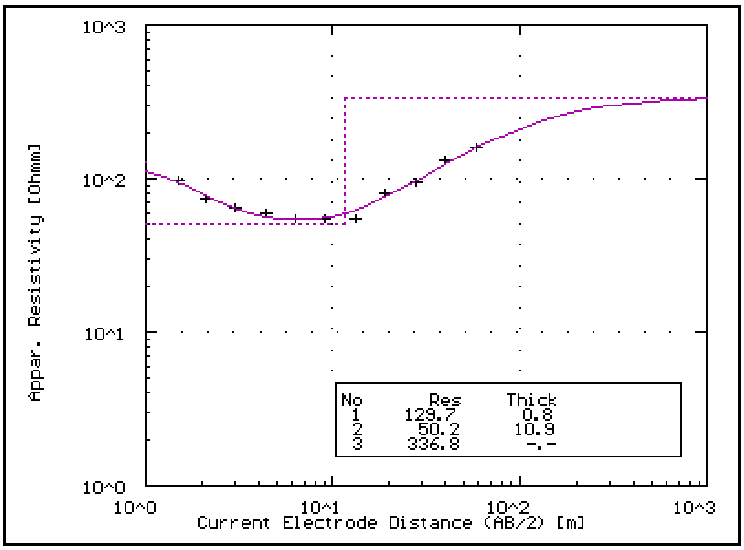


Figure 13. Modelled curve for VES at the middle of the Atankuidi Basin

Generally, the top layer is thin; this is the top dry portion of the regolith (overburden) or the dry soil (collapsed zone). The lower "high resistivity" layer constitutes the slightly weathered bedrock (sap rock) or the fresh bedrock. The middle low resistivity layer is the moist part of the regolith (highly weathered zone or saprolite) that constitute the shallow aquifer. The results indicate that the thickness of the overburden that constitutes the aquifer varies from 2.6 m to 13.7 m with the median and mean values of 6.6 m and 6.8 m respectively. The standard deviation is 3.2. The overburden generally has low resistivity. The resistivity of the saprolite is in the range 3.2-55.3 ohm-m with median and mean values of 28.0 ohm- m and 29.0 ohm-m respectively confirming the earlier derivative from the electromagnetic survey that permeability and transmissivity values could be low. In other words, the lower the resistivity of the saprolite (overburden) the higher the clay content, the higher the porosity and the lower the permeability and transmissivity.

Hydraulic conductivity and porosity

Hydraulic conductivity (K) can be estimated by particle size analysis, using empirical equations relating either "K" to some size property of the sediment. Vukovic and Soro (1992) analyzed empirical methods from former studies and presented a general formula:

$$K = \frac{g}{v}.C.f(n).d_e^{\ 2} \qquad (1)$$

Where K = hydraulic conductivity; g = acceleration due to gravity; v = kinematic viscosity; C = sorting coefficient; $f(n)$ = porosity function, and d_e = effective grain diameter. The values of "C","$f(n)$" and "d_e" are dependent on the different methods used in the grain-size analysis. According to Vukovic and Soro (1992), porosity *(n)* may be derived from the empirical relationship with the coefficient of grain uniformity *(U)* as follows:

$$n = 0.255.(1 + 0.83^U) \qquad (2)$$

where U is the coefficient of grain uniformity and is given by:

$$U = \frac{d_{60}}{d_{10}} \qquad (3)$$

Here, d_{60} and d_{10} in the formula represent the grain diameter in (mm) for which, 60% and 10% of the sample respectively, are finer than.
The equation (2) proposed by Vukovic and Soro (1992) was used to compute porosity (n) for all eight samples. The results of the grain size analysis based on the above methods give an average grain size of 0.26 or 26%.

Estimation of cross-sectional area
The cross-sectional area of the catchment was determined by dividing it into 5 sections, almost perpendicular to the length of the river channel (Figure 14). Minute trapeziums were created out along each section. The lengths of the parallel sides of the trapeziums are the depths between the water table and the bed-rock, derived from the electromagnetic profiling and VES measurements. Figure 14 shows the location of the five cross-sections in the catchment. The cross-sectional area was computed using Simpson's rule.

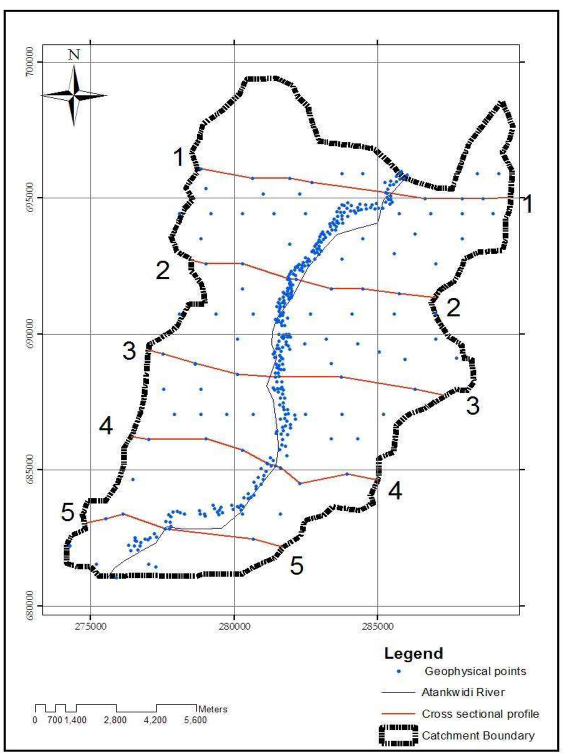


Figure 14. Location of cross-sections in the catchment

An estimate of the volume of water that can be stored in the underlying aquifer in the Atankuidi was, thus, calculated by multiplying the average cross-sectional area (see Table 2 below) of the aquifer along the selected traverses with the porosity and the length of the basin. The length of the basin was found to be 20.415km.

Table 2. Volume of water stored in the Atankuidi Aquifer

<table>
<tr><td>SECTION</td><td>AREA (m^2)</td><td rowspan="7">Groundwater Storage

Length of Catchment = 20 415m

Volume = Avg. porosity X Length X Avg. sectional area

Volume = 0.262401 X 20415 X 69214.67

Volume = 370,777,191.2 m^3 (370 MMC)</td></tr>
<tr><td>1-------1</td><td>80,066.67</td></tr>
<tr><td>2-------2</td><td>51,440.00</td></tr>
<tr><td>3-------3</td><td>66,400.00</td></tr>
<tr><td>4-------4</td><td>88,066.67</td></tr>
<tr><td>5-------5</td><td>60,100.00</td></tr>
<tr><td>AVERAGE</td><td>69,214.67</td></tr>
</table>

Results and Discussion

The underlying aquifer in the Atankuidi catchment was found to be capable of storing about 370 MMC of water per year (see Table 2 above for details). It must be stated that this includes soil moisture. Access to this groundwater for SGI is mainly through the digging of shallow wells. Farmers dig shallow wells along the Atankuidi river for dry season farming (irrigation). Distance between wells and the river bed ranges from as low as 15m to as high as 500m. The location to dig a shallow well is purely based on the farmer's local knowledge of the area. Farmers use trial and error methods to find suitable areas where one can get good water yield. Shallow wells are dug from late September to late October. Farmers with fields close to the river wait till the river stops flowing in October, farmers further away start digging earlier. Wells are closed at the end of the dry season to prevent animals falling into them or rains eroding the area close to the well, resulting in well instability. Typically, there are 2-3 wells on smaller farms whereas larger ones have between 3 and 5 wells. Wells run dry as the season proceeds due to using the wells for irrigation. After using the well for irrigation, the water level in the well is lower than before, but all wells still contain some water. The well is left for the night to fill so that water is collected to be extracted for irrigation the next day. Most of the farmers deepen their wells 1 to 3 times during the season for approximately 0.3-0.5 m per time.

In a typical planting season (for tomatoes), irrigation by shallow groundwater is essential during two main stages - the first and flowering stages (see Table 3 for the various stages). In the "first" stage, most of the farmers do not irrigate for one or more days after irrigation round and carry out other activities instead. The flowering stage, on the other hand, requires more water. The amount of irrigation water that is applied is increased in this stage, and almost all farmers irrigate every day. Van den Berg (2008) noted that farmers need 1 to 4 days to irrigate in the first stage, with a mean of 2.5 days and 2 days rest. One bucket of water is applied to 1 to 3 crop gutters with a mean of 6.5 litres per crop gutter. In the flowering stage farmers typically need 2 to 5 days to irrigate, with a mean of 3.2 days and 0.5 day rest. They apply one to two buckets per crop gutter with a mean of 14 litres per crop gutter in this stage. The irrigation data is converted to water use in litres per day per square meter, 1.0-4.6 $l/d/m^2$ is used for the first stage, whereas the water use is 3.0-8.9 $l/d/m^2$ in the flowering stage, with a mean of 5.5 l/d/m2. Table 4 summarizes the volume of water required in the two stages (each planting season for that matter)

Table 3. Stages in the cultivation of tomatoes in the Atankuidi catchment (Van den Berg, 2008)

End of rainy season																						
Nursery stage																						
Clearing the land																						
First stage																						
Flowering stage																						
Maturing stage																						
Harvest																						
Week	-1	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20

Plant nursery crops

Remove rainy season crop waste
Start digging of crop gutters
Start digging wells

Transplant nursery crops
Small crops develop to larger green crops

Small yellow flowers can be noticed

Tomatoes start to form and getting red

Harvest with 3-6 intervals

Table 4. Volume of water required in a typical planting season (Source: Van den Berg, 2008)

	Range	Mean
First stage		
Number of days for irrigation	1 - 4 days	2.5 days
Rest after an irrigation interval	0 - 3 days	2 days
Irrigation volume	1.0 - 4.6 l/d/m^2 of irrigated field	2.2 l/d/m^2
Flowering stage		
Number of days for irrigation	2 - 5 days	3.2 days
Rest after an irrigation interval	0 - 2 days	0.5 days
Irrigation volume	3.0 - 8.9 l/d/m^2 of irrigated field	5.5 l/d/m^2

Comparisons of figures in tables 2 and 4 indicate that the groundwater resources in the underlying aquifer are capable of sustaining shallow groundwater irrigation in the Atankuidi basin if all conditions remain the same.

Conclusions

The characteristics of the underlying aquifer in the Atankuidi catchment have been successfully studied by conducting extensive fieldwork. Results indicate that the overburden, which constitutes the shallow groundwater aquifer, is highly heterogeneous and varies in thickness from 2.6 m to 13.7 m with a median value of 6.6 m. The aquifer can up to 370 MMC annually and is capable of sustaining SGI, considering the volume of water presently required for irrigation. The GW catchment is low to medium in salinity hazard and low in sodium hazard. It is, thus, suitable for irrigation purposes.

Objective 2.3 Groundwater flow modeling, Volume and Sustainability

Methods
Field Data Collection
A number of data important for the modeling were collected on field. Electromagnetic profiling was done using the Geonics EM34-3 ground conductivity meter to detect fissured zones and thick overburden or weathered zones (regolith), which control shallow groundwater occurrence. Profiling was carried out along 30 traverses in the Atankuidi sub-basin. Conductivity was measured in both horizontal and vertical dipole modes.
Electrical resistivity sounding was carried out to determining the thickness of the various layers and their formation resistivities and, therefore, the depth and thickness of the shallow aquifers at various points. VES was conducted using the Schlumberger four-electrode configuration and expanding procedure.

Data on groundwater levels were obtained from piezometers that were installed at various locations in the catchment. The depth of the piezometers ranges between 4.64 m at and 7 m, with a mean depth of 5.83 m.

Meteorological and hydrological data for the study were obtained from the meteorological services agency and hydrological services department respectively. Other data collected include

Conceptual Model
A simple conceptual model of groundwater flow in the Atankuidi watershed was developed and a number of simplifying assumptions were also made. It was assumed that (i) the shallow groundwater aquifer is fully located within the downstream portions of the catchment (Ghana). The upper portion (in Burkina) was not considered because of the rocky nature the geology and the absence of any SGI activity. (ii) The aquifer physical boundaries correspond to the catchment and

therefore there is no flow in or from the neighboring basins. (iii) The aquifer is heterogeneous and anisotropic and groundwater flow could be represented as three-dimensional mesh grid.

The mass water balance was simulated with recharge as a source factor whereas evapotranspiration, production wells and outflow from the catchment were considered as sinks. Recharge was however assumed to be applied vertically and uniformly over the entire catchment and it forms just 7% of the rainfall (Martin, 2006). In addition, the analysis was limited to the lower section at Anayeree, the mid-section at Alia and the upper part at Bembisi. The analysis was limited to these three locations because of the extent and high intensity of SGI around these locations and the presence of a large number of monitored wells and piezometers equipped with divers.

Vertical hydraulic conductivity was assumed to be 50% of the horizontal hydraulic conductivity. However, horizontal hydraulic conductivity was estimated based on the soil map of the Atankuidi catchment and slug test data from 3 piezometers. A significant set of data was obtained from field activities and from reports of previous works carried out in the basin to transform this simple conceptual model into a quantitative numerical model.

Model Development
Numerical Groundwater Model
Simulations were done using the three dimensional (3D) numerical model MODFLOW (Harbaugh and McDonald, 1996). MODFLOW is a finite difference, 3D, time-varying groundwater flow model for groundwater-related studies. The model numerically evaluates the partial differential equations for groundwater flow (McDonald and Harbaugh, 1988) using finite-difference approximations.

$$K_h \frac{\partial^2 h}{\partial x^2} + K_h \frac{\partial^2 h}{\partial y^2} + K_v \frac{\partial^2 h}{\partial z^2} - W = S_s \frac{\partial h}{\partial t} \qquad (1)$$

Where K_h is the horizontal hydraulic conductivity, K_v the vertical hydraulic conductivity, h is the hydraulic head, Ss is the specific storativity, W is the source/sink term, t is the time and x,y,z are the space coordinates.

Model Grid and Mesh Design (Aquifer Geometry)
The underlying aquifer was considered as unconfined with a stratigraphy of 3 layers with alternating finer and coarser undifferentiated granitoids belonging to the Birimian metasediments which are made up of phyllite, schist and quartzite (Martin, 2006; Allaire, 2007).
The model domain encloses a square area of 17 x 23 km around the study area, with a regular grid size of 100m, i.e. 170 columns by 230 rows.

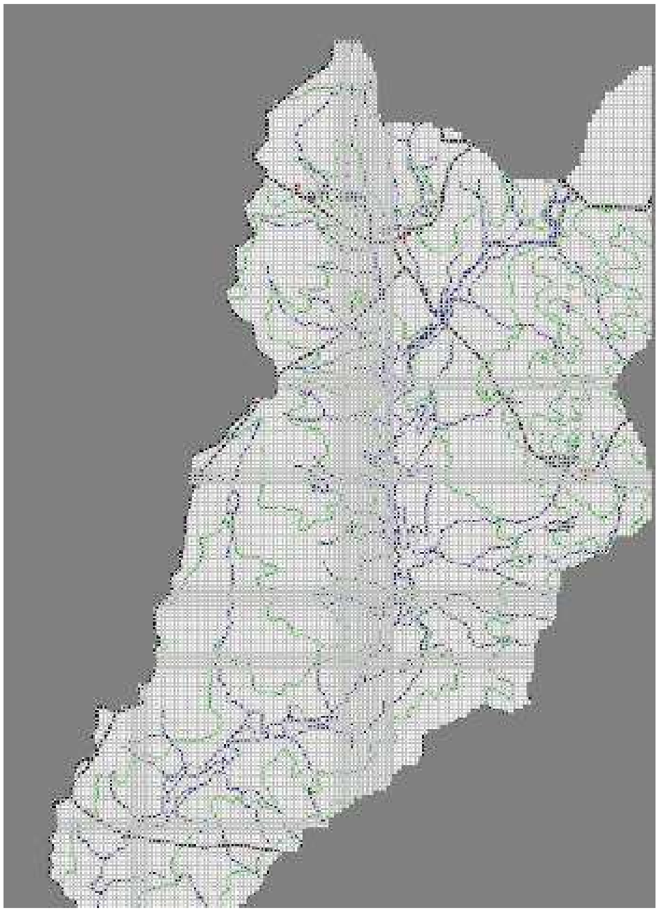


Figure 15: Model grid showing no flow zones (dark areas) and active cells

A 100 x 100-meter Digital Elevation Model (DEM) was generated from a 1:50000 contour map produced by the Survey Department of Ghana. The DEM was then used to define a 2D square-element mesh representing the top of the model domain (ground surface). Results of the electromagnetic profiling provided the lateral extents of the catchment.

The mesh was designed such that element dimensions near the SGI sites have a plan view length of 50 m, while elements further away from the SGI sites maintains the original mesh size of 100 m. This type of mesh allows a more accurate rendering of the hydrodynamic processes near the SGI sites, while reducing computational effort in terms of spatial discretization in less hydrologically active areas.

The bottom of the third layer (bedrock) and side boundaries of the catchment are assumed to be impermeable with respect to both surface and subsurface flow. Outflow is only allowed through the catchment outlet.

Input of Hydrogeologic Parameters

The model was run in a transient mode with a 10 daily stress period and a 5-day time-step. The period from October 12th, 2007 to March 30th, 2008 were used for calibration while the period between April 9th, 2008 and January 24th, 2009 were used for validation. Water level and rainfall data were available for these periods.

The Top of (TOP) the first layer corresponds to the DEM. Interpolated electromagnetic profiling and resistivity data were used to estimate the thickness of each of the layers. The bottom elevation of the first layer (BOT) corresponds to the TOP of the second layer. The bottom of the third layer was defined by the high values of resistivity (bedrock)

The horizontal hydraulic conductivity values were assigned based on the soil map of the Atankuidi watershed. Most soil profiles analyzed in the catchment were typical for Lixisols, consisting of sandy loam to sandy clay loam with high clay contents in the upper part of the profile. The subsurface hydraulic conductivity distribution was mapped onto the three-dimensional subsurface mesh from the results of a previous regional study conducted by Fosu (2004 unpublished).
Vertical hydraulic conductivity was set to 50% of the horizontal hydraulic conductivity. Vertical resistance to ground-water flow is simulated in the model with a vertical leakance term. A vertical leakance of 1 x 10^{-5} per second (default model value) was initially assumed for all cells.

Storativity values were based on typical values given in the literature. Specific yield (S*y*) values applied ranged from 10 to 30%, while specific storage (S*s*) values of 10^{-5} to 10^{-2} m^{-1} were applied.
Initial hydraulic heads were determined by running the model in a steady-state simulation mode. For the steady-state simulation, recharge and well production in the model were ignored because the month of March was selected as the starting period. Generally in March, the level of water abstraction for irrigation is minimal to nonexistent and there is no recharge too. The water levels obtained from the steady-state run of the model were then used as initial conditions of the transient simulation run.

Evapotranspiration rates used for the model were derived from the Penman-Montieth method, and an annual time series of twelve monthly values was applied uniformly over the model domain with an extinction depth of 1.0 m. Evapotranspiration rates varied from a minimum of 4 mm/day to a maximum of 6 mm/day.

Results

MODEL CALIBRATION

Calibration was carried out to find a set of parameters that would allow the model to reproduce the field data, i.e. hydraulic heads and boundary fluxes.
Calibration was performed iteratively with storage terms (specific yield and specific storage), vertical hydraulic conductivity (initially set at 75% of the horizontal hydraulic conductivity) and vertical leakance values were adjusted within physically realistic bounds until the best possible match was found between the simulated and observed heads. Parameters used in the best-fit calibration are summarized in Table 5 below.

Table 5. Summary of Input Parameters for the Calibrated Model

Parameter	Value	Applied Layer
VHC	50% of HHC	All Layers
Specific Storage	2.6 x 10^{-4} m^{-1}	All Layers
Vertical Leakance	2.8 x 10^{-5} s^{-1}	All Layers
Effective Porosity	45 and 35%	Layer 1, and Layer 2 & 3 respectively
Specific Yield	0.12	All Layers

Where VHC = Vertical Hydraulic Conductivity and HHC = Horizontal Hydraulic Conductivity

A plot of the observed and corresponding simulated hydraulic heads is presented in Figure 16. There's a reasonable correspondence between the observed and model-computed hydraulic heads. The model predicts groundwater levels (piezometric heads) with an accuracy of 0.80 according to the Nash-Sutcliffe (1970) Coefficient of efficiency, (COE). An R^2 of 88.2% was obtained, which is an indication of close relationship between measured and predicted values.

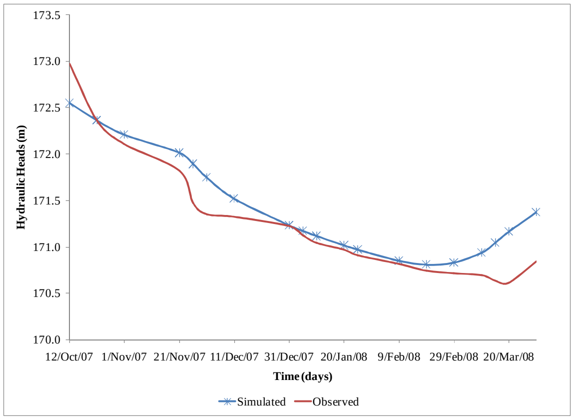


Figure 16. Comparison of calculated and simulated hydraulic heads response (transient simulation)

Calibration results were expressed as water table contour maps and groundwater flow direction together with mass water balances of the catchment and zonal water budgets at selected stress periods. Water level contours and flow paths just before the introduction of the hand-dug wells and just after the introduction of the hand-dug wells is shown in Figures 17. The distribution indicates that water is flowing in the subsurface away from topographic highs (corresponding to areas of greater hydraulic head) and converging towards the outlet of the basin and low land areas.

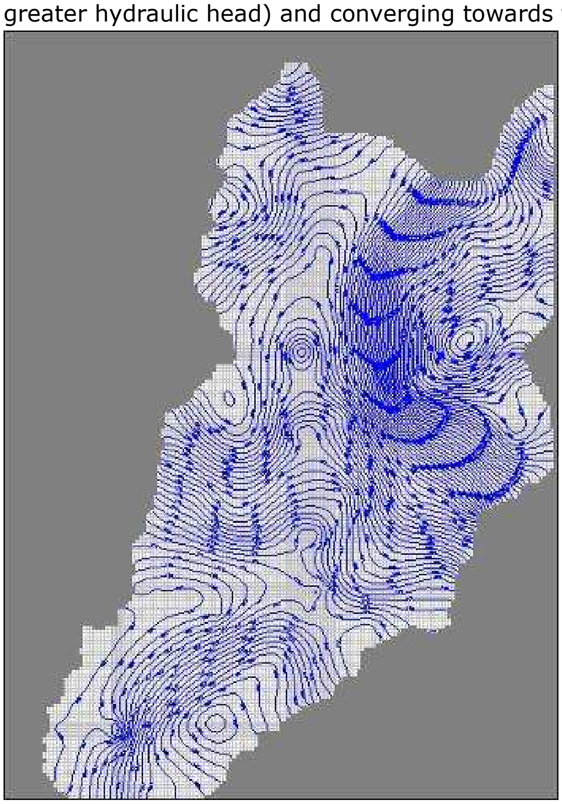


Figure 17: Distribution of hydraulic heads in stress period 37 (February 24th 2007).

MODEL VALIDATION

The model was validated for the period from April 2008 to January 2009.The observed piezometric heads compare well with predicted heads. COE was found to be 0.73 and an R^2 of 0.87 indicates a close relationship between measured and predicted piezometric heads.

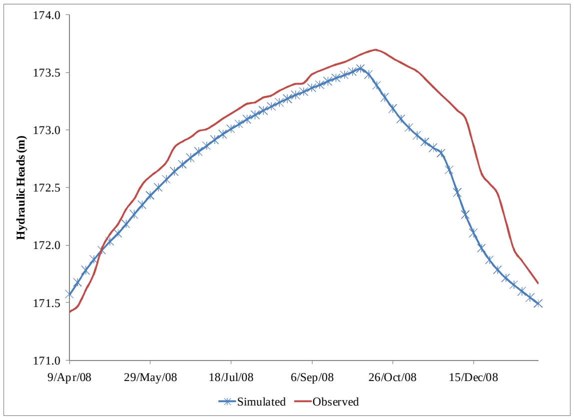


Figure 18: Comparison of model-computed and observed hydraulic heads for the validated transient simulation

The cumulative mass balance at the end of the validation period is presented in Table 6 below. It shows that the difference between total inflows and total outflows is 2 m^3, which is negligible compared to the total flows, indicating an agreeable solution. The table further reveals that the storage component of the input forms 99.87% whereas the recharge component of inputs forms less than 1% of the total inputs. This indicates that the major source of recharge may not necessarily come directly from the precipitations in the catchment. The boundary conditions imposed on the model which does not allow any groundwater flow to neighbouring basins may also not reflect the real situation. Indirect recharge due to frequent floods during the rainy season could be the main source of groundwater recharge. For instance, most farmers interviewed during fieldwork in December 2007 mentioned that the groundwater level was higher during the following dry season compared to 2006. Groundwater abstraction for the application of SGI was found to be approximately 3% of the model output and one-fourth of the evapotranspiration.

Table 6: Cumulative mass balance at the end of validation (3rd June 2009)

	IN (m^3)	**% of Total**	**OUT (m^3)**	**% of Total**
Storage	28,125,640	99.87	23,912,620	84.91
Recharge	35,208	0.13	-	-
Evapotranspiration	-	-	3,412,330	12.12
Abstractions (Wells)	-	-	835,900	2.97
Total	28,160,848		28,160,850	

Discussion/ Scenarios Analysis

The impact of a possible expansion of SGI in the catchment on GW resources was evaluated through scenarios. In the first scenario, it was assumed that the current land area under SGI (i.e. 48 ha) is increased by 50%. The second and third scenarios assumed a 75% and 100% increase in cropping area. Irrigation application rates is set to 2.2 $l/day/m^2$ at the first phase (50 days after planting) and 5.5 $l/day/m^2$ at the flowering stage (van den Berg 2008). This translates into an abstraction rate of 105.6 m^3/day and 264.0 m^3/day for the first and second stages of planting respectively.

The water budget from the model output indicates that increasing the irrigated land area by 50% would require a total volume of 396,000 m^3 from the groundwater for the 2006/2007 irrigation season which represents about 1.97% of the storage volume. During the 2006/2007 cropping season only 0.92% of the storage was then abstracted. However, increasing the abstraction rates by 75 and 100% for the same period would lead to an increase in the amount of groundwater withdrawal by 2.30% and 2.63% of storage respectively.

Analysis of the first scenario further shows that the hydraulic head will drop by 8.55 m from the beginning to the end of the 2006/2007 cropping season (October 2006 to February 2007) compared to that of 6.17 m for the same period if business as usual. In the case of the 75 and 100% increment, the hydraulic heads will drop by 11.11 m and 12.71 m respectively for the same period. From the aforementioned changes in the hydraulic heads, it can be observed that increasing the groundwater withdrawal by 50% would imply that farmers must deepen their wells by twice the depth of the current situation to obtain adequate water if current rates of abstractions are maintained. Figure 19 presents the impact on drawdown as a result of groundwater abstraction for the various scenarios at selected stress periods.

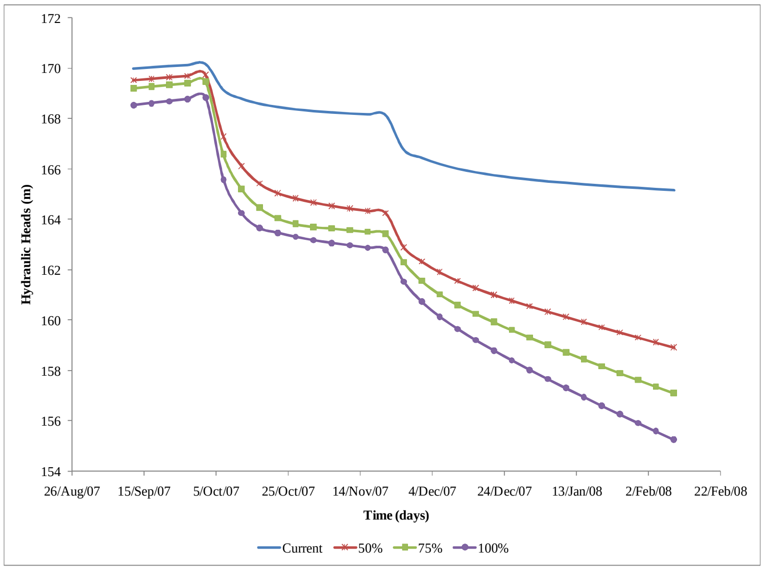


Figure 19: Comparison of changes in hydraulic heads under different scenarios

Abstraction from the wells has a significant effect on the falling of groundwater level in the alluvial aquifer. The analysis shows that the thickness of the aquifer layer and water use by the farmers result in the highest influence in groundwater level decrease. Other sinks (vegetation and losses to fractured zone) probably cause an extra decrease.

Results obtained in this study suggest that the effect of increase in SGI on GW resources is significant. The model tests show that the local decrease in groundwater level is significant and may lead to local over-extraction, even as irrigation areas increase.

CONCLUSIONS

SGI as currently practised in the Atankuidi catchment, has still enough room to expand and improve. The application of water by SGI-farmers is very efficient but too labour intensive.

The total volume of abstractions is still insignificant compared to the total storage that is annually available. From the output of the applied numerical model, the limiting factor of SGI during the study period is not really the annual volume that is available but rather finding and implementing groundwater affordable development techniques adapted to the local geology conditions. Permanent technologies such as tube wells allowing abstraction from the second and third layers could, if the location is carefully chosen, significantly increase efficiency of groundwater abstraction. SGI farmers in the catchment as well as in other parts of the White Volta basin will then be less occupied every year with a risky activity such as hand-digging seasonal narrow and very shallow wells.

There is a strong need for a long-term monitoring of groundwater levels to determine if groundwater levels show a certain trend over time. Such information would give more insight into the sustainability of the groundwater level and therefore in the application and possible extension of SGI in the Atankuidi catchment and the whole Volta Basin. Moreover, since extreme events in rainfall largely determine groundwater recharge it is useful to compare these results to determine if the availability of water in the alluvial aquifer can be predicted from rainfall and extreme events such as floods frequency.

Due to floods of September 2007 many smallholder farmers lost their rainfed crop harvest and did not have enough resources to start cultivation in the following dry season. The total irrigated area was therefore smaller and could have influenced this research results, for example the total water extraction by farmers in the irrigated area. It would be useful to conduct the same research in adjacent basins to further investigate the impact of SGI on the alluvial aquifer levels.

Objective 3: Generate knowledge on the crop and water productivity of SGI agro-ecosystems

Methods

To assess water productivity (WP) in the Atankuidi catchment, five farmer plots were selected to monitor hand-dug-well and dug out irrigated plots under individual farmer's management. Two (2), out of the five, plots (Aplot1 and Aplot2) use pumps to draw water from the dug outs and the remaining three plots were irrigated by using buckets to fetch water from shallow wells. Cultivated plots varied from 0.11 to 0.13 ha for pump irrigated plots and from 0.03 to 0.11ha for bucket irrigated plots. All plots were transplanted with tomato (*Lycoperscon esculentum*). Two varieties (*Pectomech and Vis Locally known as no-name*) are generally cultivated in the sub-catchment. In each sample plot, the volume of water during every irrigation event, duration of irrigation and number of irrigations were measured and recorded for the entire crop season.

Crop WP was estimated as a ratio of crop yield to: irrigation supply, potential and actual crop water use. Irrigation water supply to the pump-irrigated plots was measured with a mechanical water flow meter from the Ghana Water Company office in Bolgatanga, whereas the volume of bucket and the number of buckets for every irrigation event were recorded for the bucket irrigated plots. The water flow meter was attached to the water outlet pipe of the pump. As farmers were unwilling to agree to a permanent attachment of the flow meter to the pump outlet, the amount of water used for the watering of the full farm was repeatedly measured and the number of watering events recorded. At the end of the season, total volume of water used was calculated as the average of the water required for the watering of an entire farm multiplied by the number of watering events. In addition to irrigation measurements, shallow groundwater levels were measured in open hand-dug-wells. This was done using locally fabricated Plopper and a tape measure. Transplanting dates, crop development stages, root growth, and the start and end of harvesting were monitored and recorded in situ. Quantities and costs of farming inputs (machinery hire for plowing, seeds, chemical fertilizers, pesticides and hired labor), plot sizes and economic crop yield were also collected from each sample plot. Selling prices of harvested tomato during each harvesting event were also collected.

Estimation of crop water use

Soil-Water-Atmosphere-Plant (SWAP), an Agro-hydrological model (van Dam et al., 1997) was applied to estimate potential and actual crop water use (ET_c and ET_a) as components of the water balance in the output of water transport simulation module for Tono and Dorongo. Potential evapotranspiration (ET_o), rainfall (P) and irrigation (I) are used for defining top boundary condition in SWAP. ET_o was estimated using FAO-Penman Motheith equation (Allen et al., 1998) using climatic data (temperature, relative humidity, wind speed, solar radiation and sunshine hours) collected from HOBO automatic weather station at Tono and Ghana Meteorological Agency (GMA)-Bolgatanga weather station. The pressure head h (m) recorded from the piezometers or free drainage were applied to define bottom boundary condition for the model. Water levels in open borehole recorded at the beginning of the dry season or the initial soil moisture generated by running SWAP for the previous rainy season were used as the model initial conditions. A numerical analysis was applied to determine crop water use. ET_c was determined from ET_o estimated using climatic data from Bolgatanga weather station and crop factors (*kc*). Initial *kc's* for tomato obtained from the FAO guidelines for crop water requirement estimation (Allen et al., 1998) were adjusted based on the amount of irrigation applied and crop development stages. ET_a was calculated as a product of water stress (*Ks*) and ET_c. *Ks* was estimated from $Ks = (TAW-Dr)/((1-p)\ TAW)$. The total available water (*TAW*) for the crop was estimated as product of soil available water (*AW*) and rooting depth (*Zr*) using the average *AW* of 0.14 cm^3cm^{-3} for loamy sandy and sandy loam top and sub-soils and the initial *Zr* of 0.25 m with assumed root growth of 0.005 m/day and 0.01m/day at initial and rest of plant growth respectively until a maximum rooting depth of about 0.9 m is reached at the mid-season crop stage. A value of zero was used for the initial root zone soil moisture depletion (Dr_i). The *Dr* for the following days (Dr_{i+1}) was estimated as $(Dr_i+ET_c+Dp)-I$, where deep percolation (*Dp*) was assumed to occur whenever irrigation exceeded field capacity of the soils (0.18 cm^3cm^{-3}). A 40% of *TAW*, adjusted to daily ET_c was used for the fraction of root zone crop extractable water or readily available water to crop plants without suffering water stress. Crop water productivity was estimated as a ratio of crop yield to *I* (WP_I), ET_c (WP_{ETc}), and ET_a (WP_{ETa}). Gross margins for each plot and return to water were also estimated. Water productivity values, gross margins and return to water are compared across the three contrasting tomato production systems and also in relation to reported findings elsewhere.

Results & Discussion

Tables 7 and 8 details results of the WP study undertaken in the Atankuidi catchment. Pump irrigated plots were supplied with 274 mm and 338 mm while two of the bucket irrigated plots were irrigated with above 800 mm and Aplot5 was irrigated with 617 mm. Bucket irrigators use far more water than pump irrigators because of the localized nature of bucket irrigation. Farmers who do bucket irrigation cultivate in gutters. They irrigate their crops by pouring water (fetched with buckets) into the gutters, which normally stay in the gutter for some time before it completely infiltrate into the soil. Pump irrigators, on the other hand, pump water from shallow wells which normally dry up even before their whole fields are irrigated, thus end up using little water. Average ET_c was about 457 mm for all the five plots. ET_a for Aplot1 and Aplot2 (pump irrigated plots) was about 90% and 71% of irrigation water supply respectively. For bucket irrigated plots, ET_a was about 53%, 48%, and 74% of irrigation supply for Aplot3, Aplot4 and Aplot5 respectively. The average crop yield for all plots was found to be 27.87 tons/ha. Aplot1, a pump irrigated plot recorded the lowest yield (19.94 tons/ha) while Aplot3, a bucket irrigated plot, recorded the highest yield of about 36.83 tons/ha.

Table 8 shows the WP values in the Atankuidi catchment. Overall average yield at Atankuidi was found to be generally higher, compared to other irrigation sites in the region (Mdemu et al. 2009). The High WP at Antankuidi was mainly influenced by a high crop yield, which, in turn, might have been caused by high soil fertility. Plots in the Atankuidi catchment, since the late 1990s, are cropped only during the dry-season, contrary to practice in other sites where plots are constantly cultivated throughout the year. During the rainy season most of the plots are used for rainfed rice cultivation, and fertilizers such as urea are applied.

The high WP values for hand-dug-well irrigated plots could also be attributed to good management of irrigated plots. Farmers in the catchment are able to better schedule the transplanting of crops, water supplies, and other farming inputs. Furthermore, the rather small size of their farms allowed them to more easily attend to their crops.

High WP values from hand-dug-well irrigated plots highlight the potential of improving WP in medium and small reservoirs through proper crop timing in the season, better field water management and proper control of factors such as pests and diseases that affect crop yields.

Table 7. Water supply and water use in the Atankuidi

Location and plot identity	Irrigation (mm)	Number of irrigations (No.)		Average irrigation (mm)		ETc (mm)	ETa (mm)
		Initial stage	Rest of growth period	Initial stage	Rest of growth period		
Aplot1	274	3	9	23	23	455	252
Aplot2	338	3	11	24	24	508	250
Aplot3	820	4	28	9	24	445	431
Aplot4	838	4	28	9	28	403	402
Aplot5	617	4	37	6	18	476	457
Average	577	4	23	11	24	457	358

Table 8. Crop yield and physical water productivity of tomato farms in the Atankuidi catchment

Location & Plot	Yield (kg)	Yield (tons/ha)	Water productivity (kg/m^3)		
			WP_I	WP_{ETc}	WP_{ETa}
Aplot1	2592	19.94	7.27	4.38	7.91
Aplot2	3456	32.91	9.74	6.48	13.14
Aplot3	1105	36.83	4.49	8.28	8.55
Aplot4	652	23.53	2.81	5.85	5.85
Aplot5	2963	26.12	4.25	5.51	5.74
Average	2154	27.87	5.71	6.18	8.24

Plot	Total Cost ($/ha)	Total Revenue ($/ha)	Profit ($/ha)	Return to irrigation water ($/m^3)
Aplot1	1823	1940	117	0.08
Aplot2	1142	3999	2855	1.04
Aplot3	1021	3699	1710	0.21
Aplot4	813	2450	1612	0.48
Aplot5	856	3980	3122	0.51
Average	1131	3214	1,883	0.46

Conclusions

WP values at Atankuidi are similar to values reported for surface irrigation systems under intensive cultivation and even some drip irrigation systems. The high WP values for hand-dug-well irrigated plots could be explained by good management of irrigated plots. Farmers are able to better schedule the transplanting of crops, water supplies, and other farming inputs. Furthermore, the relatively small sizes of all plots allow farmers to more easily attend to their crops. High WP values from hand-dug-well irrigated plots highlight the potential of improving WP in medium and small reservoirs through proper crop timing in the season, better field water management and proper control of factors such as pests and diseases that affect crop yields. Understanding the fertility of soils, although not dealt with in this study, is critical for any WP improvement intervention strategies. Further detailed analyses of production inputs and other contributing factors such as soil fertility and soil water holding capacities and the dynamics of market conditions which affect the value of final harvest are imperative for determining the most likely productive system in the near future.

Objective 4: Study the Socio-economic drivers of uptake and expansion of shallow groundwater irrigation systems

Methods

SAMPLING STRATEGY AND SAMPLE SELECTION

The basic sampling unit for the study was determined to be households within the study area. First, a rapid "census" was conducted by a team of enumerators (this team was different from the one that conducted the actual study) to do the following:

- Identification of the boundaries of the watersheds
- Listing of all compounds within a reasonable distance of shallow ground water irrigable areas in the watersheds
- Determining the number of 'households' living in each compound
- Identifying non-irrigators and irrigators households
- Categorizing households practicing irrigation according to their source of water (i) shallow seasonal wells, (ii) permanent wells, and (iii) drainage water

.
Using the list of households obtained through the rapid census in the study area, a computer aided random sampling was done to select the household to be interviewed in each category as contained in column A of Table 9 below.

Table 9 Sample Size Differentiated by irrigation Typology

Irrigation Typology	A Number of farmers randomly selected for Interviews	B Actual Number Interviewed
Non- Irrigators	137	141
Drainage water	50	4*
Shallow Seasonal Well	152	212
Permanent Well	50	23
Total	439	420

* Most of the farmers who use drainage water from the Vea scheme to irrigate explained that there was no drainage water from the scheme during the 2008/09 season and they have to turn to seasonal well irrigation. Drainage water was then eliminated in the analysis since only 4 households are involved.

FIELD WORK - Reconnaissance Visits

Two rounds of reconnaissance visits were made to the study area at the inception of the study to develop the survey instruments.

General Socio-economic/Agronomic/water Management Module

The questionnaire for this module was very exhaustive and designed to capture the socio-economic characteristics of the respondent's household. In the case of irrigators this module also captured the irrigation practice, agronomic, water /soil fertility management, labor, support services and other key variables essential to the study.

Household Consumption Expenditure Module

Household consumption expenditures consist of two broad categories: food and non-food consumption expenditures. Therefore two separate standard questionnaires were designed to capture the food and non-food expenditures.

Two other questionnaires were also designed to capture household dietary diversity and the months with inadequate food provisioning. Community level information on livelihood assets broadly captured under titles such as natural, human, physical, social, and financial capital were also gathered.

Data collection, entry and Analysis

Data collection took place from the 8th October – 21st November 2009. From the 8th to 20th October 2009, enumerators concentrated on administering the general socio-economic/agronomic/water management questionnaires alongside the collection of data on the months of inadequate food provisioning as well as data on household dietary diversity. From the 21st October -21st November 2009 enumerators focused on the household consumption expenditure modules ensuring that each enumerator had exactly four weeks to complete the 4-round 7-day recall of food consumption and food consumption expenditures data. GPS information of household as well as community locations was recorded.

SPSS for Windows 16.0 and Microsoft Access were used for data entry and analysis. The data on general socio-economic/agronomic/water management practices were imputed, cleaned and analyzed using SPSS for Window 16.0. The nature of the household consumption expenditure questionnaires required the use of Microsoft Access for data entry which was later exported to SPSS for Windows and Microsoft excel for analysis.

Results & Discussion

DEMOGRAPHIC STRUCTURE AND SOCIOECONOMIC CHARACTERISTICS

The mean ages of farmers range between 38 and 54 years. Heads of non-irrigating household were found to be at least 7 years older than irrigating household heads. Shallow ground water irrigation is said to be very difficult because most farmers use buckets and watering cans to fetch water from the source and walk around to water the crops manually. This could be the reason why most of the farmers engaged in irrigation activities are relatively younger. The relatively young age of farmers engaged in irrigations gives a strong indication that investing in irrigation development in the area has a potential of creating jobs for the youth.

The gender composition of the households differentiated by irrigation typology cluster does not show any marked difference among the various irrigation typologies. Males constitute 49.5 %, 50.2%, and 48.9% of non-irrigators, shallow seasonal wells, and permanent wells respectively. The gender composition of a household is therefore not likely to be a determining factor of the choice of an irrigation technology by a household or whether the household irrigates at all. Women and the youth have long been involved in dry season gardening in the area.

Crop farming is the predominant occupation of the people in all the irrigation typologies. It is however, observed that on the average non irrigators (42.7%) seem to rely more on crop farming than the others who do irrigation, 40.1% and 31.6% for shallow seasonal wells and permanent wells respectively. This suggests that households engaged in irrigation may have other source of income generating activities. The results indicate that 11.3% household members who use permanent wells also engage in petty trading suggesting that extra income obtained from irrigation is being invested into petty trading to diversify household livelihood.

HOUSEHOLD RESOURCE ENDOWMENT

Land ownership and Use Crop farming is the main stay of most people in the study area. Information on ownership and/or access to use of farmland is, thus, critical to the livelihoods of the people. Results indicate that non irrigators and shallow seasonal well irrigators own an average of 5.1 acres (about 2ha) of rainfed farmlands, where as permanent well own a mean of 3.1 acres. Seasonal shallow well irrigators have a higher mean irrigable area owned (1.4 acres). The purchase of land for farming purposes is not a common practice in the area. Land is often obtained from friends and/or relatives for farming purposes. A token gift is given to the owner of the land after harvest, to maintain a cordial relationship.

Table 10: Mean Sizes of Agricultural Land Owned Differentiated By Irrigation I Typology

Irrigation type	Mean land owned-rain-fed acres	Mean land owned-irrigable acres
Non –irrigators	5.1	0.9
Shallow seasonal well	5.1	1.4
Permanent well	3.1	0.5

With respect to land area put under cultivation, the results show that non-irrigators have the highest mean area of land put under rain fed cultivation (4.8 acres). It is possible that non-irrigating households as a livelihood diversification strategy tend to put more rain fed land under cultivation to ensure household food security. Mean land under rain-fed farming is the lowest for permanent well irrigators who have guaranteed access to water for irrigation purposes in the dry season.

Table 11: Mean Cultivated Land by Irrigation Typology 2008/09

Irrigation type	Mean cultivated land 2009-rainfed	Mean cultivated land 2009-irrigable
Non –irrigators	4.8	0.0
Shallow seasonal well	4.7	1.2
Permanent well	2.7	0.5

SHALLOW WELL DEVELOPMENT COST AND CHARACTERISTICS

Seasonal Shallow Well Irrigators

A mean depth of 5.63 meters and 5.82 meters were reported for the riverine (dugouts) and in-field (hand-dug) seasonal shallow wells respectively. Even though the dugouts are relatively less deep, and cost about GHC 5.26 more to construct compare to the hand dugs seasonal shallow wells. More time is required in the preparation dugouts seasonal shallow wells despite the fact that they are less deep. On average there are more hand-dug wells (about 3 per farmer) than dugouts (2 per farmer). The main cost element in the preparation of both types of wells is in the provision of food for friends and /or relatives who help in the preparation of the wells. All farmers that have while those with hand dug shallow wells commonly use rope and bucket.

Table 12: Mean Numbers and Cost of Shallow Well Development

Shallow Well Description	Mean Number /Farmer	Mean Depth (Meters)	Mean Labor (Hours of Digging)	Mean Total Construction Cost (GHC)
Riverine shallow well	2.4	5.63	38.53	17.37
In-field shallow wells	3.3	5.82	32.57	12.11

Permanent Shallow Wells
9 of the 23 Permanent Shallow Wells irrigators owned permanent lined wells. The mean depth of permanent shallow well as reported by the farmers is 12.2m with an initial average drilling cost of GHC586.1. The mean cost of lining is GHC 21.3 and 23.5 for materials and labor respectively. This brings the total start-up capital of a permanent lined well to about GHC 630.9 compared with GHC532.8 for a permanent unlined well. The main equipment used for abstracting water from the permanent shallow well is a bucket and a rope which cost about GHC 8.05 to acquire with a service life of about 3.8 years.

Table 13: Mean Numbers and Cost of Permanent Well Development

Permanent well Description	Mean Number /Farmer	Mean Depth (Meters)	Mean cost of Drilling GHC	Mean cost of Lining (material) GHC	Mean cost of Lining (labor) GHC
Lined Permanent well	1.3	12.2	586.1	21.3	23.5
Un-Lined Permanent well	2.0	10.4	532.3	-	-

AGRONOMIC AND WATER MANAGEMENT PRACTICES AND INPUT LEVELS

Size of irrigated land by crop type and irrigation typology
Among the shallow seasonal well irrigators, tomatoes are the dominant crop (90.6%). The mean area under cultivation is about 1.02 acres. Only 9.4 % of the shallow seasonal well irrigators do cultivate some pepper with a mean area of 0.36 acres. Obuobie (2008) reported that farmers involved in the use of shallow ground water for irrigation are mostly small scale farmers (0.04-1.5 ha). Other crops cultivated include vegetables such as carrot, onion, tomatoes, cabbage and shallot.

With respect to the permanent well irrigators pepper is the dominant crop, accounting 82.6%, with tomatoes accounting for only 17.4%. Pepper stays longer on the field compare to tomatoes, this may explain why permanent well irrigators tend to favor pepper cultivation. The mean area under permanent well irrigation is 1.0 acre.

Land Preparation Methods
Manual land preparation using basic traditional tools such as the hoe and cutlass is the main method of land preparation for the shallow ground water irrigators. 31.5 % and 45.8% of the irrigators prepare land using only the traditional hoe and a combination of the traditional hoe with cutlass respectively. A few farmers (9.5%) undertake bullock ploughing. Only 2.4% of the farmers

reported that they used herbicides during land preparation. The farmers that employed bullock services for land preparation in the 2008/09 season paid GHC 17.3 per acre in addition to three man-days of labor. For the 2.4% of farmers that used herbicides. The results indicate that herbicide application during land preparation is more expensive, relative to the manual methods. This could partly be responsible for the low use of herbicides. Transplanting is the main method of planting among the irrigators.

Table 14: Cost of Land Preparation with Bullock and Herbicides

Bullock		**Herbicide Application**		
Mean cost per/acre GHC	Mean labor days associated with bullock ploughing	Mean qty. /acre (litres)	Price/litres	Mean appl.hours/acre
17.3	3.7	3.7	13.0	15.8

Table 15: Methods of Planting by Irrigation Typology

Planting Method	Shallow Seasonal Well		Permanent Well	
	Freq.	%	Freq.	%
Transplanting	212	100	38	95.0
Broadcasting	-	-		
Dibbling	-	-	2	5.0
Total	212	100	40	100

Weed Management

Weed control among the irrigators is exclusively by hand either with a normal hoe or hand picking. None of the irrigators uses herbicides for weed control. According to the farmers, family labor is their most important source of labor for hand weeding. They reported an average of 12.5 and 13.8 man-days for all weeding activities for shallow seasonal well and permanent well respectively.

Table 16: Weed Management

	Shallow Seasonal Well		Permanent Wells	
	Freq.	%	Freq.	%
Hand weeding	212	100.00	23	100
Labor for hand weeding/acre	12.5		13.8	

SOIL FERTILITY MANAGEMENT

Soil Fertility Management - Shallow Seasonal well Irrigators

A large number of SGI farmers (95%) apply fertilizers on their plots. However, the average quantities applied for tomatoes are 6.5Kg , 65.0kg and 98.7kg per acre of urea, ammonia, and NKP 15-15- 15 respectively. These quantities are negligible compare to the recommendations from the (GIDA)/ JICA (2004) technical guidelines for the for irrigation agriculture, the recommended chemical fertilizer rate for tomatoes is 120**/**kg acre and 40kg/acre of NPK 15-15-15 and Sulfate ammonia respectively, in addition to about 4 to 8 tons of organic manure per acre applied during harrowing.

Soil Fertility Management -Permanent Well Irrigators

82.6% and 17.4% of permanent well irrigators cultivate pepper and tomatoes respectively. With respect to fertilizer use, 75.0%, 25.0% and 50.0% of these farmers who cultivate tomatoes apply urea, sulphate of ammonia, and NKP 15-15- 15 to their fields. The average quantities applied are 75.0 Kg , 12.5.kg and 18.7Kg per acre of urea, ammonia, and NKP 15-15- 15 respectively. The farmers that use urea apply quite substantial amounts per acre. Pepper farmers seem to apply more fertilizer per acre relative to tomato farmers. Pepper is a known heavy feeder however; the fertilizer use of the pepper farmers does not appear to be in line with recommendations of technical experts. (See technical guidelines for irrigation agriculture, GIDA/JICA, March 2004)

ON-FARM WATER MANAGEMENT

About 56% of shallow seasonal well irrigators do not irrigate during land preparation and 44% do irrigate between 1-14 times during land preparation to make the land softer for manual land preparation with a hoe. During crop season 91% of the shallow seasonal well irrigator's, who cultivate tomatoes, reported that they irrigate about 41 times from planting to harvesting which required on the average 47man-days of labor Farmers t using motorized pumps, reported an average of 5.43 litres of fuel consumed per week during crop growing season at an average price of GHC 0.93 per litre.

Permanent well irrigators none do not use a motorized pumps. They however, undertake more irrigation during crop growth. 91% of of them cultivate pepper, and irrigate about 88 times from planting to harvesting. An average of 66 man-days was reported as irrigation labor for the entire cropping season, suggesting that they spend fewer hours per each irrigation session compared with the Shallow seasonal well irrigators. This is not surprising since permanent wells are mostly close to household dwellings.

HARVESTING

The mean number of harvest for tomatoes in the 2008/09 season was 4 times, and 7 times, for shallow seasonal well, permanent wells respectively. The low number for shallow seasonal well irrigators could be attributed to water availability; the permanent irrigators have access to perennial source of water and could irrigate the crop as long as it continues to fruit, unlike the shallow seasonal wells which dry-up as the dry season progresses. For pepper, the mean number of harvest as reported by the farmers were 9 times, 7 times, and 8.0 times for shallow seasonal well, and permanent wells respectively. Pepper, unlike tomatoes, is drought tolerant.

The mean total output per each round of harvest as reported by the farmers is shown in the table below.

Table 17. Mean total output per each round of harvest

Irrigation Typology	**Sale of Output by Irrigation/ Crop Typology**			
	Crops Cultivated	**Mean Output Sold per Harvest (KGs)**	**Mean Value of Total Output per harvest (GHC)**	**Mean Cost of Transportation (GHC)**
Shallow Seasonal Well	Tomatoes	348.4	172.41	1.3
	Pepper	128.0	59.7	0.00
Permanent Well	Tomatoes	140.4	24.8	0.00
	Pepper	136.0	61.8	0.00

ECONOMICS OF IRRIGATED CROP PRODUCTION BY IRRIGATION TYPOLOGY

Profitability Estimates

The profitability analysis is done for the two important cops cultivated by the irrigators - tomatoes and pepper. For tomatoes, the average cost (excluding cost of labour) of production per acre for the 2008/09 cropping season was GH¢ 223.8 and GH¢ 229.3 for shallow seasonal well and permanent well irrigators respectively. The gross profits per acre are GH¢ 465.8 and GH¢ -55.7 for shallow seasonal well and permanent well irrigators respectively. The difference in gross profit is due largely to the difference in the mean value per harvest, which is lowest for the permanent well irrigators. The low mean value per harvest is due to two main factors; poor yield and low prices. The Permanent irrigators cultivate tomatoes in relatively small quantities hence do not attract commercial buyers. It is therefore not surprising that over 80.0% of the permanent irrigators are engaged in pepper cultivation which is comparatively more rewarding to them.

With respect to pepper cultivation, both Shallow seasonal well irrigators post a positive gross and net profit. However, permanent well irrigators have a negative net profit even if the cost of labour is deducted. It is important to note that the permanent wells serve two important uses; irrigation and domestic use (drinking, cooking and watering of livestock). Though it could not be proven from this study, permanent well irrigators are suspected to use more of their harvest for household consumption than Shallow seasonal well irrigators. The profitability estimates suggest that the shallow seasonal well irrigators do make some profit from engaging in the vegetable cultivation. However, the profits are very much dependent on prices, which are highly volatile.

Table 18 Profitability Estimates

ITEM	Infield-Shallow Seasonal Wells/acre		Permanent Wells/acre			
	Tomatoes	Pepper	Tomatoes	Pepper		
Well preparation	14.74	14.74	58.6	58.6		
Land preparation	17.3	17.3	17.3	17.3		
Seedling purchase	50	50	50	50		
Rope & bucket for water (annual value)	3	3	3	3		
Irrigation service Charge	0	0	0	0	5	5
Total cost of chem. Fert.	137.5	179.6	100.4	107.9	140.3	105.1
Transport cost	1.3	0	0	0	0	0
Total cost exc. cost of labour (A)	223.8	264.6	229.3	236.8	215.6	180.4
Mean value per harvest (B)	172.41	59.7	24.8	61.8	212.98	77.5
Number of harvest (C)	4	9	7	7	6	8
Total Revenue D = (C*B)	689.6	537.3	173.6	432.6	1277.88	620
Gross profit E=(D-A)	**465.8**	**272.7**	**-55.7**	**195.8**	**1062.3**	**439.6**
Total labour input (# of man-days) F	161.9	161.9	206.1	206.1	184	184
Value of Total labour G= (F *1.50)	242.85	242.85	309.15	309.15	276	276
Net Profit = (E-G)	223.0	29.8	-364.9	-113.4	786.3	163.6

***Annualised (assumed 10 year life span for a permanent well)

The Welfare Impacts of Groundwater Irrigation

The annual per capita household food consumption expenditure is GHC 359.0 375.0, and 352.3 for non irrigators, shallow seasonal well, permanent well respectively. The annual per capita non-food consumption expenditure is 259.4, 304.3, and 217.8, for non irrigators, shallow seasonal well, and permanent well respectively.

The results show that seasonal shallow well irrigators have higher per capita household consumption expenditure (GHC 679.1) when compared with the non-irrigating households (GHC618.4). With the exception of the permanent irrigators, irrigating households have higher consumption expenditure relative to non-irrigating counterparts. This means that irrigating household are more likely to spend more on items such as housing (rent payment, repairs construction etc) utilities, fuel , clothing and other personal effects, durable/non durable goods, health/transportation cost, recreation/gifts/donation, and education. Thus irrigation households are more likely to experience a better material standard of living.

Conclusions

A number of conclusions have been drawn and recommendations made in various parts of the write-up. The following represent a summary of some conclusions and recommendations.

1. Non-irrigating household heads are much older than irrigating household heads. The relatively young age of farmers engaged in irrigations gives a strong indication that investing in irrigation development in the area has a potential of creating jobs for the youth. Youth unemployment is a major concern of government and other stakeholder in the area.

2. Non-irrigating household have the highest mean area of land put under rain fed cultivation (4.8 acres). It is possible that non-irrigating households as livelihood diversification strategy tend to put more rain fed land under cultivation to ensure household food security. This strategy further exposes them to the vagaries of the weather. Erratic rainfall has long been a source of concern to many farmers in the Upper East Region.

3. The poor soil fertility conditions in the area, has made application of inorganic fertilizers a must for all the irrigators. The high cost fertilizers have implication on cost of production. About 57.1 % of all cash spent on production goes into the purchase of fertilizers.

4. The gender composition of the households differentiated by irrigation typology cluster does not show any marked difference among the various irrigation typologies. The gender composition of a household is therefore not likely to be a determining factor of a decision to irrigate.

5. The profitability estimates suggest that shallow seasonal well irrigators do make some profit from engaging in the vegetable cultivation. However, the profits are very much dependent on prices, which are highly volatile. Intervention that will help address the high volatility of prices could go a long to improve the welfare of the shallow ground water irrigators.

6. Generally, irrigating households have higher household consumption expenditure than non -irrigating households. This is particularly prominent with respect to non-food expenditure on items such as housing (rent payment, repairs construction etc) utilities, fuel, clothing and other personal effects, durable/non durable goods, health/transportation cost, recreation/gifts/donation, and education.

OUTCOMES AND IMPACTS

This Project has put together along with IWMI, several partners from NARES (2iE, University of Ghana Legon, Water Research Institute (WRI), ARIs (ZEF-University of Bonn, DELFT-TU, West African Wetland Center (WCA)), Local development organizations (Water Resource Commission (WRC), Ghana Irrigation Department Agency (GIDA), MoFA, Regional Ministry)), Farmers and NGOs.

In the White Volta Basin, SGI is widely spread but not being accounted in the country official agricultural statistics. In rural areas a large number of people are involved in this dry season activity which generates a substantial income for a large number of smallholder farmers growing tomatoes and onion. This project has helped assess in the Atankuidi catchment, the potential of SGI and highlighted its benefits. Data generated through the project have enhanced agricultural statistics by providing information on acreage, production and income generated.

The project activities have helped map the potential of SGI in the study area. Possibility for farmers to increase their production by using just the right amount of water for irrigation along with the right agricultural practice was successfully studied and information has been shared with farmers and extension agency. Methodologies on how to use new technologies such as Remote sensing to assess SGI at a basin level were successfully developed and shared with NARES.

Based on the outputs of the SGI project, the international NGO, International Development Enterprise (IDE) has initiated a number of activities aimed at improving irrigation performance in the Project study area. IDE has planned to improved irrigation practices through the introduction and dissemination of simple but water efficient technologies. Because of the key role that SGI could play in improving food security and rural livelihoods, IDE intervention in northern Ghana and especially in the UER has focussed on improving water abstraction and delivery in areas where SGI is practised. The project study area (the Atankuidi catchment) was selected by IDE as one of their training sites for the drilling of tube-wells and introduction of drip irrigation kits. The selection was primarily based on the potential groundwater map developed by the project. Two tube-wells have successfully been developed in the lower section of the catchment at the Anateem location.

Development of tube-wells will facilitate the emergency of new local entrepreneurs at locations where SGI is practised. It will involve new abstraction methods such as treadle or motorized pumps to fully benefit from the technology. The introduction of tube-wells which are permanent water structures will significantly reduce the hard work of digging hand dug wells at the beginning of the cropping season and their refilling after harvest. The gain of time and the better yield that tube-wells provide could be used by farmers to increase their cropped acreage and better manage their crops.

- NARES Scientists from Burkina Faso and Ghana and other collaborators in both countries benefited from the wide range of information collected by the SGI project
- Project partners from Burkina Faso and Ghana gained experience in the methods and tools used for SGI analysis
- Various stakeholders including extension agents, and scientists have a better understanding of the extent of SGI in the White Volta Basin
- Partners from the national programs have deeper insights into farmers’ knowledge and perceptions about constraints to SGI.

Outcomes and Impacts

Summary Description of the Project's Main Impact Pathways

Actor or actors who have changed at least partly due to project activities	What is their change in practice? I.e., what are they now doing differently?	What are the changes in knowledge, attitude and skills that helped bring this change about?	What were the project strategies that contributed to the change? What research outputs were involved (if any)?	Please quantify the change(s) as far as possible
Research level: WRI	Now they use remote sensing and GIS for groundwater assessment and use. Previously they apply only biophysical features for mapping on specific location without drawing inferences on larger scales	Now knowledgeable and skillful on the application of remote sensing for assessing groundwater resources. They proceeded to purchase the required tools (GIS/remote sensing packages) to apply the acquired skill	Training and capacity development through customized training workshops The project developed Methodologies (conceptual model) on how to use Remote sensing to assess SGI at a basin level	Four WRI staff trained at two training workshops. Attitude changed is evident in their effort to acquire the necessary tools for subsequent application
Policy level: WRC	WRC so far ignored SG use in the development of the new buffer zone policy. Through the project implementation, now realized that application of the policy will push many farmers out of business. Therefore they are trying to ensure that the policy allows the contribution of SGW.	WRC is now better informed on the SGI through the statistics of the available GW show the extent of availability and key role in livelihood and food security. So new approach for the implementation of the policy is being proposed.	Sharing of information and research findings on shallow groundwater irrigation: Regular joint field visit to expose them to the issues around SGI	
NARES: GIDA	Now they have expanded their scope of irrigation to cover shallow groundwater as part of informal systems. Since 2008 cropping seasons, the GIDA extension workers have been	Through the project, they become better informed about the importance of SGI and their attitude changed	Stakeholder meetings (2) as well as regular joint field visits (up to 10) to present and discuss project findings: sharing of project findings (maps, presentations,	GIDA-initiated monitoring of SGI has already covered the UER

	mandated to monitor farmers use of SG		dissertations etc)	
Students	Can discuss SGI more competently	Acquired knowledge on the application of remote sensing in GWI assessment	Training and capacity development through involvement in the research	4 MSc 2 B.A 1 PhD (partial support)
NGOs: IDE	Use of maps as guide in drilling tube-wells	Acquired knowledge on the availability of groundwater in the study area	Sharing of project methodology and results. Filed visits.	Groundwater availability Maps produced from the conceptual model was used in training the community on drilling

Of the changes listed above, which have the greatest potential to be adopted and have impact? What might the potential be on the ultimate beneficiaries?

The use of developed maps as a guide in drilling tube-wells.

This responds directly to the beneficiary's need and apart from the farmers who are direct beneficiaries, local entrepreneurs can be involved in tube-well drilling there by reaching larger group of community members
It will benefit farmers by eliminating the hard labour and time involved in hand digging of wells
There will be reduction in risk of failure
Eliminate the problem of death trap when digging narrow shallow wells
Due to resulting high well yield, more land could be cropped and more time spend on crop management rather than deepening wells in search of water

What still needs to be done to achieve this potential? Are measures in place (e.g., a new project, on-going commitments) to achieve this potential? Please describe what will happen when the project ends.

IDE is successfully taking up the application of the research project results to ensure the above potential and impacts are achieved in the study area.

New project required to develop similar GW maps throughout the White Volta basin. It is important to have a long term monitoring of the water table which will help link extreme events (such as flood, drought, heavy rainfall etc) to groundwater recharge. For better planning of GW use, stochastic modeling approach would be the best. However this will require a long term series observation which a short term project cannot provide.

Each row of the table above is an impact pathway describing how the project contributed to outcomes in a particular actor or actors. Which of these impact pathways were unexpected (compared to expectations at the beginning of the project?)

The IDE related impact pathway

Why were they unexpected? How was the project able to take advantage of them?

IDE was not part of the project initially, so the immediate application of research results during the lifetime of the project was not envisaged. However, IDE heard about what we were doing and came around for help, hence the project too took advantage of this by ensuring that they include the project study area

What would you do differently next time to better achieve outcomes (i.e. changes in stakeholder knowledge, attitudes, skills and practice)?

Longer time for implementation (3-4years) would be better to allow to have a longer monitoring period of the water-table levels and collect more climatic and biophysical data to develop a stochastic model which would be more appropriate.

International Public Goods

The project has produced a number of scientific papers that provide a good understanding of SGI and its contribution on food security and rural livelihoods. The methods and analysis used during the project lifetime could easily be applied in other parts of the Volta Basin and the sub-region.

Tools and Methodology

The delineation of landuse/landcover (LULC) classes including SGI areas using a high resolution image (QuickBird) classified using an unsupervised classification algorithm (ISODATA) after which classes were merged using bi-spectral plots, intensive groundtruthing and Google Earth imagery to assess the extent of SGI. The method can also be applied with success to other form of irrigation.

The geophysical investigations (electromagnetic profiling using Geonics EM 34-3 and vertical electrical sounding using Abem SAS 1000 terrameter) for the determination of the underlying shallow aquifer geometry and subsequently the volume of water stored have proven to be an excellent tool which can be applied in other regions where SGI is practised.

Project Insights

The study revealed that irrigation application as practised by local farmers and which consists of pouring a limited volume of water (2.2l/m^2/day for the first 50days after transplanting and 5l/m^2/day at the flowering stage) in gutters where tomato plants are transplanted is water efficient. Very little amount of water is hence lost through evaporation or deep percolation with "Gutter irrigation". Because only very limited volumes of water are abstracted from the shallow hand-dug wells, localized irrigation like "gutter irrigation" is a highly efficient irrigation practice.

Partnership Achievements

IWMI: *(International Water Management Institute)*

Development of a numerical conceptual model for SGI in the Atankuidi basin
Socio-economic study of SGI in the Atanwidi catchment
Mapping of the SGI extent in the study area using high resolution images
Mapping of SGI potential in the Atankuidi catchment

DELFT-TU: *(Delft University of Technology)*

Exhaustive background information on the use and potentials of SGI and the description of the physical characteristics of the Atankuidi basin.
Estimation of the recharge rates of the shallow groundwater during wet season
Mapping of the flood plains multi-temporal satellite data together with the SOBEK-modeled DEM

WRI: *(CSIR/ Water Research Institute)*

Hydrogeology investigations using Geonics EM 34-3 and vertical electrical sounding using Abem SAS 1000 terrameter) for the determination of the shallow aquifer geometry, soil sampling and grain-size analysis for the determination of porosity and hydraulic conductivity, water sampling and laboratory analysis for water quality analysis for both drinking and irrigation.

CAW: *(Center for African Wetland)*

Identification and delineation of wetlands in the UER
Analysis of Wetlands contribution to poverty alleviation in the Kassena-Nankana District in the UER

ZEF: *(Centre for Development Research (ZEF), University of Bonn, Germany)*

Documentation of local knowledge of farmers in northern Ghana in relation to shallow groundwater occurrence
Analysis of local livelihood adaptation in Northern Ghana in response to ecological changes and economic challenges
Analysis of property rights and land access in north-eastern Ghana
Successfully coordinates and organizes two stakeholder workshops

WRC: *(Water Resource Commission)*

Monitoring of water able levels in the study area
Facilitation stakeholder workshops

2iE: *(International Institute for Water and Environmental Engineering)*

Documentation and assessment of Shallow Groundwater irrigation in the White Volta Basin

Recommendations

Long-term monitoring of groundwater levels is highly necessary to determine if water-table levels show a certain trend over time. Such information could give more insight into the sustainability of the groundwater level and therefore the possible extension of SGI in the Atankuidi catchment and the whole Volta Basin. Moreover, since extreme events such as heavy rains and floods largely determine groundwater recharge, a longer monitoring period of water-table levels could be used to figure out whether or not the availability of groundwater in the alluvial aquifer can be predicted based on rainfall patterns.

Due to the September 2007 floods a lot of farmers in the Upper east region, lost their rainfed harvest and did not have enough resources to start SGI in the following dry season. The total irrigated area was therefore smaller and this could have influenced some of the project results such as the total abstraction groundwater volume by farmers for irrigation. It could be useful to conduct the same research, possibly not only in the study areas but also in another catchment to out-scale findings to the whole of the White Volta basin. Research in other catchments can give information on the applicability and sustainability of SGI in those areas to enable more people to start dry season irrigation.

Market conditions determine the cultivation of mainly tomato. All farmers cultivate tomato and only a few farmers cultivate other crops next to tomatoes, but the total coverage of the area with tomatoes is 90%. Concerning market strategy and crop diseases it is interesting to study which other crops can be cultivated at a larger scale together with the suitability of the soil and water conditions in the valleys. Laube et al. (2008) stress the importance of crop diseases, environmental changes and market failures that show large limitations in the application of SGI. Since many factors determine the application of SGI it is important to take these aspects into account and ask for integration of these different aspects in further research.

It might also be useful to study if and how governmental involvement can be applied on SGI keeping in mind the key role that this dry season farming activity plays in food security and rural livelihoods. In many parts of White Volta Basin, it is the main source of income for many young farmers, who otherwise would have migrated south in search of a job during the long dry season.

Publications

1.1 BA Thesis:

Deiting Lukas, 2009: Property rights and access to land in Northeastern Ghana; BA Thesis Final report University of Bayreuth/ZEF Germany.

Fabian Lehmann, 2009: Local Knowledge of Farmers in Northern Ghana in Relation to Shallow Groundwater Occurrence. BA Thesis Final report University of Bayreuth/ZEF Germany.

1.2 MSc Thesis:

Joost van den Berg, 2008: Exploring shallow groundwater irrigation: current status and future application. A case study in the Atankuidi catchment, Ghana. MSc Thesis Final Report Delft University of Technology.

Andrej Nikolaev, 2009: Mapping of Floodplains in the Atankuidi River Basin. MSc Thesis Final Report Delft University of Technology.

Samuel Barnie, 2010: Hydrogeological and Hydrochemical Framework of Groundwater for Irrigation in the Atankuidi sub-basin of the White Volta Basin. MSc Thesis Final Report. KNUST-Ghana.

John Tawiah Aidoo, 2010: Study of Wetlands, Shallow Groundwater and Crop Production the in the White Volta Basin in the Kassena Nankana District in the Upper East Region. MSc Final report University of Ghana Legon.

1.3 PhD Thesis: (*partially funded by CP65*)

Benjamin Schraven 2010: Irrigate or migrate? Local livelihood adaptation in Northern Ghana in response to ecological changes and economic challenges. PhD. Final Report University of Bonn/ZEF Germany

1.4 Journal Articles:

M. Mdemu, W. Laube and B. Barry 2010: Temporal water productivity of tomato irrigated from a small reservoir and hand-dug wells in dry season cropping in the Upper East Region, Ghana in online Journal of Irrigation Zeitschrift für Bewässerungswirtschaft, 45. Jahrg., Heft 1 /2010, ISSN 0049-8602 Seiten 75 - 93

Gumma. M.K, Thenkabail. P.S, Barry. B., and Simon. S., 2010: Delineating shallow ground water irrigated areas in the Atankuidi watershed (Northern Ghana, Burkina Faso) using Quickbird 0.61-2.44 meter Data In African Journal of Environmental Science and Technology AJEST-10-052.

1.5 Research Reports: *(under review)*

Mawuli L., B. Barry, Gerald F., 2010: Modeling Groundwater Flow in the Atankuidi Catchment. IWMI *(STATUS: Under review)*

B. Barry, G. Murali, B. Kortatsi, G. Forkuor, R. Namara, J. Van Den Berg, W. Laube ,L-M. Rebelo, 2010: Understanding Shallow Groundwater Irrigation In The White Volta Basin: Current Extent And Future Sustainability. Iwmi *(STATUS: Under review)*

Regassa E. Namara, Joseph Awuni, and Boubacar Barry 2010: Autonomous smallholder shallow groundwater irrigation development in Upper East region of Ghana: analysis of socioeconomic impacts, constraints and opportunities. IWMI *(STATUS: Forthcoming)*

1.6 Book chapter

B. Barry, 2008: Puits Itinerants in Agricultures Singulieres Eric Mollard & Annie Walter, Chapitre 7 Fiche 46; IRD Editions Paris.

1.7 Field Reports

B. Kortatsi, B. Barry, 2010: Understanding Shallow Groundwater Aquifer: Case study in the Atankuidi Basin; WRI/IWMI

Jan Talsma, 2010: Exploring shallow groundwater recharge of the Atankuidi River Basin DELFT-TU.

D. Niang, A.H. Maiga, 2009 : Utilisation des eaux souterraines peu profondes pour l'irrigation dans le bassin versant de la Volta Blanche. 2iE Burkina Faso.

1.8 Conference Paper

R.E. Namara, J.Awuni, B. Barry 2010: Autonomous smallholder shallow groundwater irrigation development in Upper East region of Ghana. *Paper to be presented at: Towards Sustainable Groundwater in Agriculture: An International Conference Linking Science and policy,* **June 15-17, 2010, San Francisco, CA Hyatt Regency at the San Francisco Airport Burlingame, CA**

BIBLIOGRAPHY

Achard, F. and Estreguil, C., 1995, Forest classification of Southeast Asia using NOAA AVHRR data. Remote Sensing of Environment, 54, pp. 198-208.

Allaire, M., 2009, "Drought Mitigation in Semi-Arid Africa: The Potential of Small-Scale Groundwater Irrigation". SustainUs: U.S. Youth for Sustainable Development. http:sustainus.org/docs/citsci/winners/2009/Muara%20Allaire.pdf

Cihlar, J., 2000, Land cover mapping of large areas from satellites: status and research priorities. International Journal of Remote Sensing, 21, pp. 1093-1114.

Cihlar, J., Xiao, Q., Beaubien, J., Fung, K. and Latifovic, R., 1998, Classification by progressive generalization: a new automated methodology for remote sensing multichannel data. International Journal of Remote Sensing, 19, pp. 2685-2704

Eastman, R., J., 2006, IDRISI Andes Guide to GIS and Image Processing., Clark Labs, Cark University.

Eliason, E.M., McEwen, A. S., 1990, Adaptive Box Filters for Removal of Random Noise from Digital Images, *Photogrammetric Engineering and Remote Sensing,* 56(4): 453-458.

Environmental Protection Agency of Ghana; World Bank (1999) Ghana: Country at a glance (G-CAG) - Data description and instructions for the use of the G-CAG, Final Report, Environmental Protection Agency of Ghana, Accra

Fosu, M., 2004, The soil resources of GLOWA experimental site at Pungu, near Navrongo, Upper East Region, Ghana, Unpublished.

Fuller, R. M., Groom, G. B., Mugisha, S., Ipulet, P., Pomeroy, D., Katende, A., Bailey, R., and Ogutu-Ohwayo, R., 1998, The integration of field survey and remote sensing for biodiversity assessment: a case study in tropical forests and wetlands of Sango bay, Uganda. Biological Conservation, Vol. 86, pp. 379-391

Ghana Irrigation Development Authority (GIDA)/ Japan International Cooperation Agency (JICA) (2004) *Technical guidelines for irrigation Agriculture.*

Giesen, N., 2001, Characterization of West African Shallow Floodplains With L- and C-Band Radar., *Remote Sensing and Hydrology, no. 267, 2001.*

Gopal, S., and C.E. Woodcock, 1994, Theory and Methods for Accuracy Assessment of Thematic Maps Using Fuzzy Sets, Photogrammetric Engineering and Remote Sensing, 60(2):181-188.

Groom, G. B., Fuller, R. M., and Jones, A. R., 1996, Contextual correction: techniques for improving land cover mapping from remotely sensed images. International Journal of Remotesensing, Vol. 17, pp. 69-89

GSS, 2002, 2000 Population and Housing Census. Summary Report of Final Results. Ghana Statistical Services. Accra.

Gumma, M. K, Thenkabail, P. S., GangadharaRao,T. P., Nalan, S. A., Velpuri, N. M., and Biradar, C., 2009. Agriculture Cropland Change Response to Water availability using Spectral

Matching Techniques in the Krishna River Basin (India). *International Journal of Remote Sensing*, TRES PAP-2009-0162. (Review)

Harbaugh, A.W., and McDonald, M.G., 1996, User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 96–485, 56 p.

IRIN, 2010, *Ghana: 'Nearly 275,000' Affected by Floods in Little-Known Disaster.* [Online]: http://www.irinnews.org/report.aspx?ReportID=74278 [Accessed January 28th 2010]

Liebe, J., R., Giesen, N., Andreini, M., S., Steenhuis, T., S., Walter, M., T., 2008, *IEEE Transactions on Geoscience and Remote Sensing.*

Lillesand, T. M., Kiefer, W. R. and Chipman, J. W., 2004, Remote Sensing and Image Interpretation (USA: John Wiley and Sons, Inc.)

Markham, B. L., and Barker, J. L., 1986. *Landsat MSS and TM Post-Calibration Dynamic Ranges, Exoatmospheric Reflectances and At-Satellite Temperatures,* Earth Observation Satellite Co., Lanham, MD, Landsat Technical Notes, 1, Aug 1986.

Martin, N. and van de Giesen, N., 2005, Spatial distribution of groundwater production and development potential in the Volta River Basin of Ghana and Burkina Faso. Water International, 30, pp. 239-249.

Martin, N., 2006, Development of a water balance for the Atankuidi catchment, West Africa –A case study of groundwater recharge in a semi-arid climate. Ecol. and Dev. Series No. 41. Center for Development Research, Bonn.

Mather, P. M., 2004, Computer Processing of Remotely-Sensed Images: an Introduction (Chichester: John Wiley and Sons).

McNeil, J. D., 1980, General Theory of Terrain Conductivity Mapping Using Inductive Electromagnetic Techniques, Technical Note TN-6, Geonics Ltd., Ontario.

Mdemu, M., Laube, W. and Barry, B., 2009, Temporal water productivity of tomato irrigated from a small reservoir and hand-dug-wells in dry season cropping in the Upper East Region, Ghana. [*In press*]

Obuobie, E., 2008, Estimation of Groundwater Recharge in the Context of Future Climate Change in the White Volta River Basin, West Africa. Ecol. and Dev. Series No. 62, Centre for Development Research, Bonn.

Schaap, M.G., Leij, F.J., van Genuchten, MTh., 2005, ROSETTA: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. J. Hydrol. 251, 163-176.

Thenkabail, P.S., Enclona, E.A., and Ashton, M.S., 2004, Hyperion, IKONOS, ALI, ETM+ sensors in the study of African rainforests, *Remote Sensing of Environment,* 90: 23-43.

Thenkabail, P.S., Schull, M., & Turral, H., 2005, Ganges and Indus River Basin Lan Use/Land Cover (LULC) and irrigated area Mapping using Continuous Streams of MODIS Data. *Remote Sensing of Environment*, 95(3):317-341

Tucker, C.J., Grant, D.M. and Dykstra, J.D., 2005, NASA's global orthorectified Landsat data set. *Photogrammetric Engineering & Remote Sensing*, 70, pp. 313-322

Van den Berg, J., 2008, Exploring shallow groundwater irrigation: current status and future application. Msc Thesis. Delft University of Technology.

van Genuchten, MTh., 1980, A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J., 44, 892-898.

Vukovic, M. and Soro, A., 1992, Determination of Hydraulic Conductivity of Porous Media from Grain-Size Composition. Littleton, Colorado: Water Resource Publications

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Appendix A

MODELLING SHALLOW GROUNDWATER FLOW IN THE ATANKUIDI CATCHMENT

Mawuli Lumuor [1], Boubacar Barry [2] and Gerald Forkuor [2]

ABSTRACT
Shallow groundwater irrigation (SGI) is a fast growing dry season activity in the White Volta Basin. Although application of SGI goes back to the 1960s, it has been noticed during the last decade, that more and more hand-dug shallow wells are being dug throughout the upper parts of the White Volta basin. Water is abstracted from these seasonal shallow wells by means of buckets or pumps to irrigate small plots generally cultivated with tomatoes. SGI is mainly carried out in inland valleys, in alluvial material along the dry riverbeds. Water table is often shallow and with a little investment but with hard physical labour farmers can cultivate crops during the long dry season.

Geophysical as well as groundwater and irrigation data were collected and analyzed. A conceptual model was developed using MODFLOW-3D for the Atankuidi watershed which is a sub-catchment of the White Volta basin with the highest groundwater intensity use. Scenarios looking at the impact of irrigation abstraction increase of 50, 75 and 100% on the water table levels during the cropping season and on the overall volume of storage of the 3-layered aquifer are analyzed and discussed.

The model outputs show that with the current practice, that indirect recharge due to extreme events such as high intensity rainfalls and recurrent floods could be the main source of shallow groundwater renewable. It also indicates that abstractions for irrigation lead to a fast drawdown of the water table which in turn requires from SGI-farmers to continuously keep deepening their wells. With the current practice, only a small fraction of the total storage volume of the second layer is abstracted for irrigation but with a significant increase of the abstraction some portion of the second layer dry up either because of the small thickness at some specific locations or because of the intensive irrigation due to the sandy nature of the soils in some locations. The third layer remains generally untapped because it is too deep and very hard to reach with the tools used for hand-digging.

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UNDERSTANDING SHALLOW GROUNDWATER IN THE WHITEVOLTA BASIN: CURRENT EXTENT AND FUTURE SUSTAINABILITY

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Abstract
Over the past years, recurrent droughts /spells or frequent floods have led to food insecurity and increasing poverty in most of northern Ghana where formal irrigation benefits only a limited number of farmers. In the White Volta basin, and particularly in the Upper East Region (UER), hundreds of rainfed smallholder farmers began developing their own irrigation systems abstracting shallow groundwater in the lowlands and from the dry river beds of two tributaries of the White Volta River Basin - Atankuidi and Anyere.

This report presents findings of a detailed study conducted in the Atankuidi catchment aimed at (1) delineating shallow groundwater irrigated (SGI) areas using high resolution images, (2) determining the volume and quality of water available in storage in the underlying shallow aquifer and (3) assess water productivity for tomato production during the dry season.

Standard methodologies were used to delineate landuse/landcover (LULC) classes including SGI areas using a QuickBird image acquired in May 2008. The image was classified using an

unsupervised classification algorithm (ISODATA), after which classes were merged using bi-spectral plots, intensive groundtruthing and Google Earth imagery. Geophysical surveys (electromagnetic profiling and vertical electrical sounding) were conducted to determine the geometry of the underlying aquifer, and subsequently the volume of water stored. Water productivity was assessed by using five plots transplanted with tomato and irrigated from a monitored hand-dug well and dug-out. Plot sizes varied from 0.03 to 0.13 ha. Interviews were held with farmers and observations were made of their actions in the field.

Results obtained indicate that SGI is practised exclusively on low land areas and on fluvisols along the river bed on 387 ha (1.4%), rainfed areas is 15638 ha (54.7%), with the remainder being other LULC types. Comparison of this results with previous work in which a 2005 Quickbird image was analyzed indicate that SGI areas have increased by a factor of six (6) in three years. This suggests a real expansion of SGI in the Atankuidi catchment.

Results of the geophysical surveys revealed that the thickness of the underlying aquifer varies from 2.6 m to 13.7 m. The aquifer has low resistivity in the range 3.2-55.3 ohm-m suggesting high clay content The total volume of water that can be stored annually in the underlying aquifer was estimated to be approximately 3.7×10^{9} m^3, which is by far more than what is actually applied for irrigation (2 liters/day/m^2 at planting stage and 5 liters/day/m^2 at flowering stage). The quality of the water was found to be safe for drinking and irrigation, although bacteriological analysis was not performed.

WP in Atankuidi was found to be high, mainly influenced by a high crop yield, which, in turn, is caused by high soil fertility. Plots in the Atankuidi catchment, since the late 1990s, are cropped only during the dry-season every year, contrary to practice in other sites where plots are constantly cultivated throughout the year.

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Autonomous smallholder shallow groundwater irrigation development in Upper East region of Ghana: analysis of socioeconomic impacts, constraints and opportunities

Regassa E. Namara[1], Joseph Awuni[2], and Boubacar Barry[1]

The socioeconomic impact of practicing shallow groundwater irrigation in Upper East region of Ghana has been assessed using data from 420 farmers. Upper East region is the most populous of the three poorer Northern regions of Ghana including Brong Ahafo region. The population density per square kilometre of Upper East region is more than three times that of Northern and Upper West regions. The higher population density coupled with uni-modal rainfall with seven months of extended dry season might have triggered the adoption of innovations such as shallow groundwater irrigation. Tomato and pepper are the two main crops produced. The cultivation of these crops under shallow groundwater irrigation is generally profitable, particularly when the value of labour involved in the cultivation process is not considered. The economics crop cultivation using shallow groundwater is influenced by the extreme volatility of vegetable crop prices particularly that of Tomatoes, and the various production risks farmers' face (e.g., crop pests and diseases).

The effect of access to shallow groundwater on level of poverty and inequality was assessed using the FGT indices and Lorenz curve respectively. Inspection of the shape of the Lorenz curve depicted that income disparity among sample households was not that pronounced implying that income distribution is not priority policy issue in this part of Ghana. Rather interventions that improve income are highly recommendable. Regarding poverty impact, the poverty incidence among sample farmers is by far above the National average figure, re-enforcing the widely held view that poverty level is severe in the Northern Ghana regions. It is also confirmed that the incidence poverty among households with access to shallow groundwater irrigation is lower as compared to purely rain-fed farmers. Only 1.2% of the sample households reported adequate food availability all year round. In any given month, slightly lower proportion of households with access to shallow groundwater irrigation reported food shortage. Moreover, these farmers tend to have more diverse diets as compared to rain-fed farmers. The months of April, May and June are months of severe food shortage, particularly for farmers with no access to any kind of irrigation.

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Temporal water productivity of tomato irrigated from a small reservoir and hand-dug-wells in dry season cropping in the Upper East Region, Ghana

M. Mdemu[1], W. Laube[1] and B. Barry[2]

Abstract

In the Upper East Region of Ghana high population growth coupled with the impacts of climate and land-use change have led to an increasing demand for water resources. As the yields of rain-fed agriculture are decreasing and become increasingly unreliable a large number of farmers have started to engage in the production of dry-season vegetables. Thereby they are increasing the scarcity of already limited water resources of this semi-arid part of Ghana. The problems of water scarcity can be partly tackled by improving water productivity (WP) in agriculture, the largest consumer of water in the region. In order to better understand water productivity, this study assesses water productivity (WP) in three different forms of irrigated dry-season tomato production. Tomatoes are produced in medium and small-scale irrigation systems where water is provided by gravity as well as in small vegetable gardens where farmers fetch water from hand-dug wells. Irrigation water supply to sample study plots was measured using V-notch weirs at the irrigation systems and a mechanical water-flow-meter at the vegetable gardens. Potential and actual crop water use were determined as soil water balance components in SWAP model for reservoir-irrigated plots and numerically estimated for hand-dug-well irrigated plots. Crop WP was estimated as a ratio of crop yield to: irrigation supply, potential and actual crop water use. Gross margins and returns per unit land and water were also estimated based on costs of the farming inputs. WP at the medium-scale irrigation system was relatively lower than that at small-scale system. This highlights the potential of improving water productivity in medium-scale parameters. The gross margins showed that, hand-dug-wells were more water-productive than the medium and small reservoirs.

Keywords: Gross margins, land and water scarcity, irrigation, semi-arid environments, water productivity, water reservoir.

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Delineating the shallow ground water irrigated areas in Atankuidi watershed using high resolution satellite data: Case study in the Volta River Basin, West Africa

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Abstract:
The major goal of this research was to delineate the shallow groundwater irrigated areas in the Atankuidi watershed in the Volta River Basin of West Africa. Very high resolution imagery offers widely acceptable characteristics to increases the ability to map shallow ground water irrigated areas with high accuracy. We adopted standard methodologies to delineate land use classes including shallow groundwater irrigated areas. Outputs from high resolution classification

successfully separated rainfed agriculture and shallow groundwater irrigated areas with high accuracy. High resolution satellite imagery is potentially useful for delineating patchy shallow groundwater irrigated areas with shallow ground wells. Results obtained indicate that shallow groundwater irrigation is practised on a land area of 387 ha (1.4%), rainfed areas is 15638 ha (54.7%) and the remaining being other landuse/landcover types. These results were verified using field-plot data which showed accuracy between 92% with errors of omissions and commissions less than 10%.

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Autonomous smallholder shallow groundwater irrigation development in Upper East region of Ghana

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Abstract

In sub-Saharan Africa in general and in Ghana in particular groundwater resource is associated with domestic use. There is paucity of information on groundwater resource potentials and the limited information that is available based on data from specific aquifers indicates a pessimistic view about the groundwater resources in Ghana. Moreover, the agricultural use of groundwater is not reflected in the country's water and irrigation policy. Contrary to the official knowledge, farmers have started using shallow groundwater to produce horticultural crops. In Upper East region, the groundwater infrastructure is developed using extremely rudimentary digging/drilling technologies banking on the abundant human labour during the long dry season. This paper analyses: (1) the economics of smallholder groundwater irrigation, (2) food security and poverty outreach of access to groundwater resource, and (3) constraints and opportunities of smallholder groundwater irrigation systems. The paper is based on data generated from 420 farmers in 35 communities distributed in three micro-watersheds of the White Volta basin in Upper East region of Ghana. These communities are divided into 2085 compounds harbouring 4576 households and 20,962 people. Of the total 4576 households found in the area, about 61% are practicing irrigation of one sort or the other. Of those practicing irrigation, about 89.9% are using shallow groundwater. The rest are using small dams, river and drainage water. Even though, the agricultural use of groundwater had significant positive livelihood impacts further development and productivity is constrained by complex land tenure issues, lack of access to efficient drilling technology, marketing challenges, and the general lack official support services such as extension and micro-credits.

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