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Agro-climatic and Hydrological Characterization of Selected Watersheds in Northern Ghana

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IWMI International Water Management Institute

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ILSSI is a five-year research project that aims to benefit farmers in Ethiopia, Ghana and Tanzania by improving the effective use of water through interventions in small-scale irrigation. The project is identifying entry points for creating opportunities for farmers and other actors in irrigation through field interventions, and conducting assessments for scaling up technologies and practices within the context of market and environmental sustainability.

The Africa RISING program aims to provide pathways out of hunger and poverty for smallholder families through sustainably intensified farming systems that sufficiently improve food, nutrition and income security, particularly for women and children, and conserve or enhance the natural resource base.

Collaborators

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Contents

Summary

This paper provides the climatic and biophysical context of three watersheds in northern Ghana - Anyari and Zanlerigu in the Upper East region and Bihinaayili in the Northern region. The objective of the study is to describe the agro-climatic and hydrological features of the watersheds from a landscape perspective, which can be used as baseline information for intended water management interventions towards agricultural intensification. The work builds on primary and secondary data to characterize the watersheds, including historic climate analysis, watershed delineation, soil and land cover mapping, soil and water quality analysis, and characterization of agricultural production systems. The climate analyses show that average annual rainfall is close to 1,000 mm y^{-1} and no significant trend was observed. An increasing trend for potential evaporation is significant only in the Bihinaayili watershed. Temporally, a water surplus occurs about 3 months in a year, with only one month providing a significant surplus. Farmers in all three watersheds typically grow cereal crops during the rainy season for household consumption, whereas vegetable production during the dry season is typically sold at the local markets. Irrigation in the three sites is carried out between November and June. Shallow wells and small reservoirs provide water for irrigation during the dry season in the Anyari and Zanlerigu catchments. However, these sources of water dry up at the end of the dry season. Farmers in the Bihinaayili watershed have year-round access to water from the Libga Reservoir. The quality of water from wells, reservoirs and rivers in the three watersheds is good for irrigation and domestic purposes. The soil chemical parameters across the study sites show that salinity is not a concern and the soils are suitable for irrigation and crop system intensification, although it requires substantial fertilizer inputs. The textural classification suggests that soils in all the sites would be ideal for surface irrigation and other pressurized irrigation systems, because they are dominated by clay loam and sandy clay loam soils. We conclude that there appear to be opportunities from both a soil quality and water availability perspective to enhance sustainable intensification through small- and medium-scale irrigation in the selected watersheds.

1. INTRODUCTION

Agriculture is the mainstay of the livelihoods of the people in northern Ghana. Studies conducted over the years suggest there is high potential for agricultural intensification on existing land, as well as by expanding the irrigated and cropped area through irrigation and other agricultural interventions in Ghana. Multiple reports suggest that the irrigation potential in Ghana is close to 3 million hectares (Mha), but only 1.5% of the arable land is currently under formal and informal irrigation because of the initial high cost of irrigation equipment (FAO 2016; Krautstrunk 2012; Namara 2012; Obuobie et al. 2013; Namara et al. 2014). Water is a key limiting factor for agricultural production and productivity in the three northern regions of Ghana (Northern, Upper West and Upper East regions), which are characterized by a unimodal rainy season with intra-season droughts and a poorly developed irrigation sector (MoFA 2011; de Fraiture and Giordano 2014; Giordano and de Fraiture 2014; Namara et al. 2011; Namara et al. 2014). Water storage solutions and small-scale irrigation technologies offer greater security to agricultural production and productivity, and expand the options for sustaining livelihoods of smallholder farmers. Over the years, the Government of Ghana and nongovernmental organizations (NGOs) have provided some irrigation facilities to help boost agricultural production (Inkoom and Nanguo 2011).

Ghana receives an average annual precipitation of 283 x 10^9 m^3 y^{-1} and total actual renewable water resources are 54.9 x 10^9 m^3 y^{-1} (FAO 2016). In Ghana, per capita renewable water resources availability is about 2,500 m^3 y^{-1} and total dam capacity is estimated at 150 million cubic meters (Mm^3) (Namara et al. 2010). With 60% of the economically active population employed in the agriculture sector, with the majority practicing rainfed agriculture, the prevalence of poverty is very high in the region (Diao 2010). The phenomenon of food insecurity in northern Ghana could be mitigated by improving and upscaling agricultural water management technologies to make water available and accessible to smallholder farmers (FAO 2016). Water storage, which can assist in production during the dry season, increases resilience and allows farmers to invest in their land and diversify agricultural activities (Payen et al. 2012). Water can be stored in small and large reservoirs such as on-farm ponds, shallow groundwater or wetlands (McCartney et al. 2013). Shallow groundwater is an efficient way of storing excess rainfall and runoff (Namara et al. 2011). In many areas in northern Ghana, shallow groundwater is the farmers' preferred water source (Molden 2007; Namara et al. 2011). Small reservoirs and dugouts are in high demand in northern Ghana because they support multiple livelihood strategies, such as livestock, irrigation, fisheries and domestic use (van de Giesen et al. 2002; Blench 2007; Birner 2008; Namara et al. 2010). Permanent shallow wells are also widespread in several communities in northern Ghana (Lamptey et al. 2009; Payen et al. 2012). To understand the dynamics of watershed hydrology, climate, soil characteristics and agricultural production practices in northern Ghana, with a view to enhancing irrigation and water resources development and management, field studies and a literature search were conducted in three watersheds in northern Ghana (Anyari and Zanlerigu in the Upper East region and Bihinaayili in the Northern region). The aim of the studies was to:

(1) delineate the watershed, and to develop land cover, soil and river system maps to assist with decision making on potential water management interventions;

(2) document existing agricultural water management practices in the three watersheds in order to identify opportunities for sustainable agricultural intensification through water management interventions;

(3) conduct dryspell analyses to identify constraints to rainfed crop production; and

(4) evaluate soil and water quality data for suitability for agricultural use.

2. METHODOLOGY

2.1 Secondary Data Collection

Background information was obtained from various sources, including journal papers, books, theses, research reports and working papers; offices and Agricultural Extension Agents (AEAs) of the District Agricultural Development Units (DADUs) of Savelugu, Nabdam and Kassena-Nankana districts; Ghana Meteorological Agency; Hydrological Services Department, Ghana; past and ongoing projects; and online resources. Secondary data such as rainfall and potential evaporation, collected from the GLOWA Volta project, were analyzed through a desktop study (GLOWA Volta database). Additional spatial data were compiled using data from the Volta River Basin (Mul et al. 2015) and synthesized for the study catchments at hand.

2.2 Characterization of the Watersheds

Three hydrological watersheds were delineated - Anyari, Zanlerigu and Bihinaayili watersheds. Detailed information is collected from project sites located in six communities in these watersheds[1]. Nyangua, Tekuru and Dimbasinia project sites are located within the Anyari watershed. Duko and Bihinaayili project sites are located within the Bihinaayili watershed, and Zanlerigu project site within the Zanlerigu watershed (Figure 1). The delineation was done using the Soil and Water Assessment Tool (SWAT) watershed delineation model, based on the Shuttle Radar Topography Mission (SRTM) 90 m resolution Digital Elevation Model (DEM) (Arnold et al. 1998; Rabus et al. 2003). The delineated watersheds served as the spatial boundaries for which hydrological and agricultural data were collected for the project sites. Land use and soils were mapped according to the delineated watershed boundary, using data from FAO-IIASA-ISRIC-ISS-CAS-JRC (2012) and Mul et al. (2015) with a 1 km resolution.

Further characterization of the watersheds was done by analyzing the basic climate and hydrological data collected for the three watersheds. None of the watersheds had a weather station and therefore data from the nearest weather stations were used for the analyses. Data from the Tamale, Zuarungu and Navrongo weather stations were used for the Bihinaayili, Zanlerigu and Anyari watersheds, respectively (GLOWA Volta database).

Due to missing records in the dataset, the period for which records were obtained for the three weather stations differed (Table 1). Prior to the analysis, the daily climate data collected from the three weather stations were cleaned and the quality controlled (QC) using the QC tool in the RClimdex software (Zhang and Yang 2004). Monthly and annual statistics and times series were computed from the daily data using the Microsoft Excel software package.

[1] Three communities (Tekuru, Nyangua and Duko) have project sites for the Feed the Future Africa RISING program, and three communities (Dimbasinia, Zanlerigu and Bihinaayili) have project sites for the Feed the Future ILSSI project with support from the United States Agency for International Development (USAID).

FIGURE 1. Locations of soil and water sampling sites in (a) Anyari, (b) Zanlerigu, and (c) Bihinaayili watersheds.

(a) (b) (c)

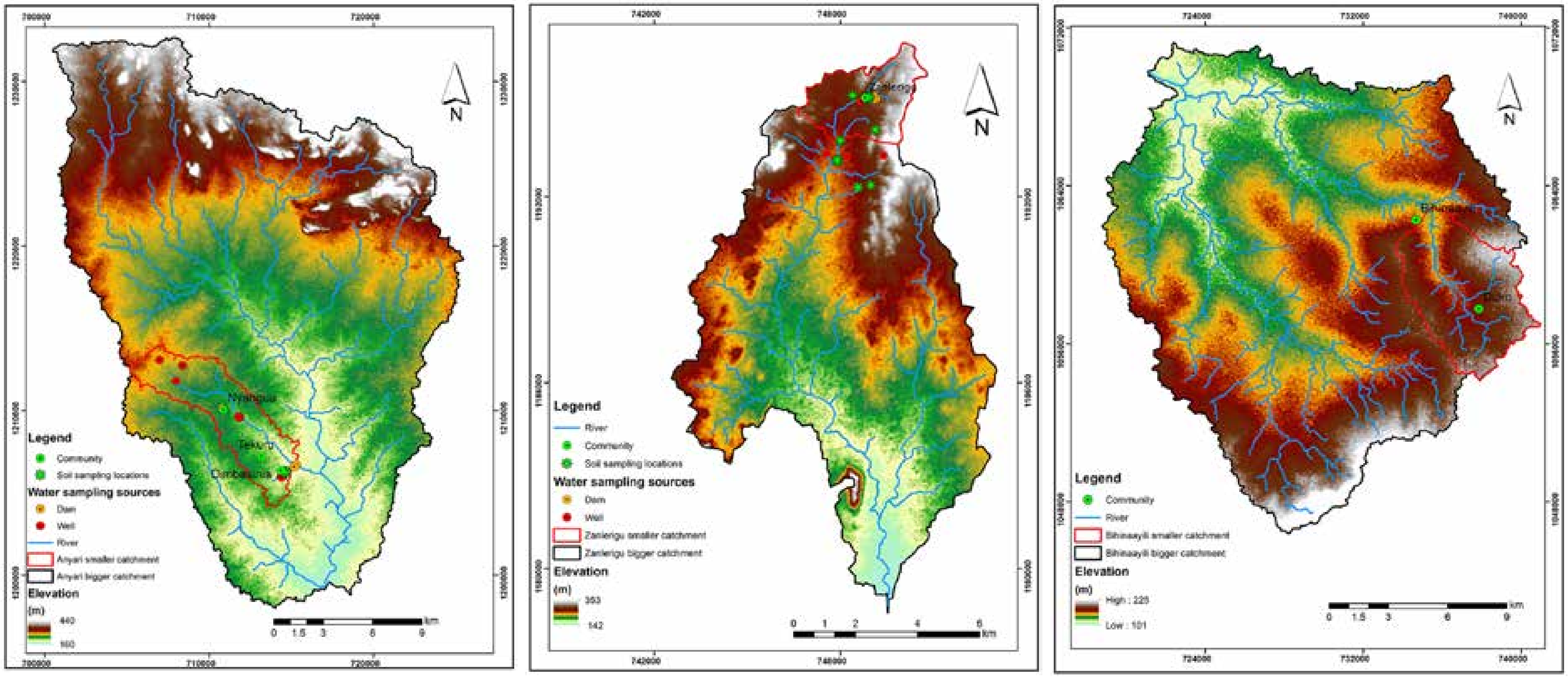


TABLE 1. Weather metadata for three weather stations in northern Ghana.

Station	Coordinates			Time period (years)	Resolution	Parameters available	Missing data (%)
	Latitude	Longitude	Elevation (m)				
Tamale	9.550	-0.850	181	1960-2012 (R) 1981-2012 (T)	Daily	Rainfall (R), temperature (T)	3.00
Navrongo	10.900	-1.100	201	1960-2012 (R) 1994-2012 (T)	Daily	Rainfall (R), temperature (T)	0.51
Zuarungu	10.783	-0.800	214	1939-2012 (R) 1994-2012 (T)	Daily	Rainfall (R), temperature (T)	2.05

Source: GLOWA Volta project.

In the absence of a full dataset on climatic parameters, the Penman-Monteith equation for potential evapotranspiration (*PET*) could not be calculated (Penman 1963; Monteith 1965). *PET* was therefore estimated using the Hargreaves method given by Hargreaves and Samni (1985), which only requires temperature as input:

$$ET_o = 0.0023 \text{ x } (T_{mean} + 17.8) \text{ x } (T_{max} - T_{min})^{0.5} \text{ x } R_a \quad (1)$$

Where: ET_o is the potential evapotranspiration (mmd^{-1}), R_a is the extraterrestrial radiation (MJm^{-2}d^{-1}), T_{max}, T_{min} and T_{mean} are the maximum, minimum and mean temperatures for a given day, respectively (^{o}C).

Non-parametric trend and homogeneity tests were carried out on the time series. Trend analysis was done using the Mann-Kendall Test (Mann 1945; Kendall 1975), while the Pettitt test (Pettitt 1979) was used to detect inhomogeneity in the time series. For the Mann-Kendall test, the null hypothesis, H_0, is the absence of a trend, while the H_1 hypothesis is the presence of a trend. The test statistic, *S*, is calculated as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign\ (Y_j - Y_i) \quad (2)$$

The sign of *S*, positive or negative, determines whether there is an increasing or decreasing trend, respectively. When *S* is zero it implies that no preferential order exists in the observations. The *p*-value obtained during the analyses can be compared to the level of significance (α), and in this case, the *p*-value must be less than α for there to exist a significant trend or to reject the null hypothesis.

2.3 Dryspell Analysis

Agricultural productivity does not solely rely on the total seasonal rainfall amount during the cropping season, but also on the distribution. The possibility of dryspells occurring within a season is sometimes an even more important factor affecting production and productivity. For dryspell analysis, a dry day is defined as a day with less than 0.85 mm d^{-1} of rainfall, while a dryspell is defined as a period with consecutive dry days once the cropping season begins. Probabilities of dryspell lengths of 7, 14 and 21 days were chosen as they represent important decision-making information for smallholder farmers. Dryspell lengths exceeding 7 days require sufficient soil moisture storage, exceeding 14 days require supplementary irrigation and exceeding 21 days require full-scale irrigation to prevent crop failure. The dryspell analysis was conducted based on work carried out by several researchers (Barron et al. 2003; Mul et al. 2017). The probabilities of dryspells of different lengths were calculated from the start date of the rainy season for a 120-day growing season.

Long-term dryspell analysis was carried out using INSTAT+ version 3.37, a general statistical package developed by the Statistical Service Centre at the University of Reading, UK (Stern and Knock 1998). The start of the cropping season (sowing date) is assumed to coincide with the onset of rainfall in northern Ghana, and is defined as the first day after the 1st of April each year when total rainfall for three consecutive days is greater than 20 mm with no dryspell lasting 7 days or more in the following 10 days. Rainfall data dating back to 1960 from weather stations located in Navrongo, Zuarungu and Tamale were used for the analyses.

2.4 Field Data Collection and Validation of Secondary Data

Secondary data sources did not provide the full set of data required. Therefore, field visits were made to the three watersheds during the period August 24-29, 2015, to collect additional information on agricultural and farming systems through focus group discussions, and to validate the information gathered from the various secondary sources. During the field visits, interviews were held with available farmers and other water users in the watersheds, as well as with the agricultural extension agents responsible for the three project areas.

Additional data on water quality and soils were collected in the study sites within the watershed to assess their suitability for agricultural use.

Water samples were collected from shallow wells, rivers and reservoirs across the six communities (Dimbasinia, Tekuru, Nyangua and Zanlerigu in the Upper East Region, and Bihinaayili and Duko in the Northern Region). Sampling was designed to cover both the wet and dry seasons. Samples were collected in April 2015 just before the wet season, while additional samples were collected in October 2015 after the rainfall (Kadyampakeni et al. 2017). For each sampling event, a number of water samples were taken from each water source type (shallow and deep wells, rivers and reservoirs) (Table 2; Figure 1). Not all the selected sites could be sampled during the two sampling campaigns. Temporal wells collapsed or were abandoned during the rainy season and could not be sampled in October. Two of the reservoirs dried up during the dry season and no sample could be collected in April.

TABLE 2. Description of sampled water sources.

Watershed	Water source	Volume (m^3)	Depth (m)	April 2015	October 2015	Samples*
Anyari	Nyangua Reservoir	25,000		Yes	Yes	4
	Nyangua permanent wells		10-20	Yes	Yes	12**
	Dimbasinia Reservoir	25,000		No	Yes	6
	Dimbasinia temporal wells		8-12	Yes	No	13**
Zanlerigu	Zanlerigu Reservoir	20,000		Yes	Yes	4
	Zanlerigu temporal wells		2-5	Yes	No	12**
Bihinaayili	Libga Reservoir	5,800,000		Yes	Yes	10***
	Duko permanent wells		5-8	No	Yes	5**

Notes: * Number of samples taken per sampling event.

** Each sample was collected from a different well.

*** Samples taken from the river located downstream of the reservoir.

The sampling and analytical procedures followed the Global Environment Monitoring System (GEMS)/Water Operational Guide (WHO 1992). Samples were collected and filtered into 1.5 liter (L) acid pre-cleaned, high-density, polyethylene bottles to remove suspended solids. The samples were sealed and stored in ice chests with ice to maintain a low temperature (<4 °C) and transported to the Environmental Chemistry Laboratory of the Council for Scientific and Industrial Research - Water Research Institute (CSIR-WRI) in Accra, Ghana, for analysis.

Electrical conductivity (EC) and potential of Hydrogen (pH) measurements were carried out using EC and pH meters, which were calibrated prior to making a note of the readings. A flame photometric method was used to determine sodium ions (Na^{+}) and potassium ions (K^{+}), while Ethylenediaminetetraacetic acid (EDTA) titration was used to determine calcium ions (Ca^{2+}) and magnesium ions (Mg^{2+}). Fluoride was determined using the SPADNS method recommended by the United States Environmental Protection Agency (US EPA), while ferric ions (Fe^{3+}) and aluminum ions (Al^{3+}) were measured by the flame atomic absorption spectroscopy (AAS). The water quality was compared to the water quality standards for irrigation water use to assess the suitability of using water for irrigation purposes (Ayers and Westcot 1994).

Soil samples were collected to determine the key characteristics (soil texture, chemical properties). The analysis was conducted to determine soil texture and salinity, as well as soil nutrient retention and exchange capacities. Soil sampling was carried out in April 2016. Soil samples were collected from experimental fields in Nyangua and Tekuru, and also from intervention, control (mixed sample) and homestead gardens in Zanlerigu, Dimbasinia and Bihinaayili. The soil samples were analyzed for the following parameters: pH, EC, soil texture, organic carbon, total nitrogen, available phosphorus, potassium and cation exchange capacity (CEC). Soil samples were collected at depths of 0-15 cm, 15-30 cm, 30-45 cm and 45-60 cm. Table 3 provides details of the sampling locations.

TABLE 3. Soil sampling protocol in the three study watersheds.

Community/ Watershed	Number of samples	Depths	Treatments			Sites
			Crop types	Nutrients	Water	
Zanlerigu/Zanlerigu	84	0-15 15-30 30-45 45-60	Onion Onion Cowpea	2 nutrient treatments	Water can Tank and hose Drip irrigation	8 8 5
Dimbasinia/Anyari	64	0-15 15-30 30-45 45-60	Tomato	1 nutrient treatment	Drip irrigation	16
Nyangua/Anyari	108	0-30	2 crops (okro and pepper) 3 crop varieties	3 nutrient treatments	Water can Drip irrigation	3
Tekuru/Anyari	106	0-30	2 crops (okro and pepper) 3 crop varieties	3 nutrient treatments	Water can Drip irrigation	3
Bihinaayili/Bihinaayili	64	0-15 15-30 30-45 45-60	corchorus	2 nutrient treatments	Water can Tank and hose	8 8

Notes: * Number of samples taken per sampling event.

** Each sample was collected from a different well.

*** Samples taken from the river located downstream of the reservoir.

Four hundred and twenty six (426) soil samples were collected in all. The auger bit was attached to a drill rod extension, and then the T-handle was attached to the drill rod. Debris (e.g., rocks, litter, twigs) was cleared from the area to be sampled. Surface debris was removed before the sample was collected. After reaching a depth of 15 cm, the auger was slowly and carefully removed from the boring. The sample in the auger was collected and added to the sample already on the sheet spread near the hole. The auger was put in the same boring and drilled to 30, 45 and 60 cm depths. Each sample was then placed in sampling bags and sealed, and labelled with the details and transported to the laboratory for analysis.

3. RESULTS AND DISCUSSION

3.1 Key Characteristics of the Watersheds

The watersheds lie completely within the White Volta River Basin, and as such are fed by tributaries to the main river. The watersheds and rivers are delineated (Figure 1). For each watershed, the upstream area for the communities was delineated, as well as the watershed before it drains into the main White Volta River. The topography of the area is relatively flat with a slope less than 5°. The project sites are all located in headwater catchments, with sizes ranging from 7 to 50 km^2. The delineated watersheds are all of similar size, ranging from 99 to 542 km^2 (Table 4; Figure 1). The larger watersheds were used as the areal extent to which hydrological and agricultural information and data were collected.

The northern parts of Ghana are scattered with small reservoirs (Liebe et al. 2005; Lemoalle and de Condappa 2009). Similarly, each watershed has one or more small reservoirs in their catchment area (Table 5). The Libga Reservoir in the Bihinaayili watershed is the largest with a storage volume of 5.8 Mm^3.

TABLE 4. Areas of the selected watersheds.

Watershed	Area (km^2)		Communities
	Small	Large	
Anyari	34.6	542.3 (253.1 in Ghana)	Nyangua, Tekuru, Dimbasinia
Zanlerigu	7.3	99.1	Zanlerigu
Bihinaayili	49.7	348.2	Duko, Bihinaayili

TABLE 5. Small reservoirs in selected watersheds.

Water source	Watershed	Longitude	Latitude	Volume (m^3)	Primary use
Nyangua Reservoir	Anyari	-1.10	10.97	25,000	Multi-purpose (no irrigation)
Dimbasinia Reservoir	Anyari	-1.03	10.90	25,000	Multi-purpose
Zanlerigu Reservoir	Zanlerigu	-0.72	10.80	20,000	Multi-purpose
Libga Reservoir	Bihinaayili	-0.85	9.60	5,800,000	Irrigation

The dominant land cover in the three watersheds is widely open, cultivated, savanna woodlands (Table 6; Figure 2; Mul et al. 2015). A large proportion of the savanna is being used for crop production under both rainfed and irrigation regimes. Additionally, the land-use type is either an open, cultivated savanna or widely open, cultivated savanna. Open savannas are savanna lands that are not used for cultivation. It may be part of land areas reserved for cultural purposes or just unattended to due to their location. The predominant land-use types are cultivated savannah woodlands, which occupy 94, 100 and 100% of the area in the Anyari, Zanlerigu and Bihinaayili watersheds, respectively (Table 6). Cultivation in this area is highly scattered and only very high resolution land-use mapping will be able to determine the true cropping extent.

According to FAO-IIASA-ISRIC-ISS-CAS-JRC (2012), the dominant soil class in the Anyari watershed is Lixisols (79%), whereas soils in the Zanlerigu watershed mainly consist of Luvisols (86%) and Leptosols (14%). Bihinaayili watershed is dominated by Acrisols (69%) and Planosols (28%) (Table 7; Figure 3). The low resolution of the dataset (1 km) necessitated the soil sampling in the specific sites.

TABLE 6. Land cover of the three study watersheds.

Land cover	Anyari		Zanlerigu		Bihinaayili	
	km^2	%	km^2	%	km^2	%
Widely open, cultivated, savanna woodlands (6-10 trees ha^{-1})	214.7	85	93.0	94	338.6	97
Open, cultivated savanna woodlands (11-20 trees ha^{-1})	23.5	9	5.9	6	9.6	3
Grass/herb with/without scattered trees (0-5 trees ha^{-1})	14.9	6			0	0
Closed, cultivated savanna woodlands (>20 trees ha^{-1})			0.2	0		
Total	253.1		99.1		348.2	
Area cultivated	238.2	94	99.1	100	348.2	100

Source of data: Mul et al. 2015.

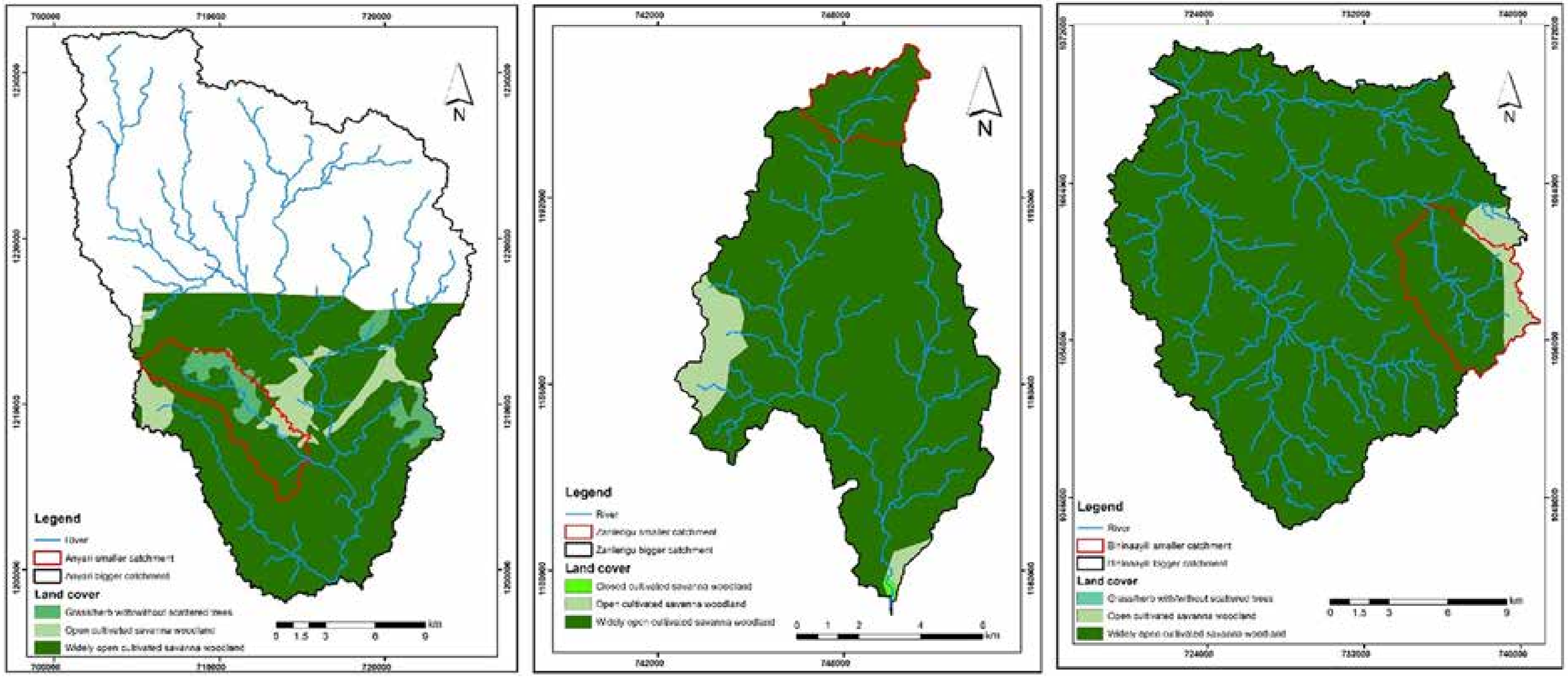
TABLE 7. Soil types within the three watersheds.

Soil types	Anyari		Zanlerigu		Bihinaayili	
	km^2	%	km^2	%	km^2	%
Fluvisols	40.8	16			2.6	0
Lixisols	198.7	79			9.4	3
Luvisols			85.3	86		
Leptosols	13.6	5	13.8	14		
Planosols					96.8	28
Acrisols					239.4	69
Total	253.1		99.1		348.2	

Source of data: FAO-IIASA-ISRIC-ISS-CAS-JRC 2012.

FIGURE 2. Land-use maps of the three watersheds: (a) Anyari, (b) Zanlerigu, and (c) Bihinaayili.

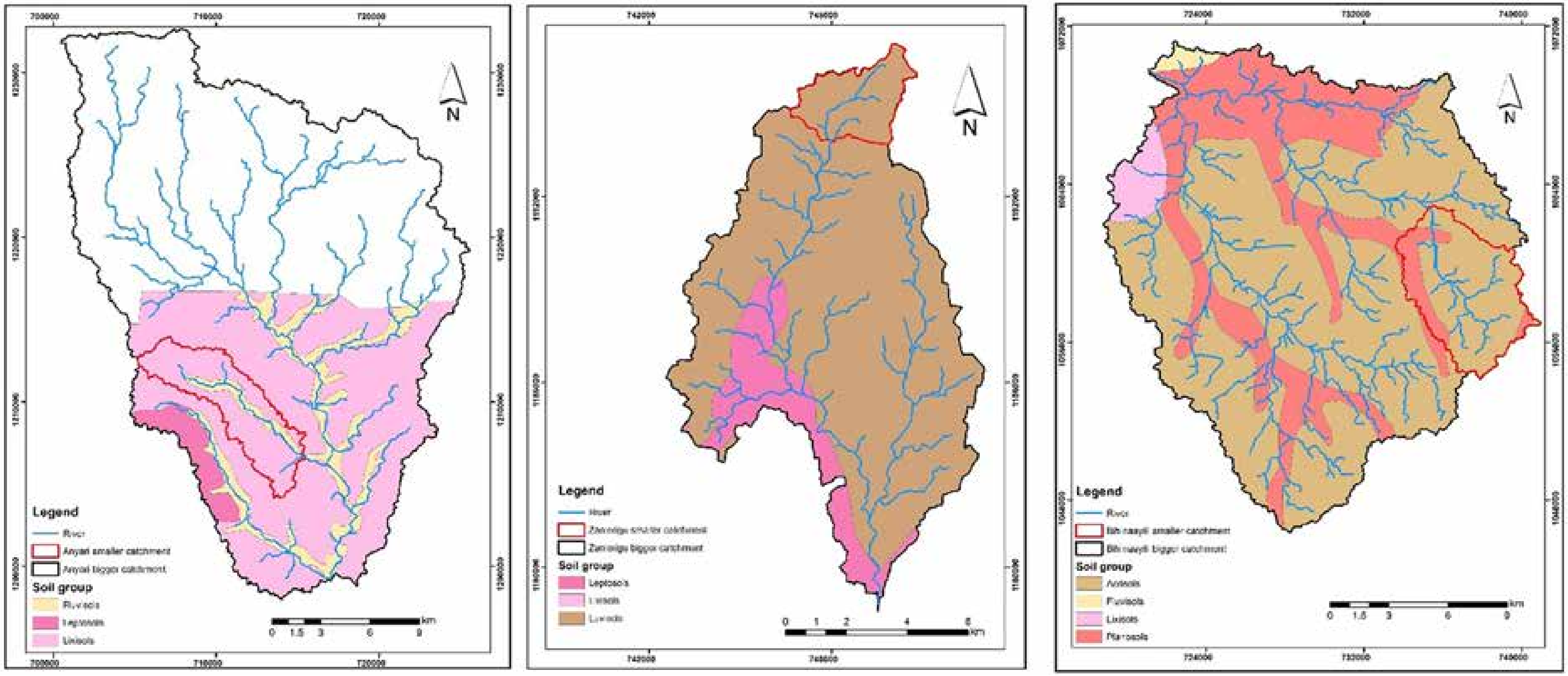
(a) (b) (c)



Source of data: Mul et al. 2015.

FIGURE 3. Soil maps of the three watersheds: (a) Anyari, (b) Zanlerigu, and (c) Bihinaayili.

(a) (b) (c)



Source of data: FAO-IIASA-ISRIC-ISS-CAS-JRC 2012.

3.2 Prevailing Agricultural Management Practices

The average agricultural land size in the selected communities is 3.31 ha per household (Tinonin et al. 2016). The majority of cereal crops grown in the rainy season are kept for household consumption, and vegetable crops grown in the dry season are sold at local markets. Leafy vegetables are usually grown, harvested and sold to raise capital to purchase inputs (e.g., fertilizers and pesticides) for the cultivation of chilli pepper and tomatoes, which require many inputs. In all the communities, the three most cultivated crops during the wet season are maize, groundnut and rice, with 91%, 59% and 47% of households, respectively, producing them (Tinonin et al. 2016). In all the sites, land preparation is mainly done by hand using hoes and cutlasses, whereas few farmers use bullock plowing as there are few trained bullocks in the north of Ghana.

Farmers in the Bihinaayili watershed grow upland rice, soya bean, groundnut, cowpea, bambara beans, sorghum, and early and late millet during the rainy season, and guinea corn, maize and leafy vegetables, such as amaranthus and corchorus, during the dry season. Surface water from the river downstream of the Libga Reservoir, which flows year round, is used for irrigation during the dry season. Farmers in the Zanlerigu watershed grow millet, sorghum, groundnut, maize, bambara beans, paddy rice, sweet potato and vegetables in the wet season, and tomatoes, green pepper, chilli pepper, onion and local leafy vegetables in the dry season. Shallow groundwater and water from a small reservoir are used for irrigation during the dry season, but these sources of water dry up at the end of this season. The main crops grown in the Anyari watershed are groundnut, maize, upland rice, sorghum, millet, cowpea, tomato, chilli pepper and local leafy vegetables. Shallow wells and a small reservoir are used for irrigation during the dry season, but these sources of water dry up at the end of this season. Farmers in Bihinaayili use a gravity system to water their fields, whereas farmers in Zanlerigu and Anyari use water cans and buckets because pumps are too expensive. Table 8 provides a summary of agricultural production practices. Typical yields are between 0.5 and 2 tons ha^{-1} for different crop types. Irrigated rice in the Libga irrigation scheme is an exception, which produces 2.6 tons ha^{-1}, which is well below the potential of 5-6 tons ha^{-1} observed in irrigation schemes.

3.3 Climatology and Water Balance Analysis

3.3.1 General Climatic Conditions

Generally, the three watersheds have similar climatology. Average annual rainfall is in the range of 1,099±193.2, 1,005±174.8 and 991±194.7 mm y^{-1} in Bihinaayili (Tamale weather station), Zanlerigu (Zuarungu weather station) and Anyari (Navrongo weather station) watersheds, respectively (Table 9). Overall, there was a slight increasing trend in annual rainfall amounts in Navrongo and Zuarungu weather stations, and a decreasing trend in the Tamale weather station. The Mann-Kendall test showed that none of the trends are significant at 95% confidence level (Figure 4). For all three weather stations, the 1980s were the driest years with a recovery of rainfall events in subsequent decades, particularly the periods 1996-2001 and 2007-2012. The 1980s are well noted to be the driest period of the twentieth century in West Africa (Jung and Kunstmann 2007; Oguntunde et al. 2006). The mean annual *PET* values were estimated to be 1,977±34.1, 2,001±33.8 and 1,866±32.8 mm y^{-1} in Navrongo, Zuarungu and Tamale weather stations, respectively. *PET* showed an increasing trend over time in all three weather stations (Figure 5). The Mann-Kendall test indicated that the increasing trend was significant ($p < 0.05$) only in the Tamale weather station.

TABLE 8. Baseline hydrological and agricultural data of northern Ghana.

No.	Data required	Bihinaayili watershed (Bihinaayili and Duko communities)	Zanlerigu watershed (Zanlerigu community)	Anyari watershed (Dimbasinia, Tekuru and Nyangua communities)
	a) Crop information			
1	Crop rotations	Crop rotation: Yearly crop rotation is practiced in the Bihinaayili watershed as follows: i. Soya bean followed by maize or sorghum ii. Groundnut followed by maize or sorghum iii. Cotton followed by maize iv. Cowpea followed by maize or sorghum	Crop rotation is very minimal. Only about 5% of the farmers practice yearly crop rotation, which is mainly groundnut followed by sorghum or soya beans. one farmer is known to rotate crops within the same season (within a year): early millet followed by maize. No crop rotation is practiced in dry-season farming. Dry-season farmers are specialized in specific crops (tomatoes, chilli pepper, etc.) and have expertise solely for those crops. Therefore, they do not want to 'experiment' with other crops.	Yearly crop rotation is practiced in rainfed cropping as follows: Groundnut followed by maize Cowpea followed by maize Sorghum followed by sweet potatoes Millet followed by sweet potatoes The sweet potatoes are cropped in the rotation to control the Striga weed that depletes soil nutrients. In the irrigation scheme, crop rotation is practiced within a year as follows: leafy vegetables followed by chilli pepper or tomatoes or garden eggs.
2	Intercropping and mixed cropping	Many farmers practice intercropping as follows: i. Soya bean (main crop)/maize (minor crop) ii. Soya bean/sorghum iii. Soya bean/guinea corn iv. Groundnut/maize v. Groundnut/sorghum vi. Groundnut/guinea corn	Most farmers practice mixed cropping and intercropping with the following combinations: i. Sorghum/early millet ii. Early millet/late millet iii. Groundnut/late millet iv. Early millet/groundnut or other combinations, but not late millet/sorghum	Mixed cropping is widespread and practiced as follows: i. Sorghum/millet (early and late) ii. Groundnut/bambara beans/maize or late millet iii. Leafy vegetables/chilli pepper/tomatoes (cropped on different beds or portions of a farmer's plot)
3	Spatial distribution of different rotations (e.g., rotations on different soils or slopes)	No map available to show spatial distribution of crop rotation. However, all groundnut-based crop rotation, intercropping and mixed cropping are done on sandy loam soils, while soya bean-related crop rotation, intercropping and mixed cropping are done on gravel and loamy soils.	Spatial distribution of crop rotation is not yet available as only one farmer is said to be practicing crop rotation	The rich uplands further away from human dwellings are usually used for growing maize. Millet and sorghum are grown on lands around the houses. Sweet potatoes are grown on sandy loam marshy lands. Groundnuts are grown on clayey and sandy loam soils. Rice is grown in the valleys and waterlogged areas.

(Continued)

TABLE 8. Baseline hydrological and agricultural data of northern Ghana (Continued).

No.	Data required	Bihinaayili watershed (Bihinaayili and Duko communities)	Zanlerigu watershed (Zanlerigu community)	Anyari watershed (Dimbasinia, Tekuru and Nyangua communities)
4	Annual crop yields	Groundnut: 2.6 tons ha^{-1} Soya bean: 1.8 tons ha^{-1} Cowpea: 1 ton ha^{-1} Maize: 1.3 tons ha^{-1} Rainfed rice: 1.3 tons ha^{-1} Sorghum: 0.8 tons ha^{-1} Irrigated rice - Libga scheme: 2.6 tons ha^{-1}	Rice: 1.94 tons ha^{-1} Maize: 1.38 tons ha^{-1} Sorghum: 1.55 tons ha^{-1} Early/late millet: 0.98 tons ha^{-1} Groundnut: 1.21 tons ha^{-1} Cowpea: 0.52 tons ha^{-1}	Maize: 1.5 tons ha^{-1} Groundnut: 2.0 tons ha^{-1} Sorghum: 2.0 tons ha^{-1} Millet: 1.25 tons ha^{-1} Cowpea: 1.0 tons ha^{-1}
	b) Agricultural management practices			
i	Timing of planting, tilling and harvesting	Tilling: May/June Planting: Rice, maize, soya beans - June/July Sorghum, millet, groundnut, soya beans - May/June Pigeon pea - July/ August Harvesting: Sorghum - July/August Groundnut/cowpea - August/September Soya beans/maize - October/November Rice/cassava - November/December Pigeon pea - December/January	Tilling/land preparation: March/April Planting: early millet/late millet/sorghum - April/May; maize, groundnut - June/July Harvesting: Early millet - August Groundnut - August/September Late millet/sorghum/maize - October/November	Tilling/land preparation: May/June Planting: Millet (early and late), sorghum - May/June Maize, groundnut, cowpea, sweet potato - June/July Harvesting: Early millet, groundnut – August/September Late millet, sorghum, soya beans, maize - October/November

(Continued)

TABLE 8. Baseline hydrological and agricultural data of northern Ghana (Continued).

No.	Data required	Bihinaayili watershed (Bihinaayili and Duko communities)	Zanlerigu watershed (Zanlerigu community)	Anyari watershed (Dimbasinia, Tekuru and Nyangua communities)
ii	Fertilizer application (annual total or kg/each application)	Inorganic fertilizer: Nitrogen (N), phosphorus (P) and potassium (K) of two kinds (15:15:15 and 23:10:5) Top-ups to inorganic fertilizer: sulfate of ammonia/urea/sulfate. Application: Recommended application - 250 kg of NPK plus 125 kg of ammonia or 125 kg of sulfate or 62.5 kg of urea per ha. Application in practice - 125 kg of NPK or 250 kg of ammonia per ha Organic fertilizer: 5,000 kg of fertisol per ha, broadcast on the field before plowing or worked into the soil during plowing. This is done 2 weeks prior to planting. Cow dung and poultry manure are applied sparingly. Few farmers prepare and apply compost, which consists of cow dung, chicken droppings, sawdust, and stalks of maize, millet and sorghum.	Inorganic fertilizer: Early/late millet - usually, no chemical fertilizer is applied. Sorghum/maize - 250 kg of NPK plus 125 kg of phosphate of ammonia (or 62.5 kg of urea in place of phosphate of ammonia) per ha are applied per cropping season. Organic fertilizer: This is applied in land preparation for planting of early and late millet in farms around compounds. Quantity applied varies and depends on what is available.	Inorganic fertilizer: Two kinds of NPK fertilizers (23:10:10 and 15:15:15) are used in combination with sulfate of ammonia or urea. These are applied to maize and vegetables only. Application rate – 250 kg of NPK plus 125 kg of sulfate or urea per ha. Organic fertilizer: animal droppings, and composting from sawdust, crop residue and animal droppings (cow dung, goat droppings, etc.) plowed into the soil during land preparation. Application rate – 6,000 kg of organic fertilizer per ha
iii	Sources of nutrients (organic and/ or inorganic)	Inorganic fertilizers: NPK, sulfate of ammonia, sulfate and urea Organic fertilizers: fertisol sold on the market; animal droppings (cow and poultry); composting made by farmers from cow dung, poultry, sawdust, and stalks of maize, millet and sorghum.	Inorganic fertilizers: NPK, Phosphate of ammonia and urea Organic fertilizers: droppings from animals, mainly cattle, goat, sheep, and pig; and compost from grasses, farm residues and sawdust.	Inorganic fertilizers: NPK, urea, sulfate of ammonia Organic fertilizers: animal droppings, farm residues, sawdust, other wastes.
iv	Irrigation timing, period and amount	Irrigation period: December-June. Irrigation timing: No specific irrigation timing, each farmer irrigates as they deem fit. Farmers on public irrigation schemes rely on the scheduling of the water managers.	Irrigation period: December-April Irrigation timing: No specific irrigation timing, each farmer irrigates as they deem fit.	Irrigation period: November-April Irrigation timing: No specific timing. Farmers irrigate as they deem fit, but usually every other day for vegetables. Farmers on public irrigation schemes rely on the scheduling of the water managers.

(Continued)

TABLE 8. Baseline hydrological and agricultural data of northern Ghana (Continued).

No.	Data required	Bihinaayili watershed (Bihinaayili and Duko communities)	Zanlerigu watershed (Zanlerigu community)	Anyari watershed (Dimbasinia, Tekuru and Nyangua communities)
v	Source of irrigation water (surface water or wells)	Surface water. Runoff from a small stream is collected in a small reservoir dam at Libga and used for irrigation. No groundwater irrigation is practiced here as the groundwater aquifers are relatively deep. Geologically, this area sits on the consolidated sedimentary rocks, with a thin overburden that contains little shallow groundwater. Further downstream, farmers dig shallow trenches to direct excess water flowing from the Libga irrigation scheme into their farms. They then irrigate by fetching the water with buckets.	Both surface water (harvested in a small reservoir) and groundwater (abstracted from shallow wells). There are several shallow wells scattered in the watershed and one small reservoir.	Surface water from a small reservoir and groundwater from shallow wells and dugouts. Several wells are dug in the dry season for irrigation.
vi	Typical plowing depth	Bullock plow: 25-30 cm Tractor plow: 15-20 cm	Bullock plow: >10 cm Tractor plow: >20 cm	Bullock plow: about 10 cm Tractor plow: about 30 cm
vii	Conservation tillage being practiced	Earth bund for rice and other crops - groundnut, soya bean, millet, sorghum, etc.; tied ridges for crops other than rice.	Terracing with stones and contour till are practiced on hill slopes; ridge till is practiced on relatively flat lands. These practices date back to several generations.	Stone contour bunds and earth bunds for rice cultivation.
viii	Local practices for tillage or irrigation	Local tillage practices: Bullock plowing, hoes and cutlasses Local irrigation practices: Gravity release of water and river pumping for flooded and furrow irrigation.	Local tillage practices: Bullock plowing, hoes and cutlasses Local irrigation practices: Irrigation with watering cans and buckets Virtually no pumping as this is not economical to farmers.	Local tillage practices: Bullock plowing, hoes and cutlasses Local irrigation practices: Use of watering cans and buckets for irrigation.

(Continued)

TABLE 8. Baseline hydrological and agricultural data of northern Ghana (Continued).

No.	Data required	Bihinaayili watershed (Bihinaayili and Duko communities)	Zanlerigu watershed (Zanlerigu community)	Anyari watershed (Dimbasinia, Tekuru and Nyangua communities)
	c) Hydrological data			
1	Long-term weather/ climate data (> 10 years)	Data on rainfall, minimum and maximum temperatures, and sunshine hours were obtained from the nearest climatological station, Tamale. The data covered the period 1981-2012.	Rainfall, and minimum and maximum temperature data from the nearest weather station, Zuarungu, have been obtained and analyzed. The rainfall data cover the period 1981-2014, while the minimum and maximum temperature data cover the period 1994-2014. There are no data for wind speed or wind run, sunshine duration or solar radiation and relative humidity for the Zuarungu station.	There are no long-term climate data from within the watershed. Climate data were obtained from the nearest synoptic station at Navrongo. Available data on rainfall, minimum and maximum temperature and sunshine hours cover the period 1981-2012.
2	Availability of remotely sensed data	Satellite remotely sensed data are available and can also be obtained from http://modis.gsfc.nasa.gov/data/ and http://glovis.com SRTM DEM	Satellite remotely sensed data are available and can also be obtained from http://modis.gsfc.nasa.gov/data/ and http://glovis.com SRTM DEM	Satellite remotely sensed data are available and can also be obtained from http://modis.gsfc.nasa.gov/data/ and http://glovis.com SRTM DEM
3	Available historical data on streamflow, sediment loads and other water quality data at or near the site	Streamflow: There are no streamflow data for Bihinaayili watershed. The nearest gauged locations are Nawuni on the main White Volta River (downstream) and Nabogo - upstream tributary of the White Volta River. Monthly flow data available for Nabogo cover the period 1962-1994. For Nawuni, flow data is available for the period 1980-2011. Sediment loads: The watershed has no data on sediment loads. However, some data are available for Nawuni, where Akrasi (2005) estimated the sediment yield to be 22.88 tons km^{-2} y^{-1}. Water quality: There are no water quality data for the Bihinaayili watershed.	Streamflow: There are no streamflow data for this watershed. The nearest gauged location is Nangodi on the Red Volta. This is upstream of this site and has monthly data for the period 1958-1977, with some missing records. Sediment loads: There is no data on sediment loads for this watershed. The nearest location with sediment yield data is Pwalugu on the main White Volta. The yield was estimated by Akrasi (2005) to be 21.65 tons km^{-2} y^{-1}. Water quality: There is no information on surface water quality. Groundwater quality in this watershed can be described as being good for both drinking water supplies and irrigation (as per irrigation water quality guidelines of WHO 2004; Ayers and Westcot 1994; Obuobie et al. 2013).	Streamflow: There are no streamflow data for this watershed. The nearest flow measuring point by the hydrological services department is Pwalugu on the main white Volta. Pwalugu is downstream of the Anyari watershed. Daily flow data covering the period 1953-2006 have been obtained. Sediment loads: There are on sediment load data in this watershed. Yield estimate is available for Pwalugu (21.65 tons km^{-2} y^{-1}) (Akrasi 2005). Water quality: No surface water quality data are available for this watershed or nearby watersheds. Data on groundwater quality are available for 18 wells in the neighborhood of the watershed.

(Continued)

TABLE 8. Baseline hydrological and agricultural data of northern Ghana (Continued).

No.	Data required	Bihinaayili watershed (Bihinaayili and Duko communities)	Zanlerigu watershed (Zanlerigu community)	Anyari watershed (Dimbasinia, Tekuru and Nyangua communities)
	d) Water sources and irrigated areas			
i	Reservoirs, their use and physical properties (storage, volume, weir height)	The watershed has one reservoir located at Libga. Storage volume: 5.8 Mm^3 (Asante 2009 cited in Johnson and McCartney 2010).	The watershed has one reservoir, which is used by for dry-season irrigation and livestock watering. Volume: 19,275 m^3; depth to free board: 4 m (Joshua nana Bondze, District Engineer, pers. comm.)	The watershed has one reservoir. This is used for domestic water needs, irrigation and livestock watering. Volume: No data available.
ii	Wells, their use and groundwater recharge rates	The watershed has about seven wells for domestic water supply, but no wells for irrigation. Based on the work conducted by Krautstrunk (2012) in the Nabogo watershed, groundwater recharge is, on average, about 36 mm y^{-1} (about 3.5% of annual rainfall – based on rainfall data from Tamale).	Numerous wells exist for dry-season irrigation. The total number of wells varies from one season to another, but, on average, each farmer owns three wells. Obuobie et al. (2013) put the annual groundwater recharge in the Zanlerigu area to be between 34 and 182 mm y^{-1}, with an average recharge of 63 mm y^{-1} (about 6.34% of annual rainfall – based on rainfall data from Zuarungu).	More than 30 shallow groundwater wells are used for dry-season irrigation (Elijah Bobby Agricultural Extension Agent pers. comm.). The estimated recharge is about 60 mm y^{-1} (about 6% of the annual rainfall) (Obuobie 2008)
iii	Location and storage capacity of small ponds and wetlands	There are four ponds at Libga which are used for fishing only. Wetlands are not used for irrigation or livestock watering.	Wetlands and ponds are not used for irrigation or livestock watering.	Wetlands and ponds are not used for irrigation or livestock watering.
	e) Irrigated areas			
1	Areas irrigated	Surface water-irrigated area in the Libga scheme is 20 ha (Johnson and McCartney 2010). Runoff from the Libga scheme is also pumped downstream for irrigation along the drainage channel.	Area irrigated with surface water: about 10 ha. About 1 ha of land is also irrigated with water from shallow wells.	Area irrigated with both surface water and groundwater in the dry season is greater than 10 ha.

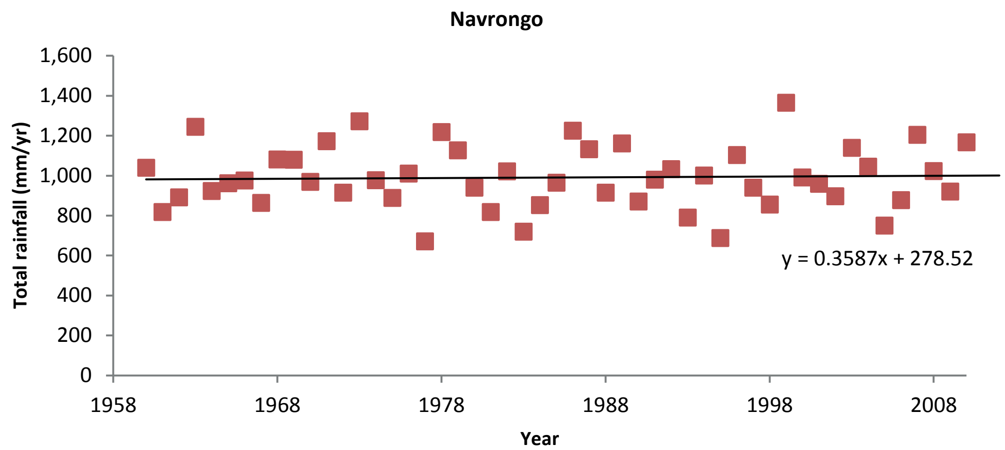
TABLE 9. Summary statistics of the climatology of the study watersheds in Ghana.

Watershed	Station	Rainfall			*PET*		Mean temp.	Min. temp.	Max. temp.
		mm y^{-1}	SD	days	mm y^{-1}	SD	(°C)	(°C)	(°C)
Bihinaayili	Tamale	1,099	193.2	72	1,866	32.8	28.2	22.6	33.8
Zanlerigu	Zuarungu	1,005	174.8	67	2,001	33.8	29.2	23.0	35.4
Anyari	Navrongo	991	194.7	65	1,977	34.1	29.1	23.0	35.2

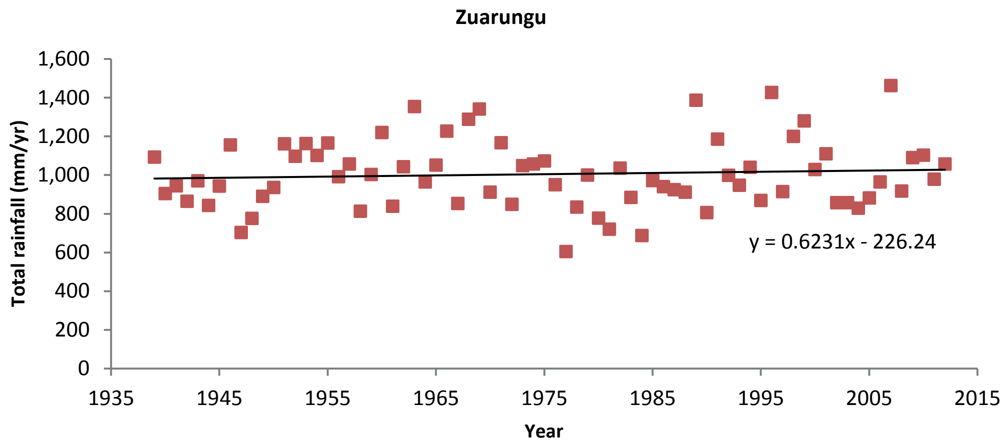
Notes: PET - Potential evapotranspiration, Mean temp. - Average temperature, Min. temp. - Minimum temperature, Max. temp. - Maximum temperature, SD - Standard Deviation.

FIGURE 4. Annual rainfall time series for (a) Navrongo, (b) Zuarungu, and (c) Tamale weather stations.

(a)



(b)



(c)

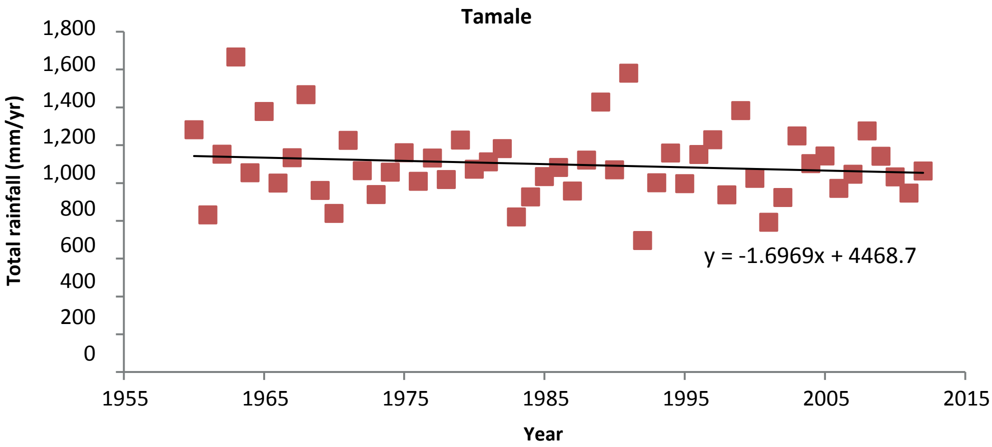
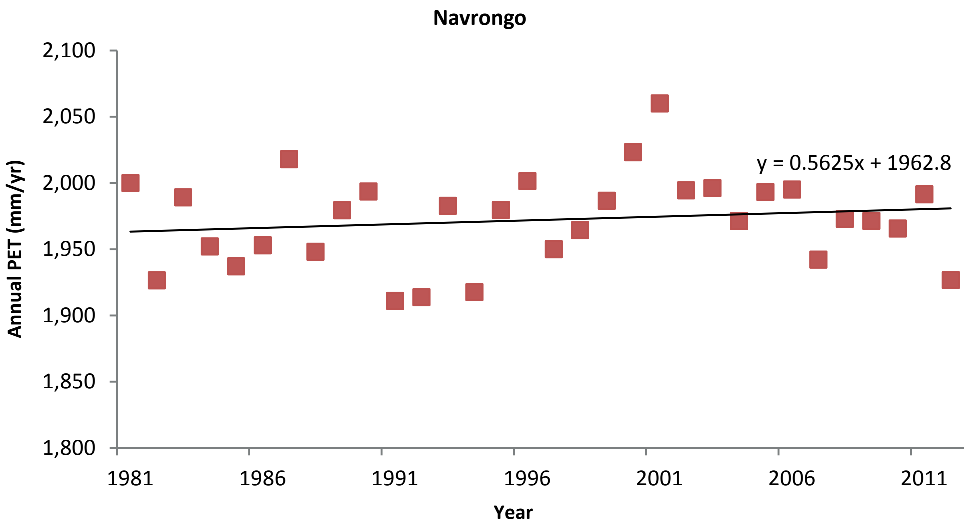
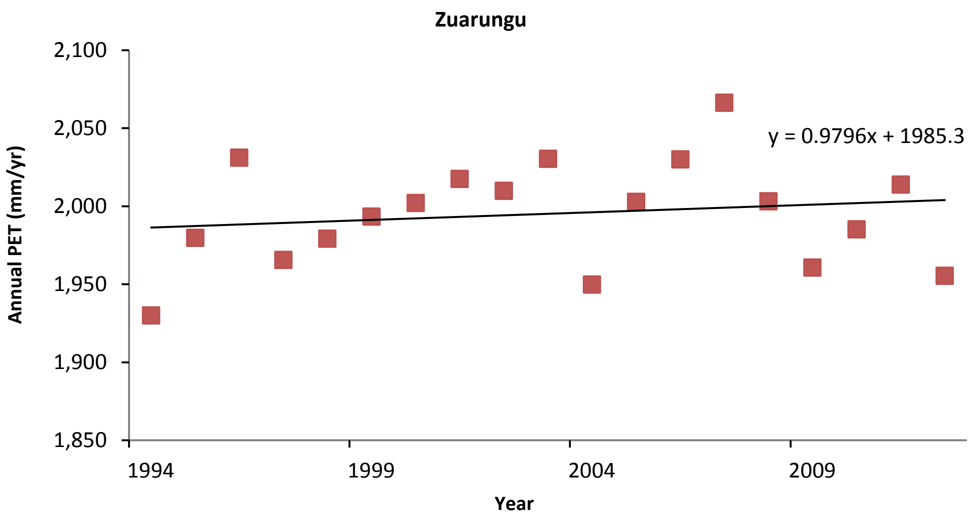


FIGURE 5. Annual *PET* time series in (a) Navrongo, (b) Zuarungu, and (c) Tamale weather stations.

(a)



(b)



(c)

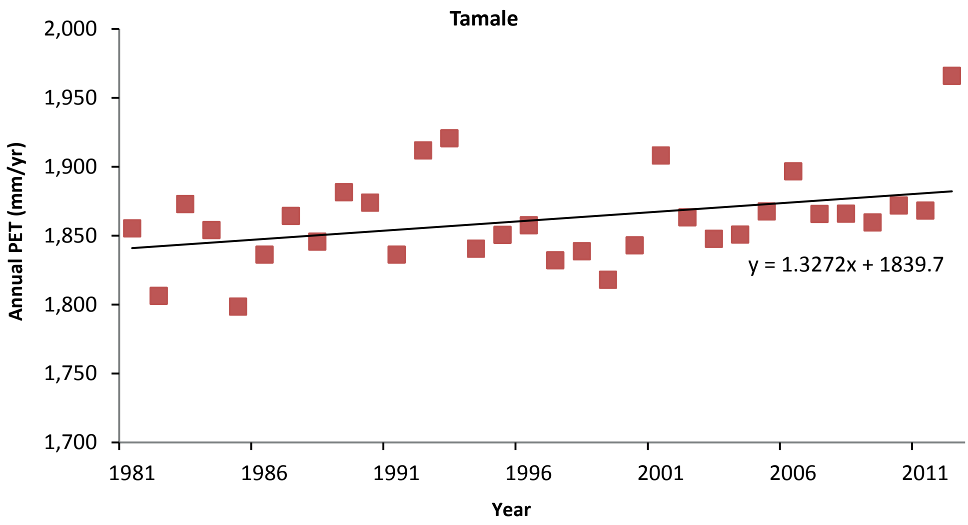
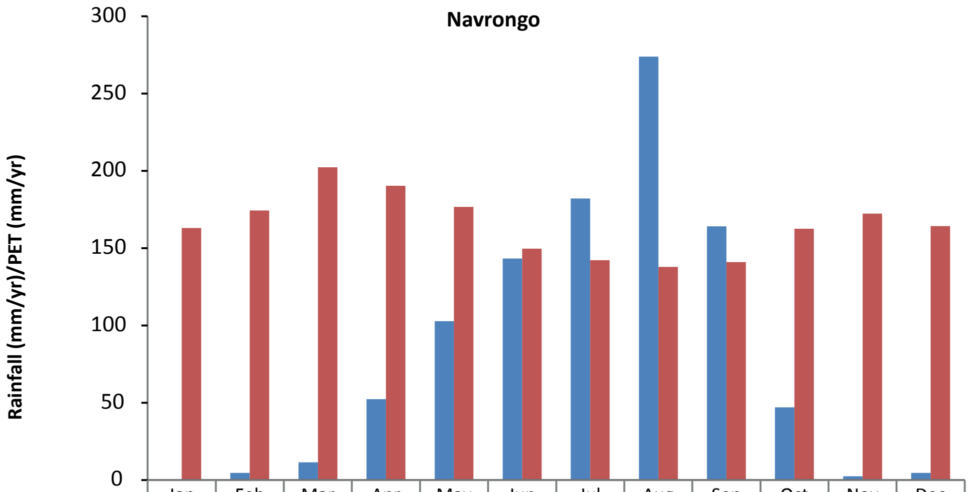


Figure 6 shows the distribution of rainfall and *PET* during the year in the three weather stations. The rainfall exhibits a uni-modal pattern, with peaks in August. The average monthly *PET* peaks in March, which is the hottest month. The monthly trends show that *PET* is greater than rainfall for most part of the year (9 months in Navrongo and Zuarungu, and 8 months in Tamale). All three weather stations experience a high annual water deficit, limiting water availability, especially during the dry season.

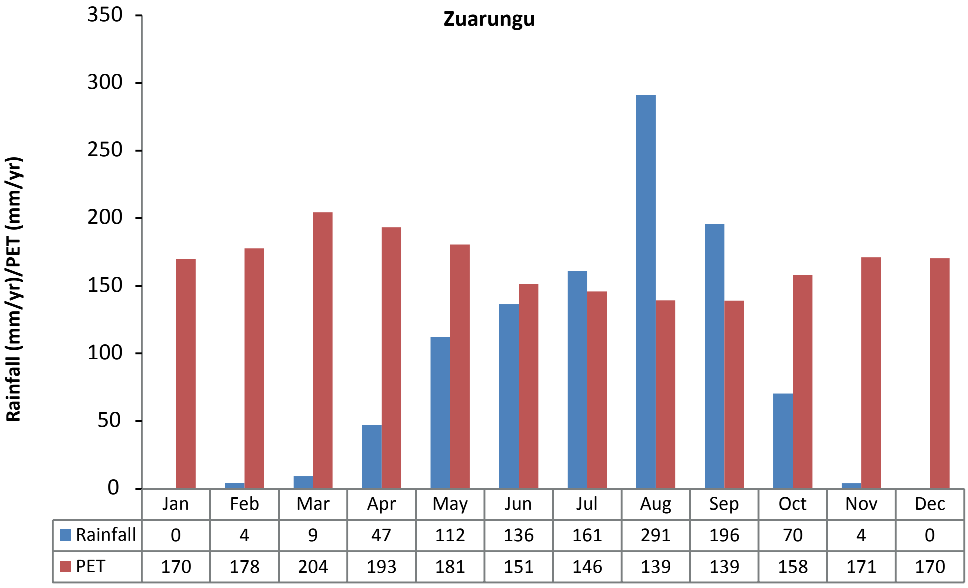
FIGURE 6. Monthly rainfall and potential evapotranspiration in (a) Navrongo, (b) Zuarungu, and (c) Tamale weather stations.

(a)

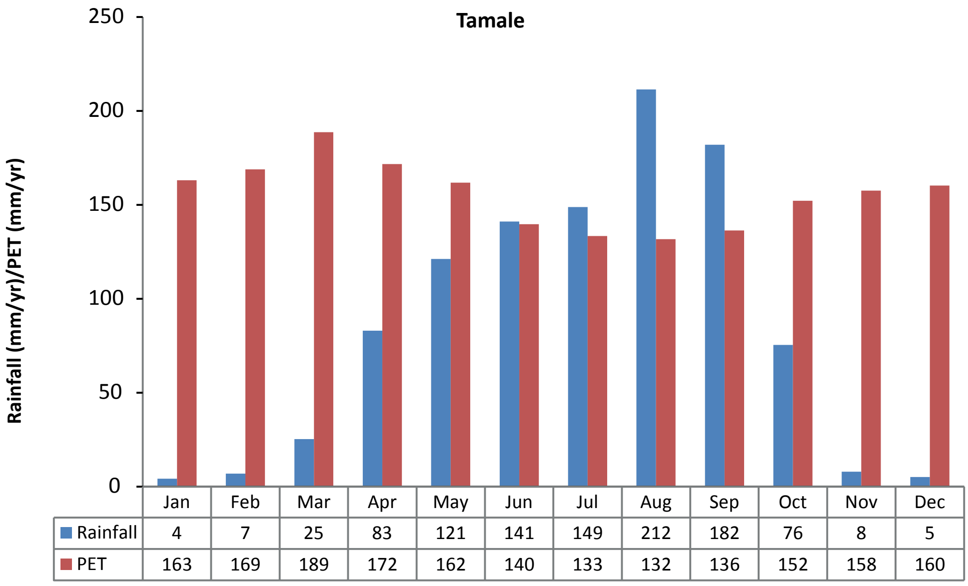


	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall	0	5	12	52	103	143	182	274	164	47	2	5
PET	163	174	202	190	177	150	142	138	141	163	172	164

(b)



(c)



3.3.2 Dryspell Analyses

The occurrence and duration of dryspells in rainfed cropping systems can significantly reduce crop yield or even cause complete crop failure, especially if it occurs during the crucial stages of development such as flowering and grain filling. Although there is spatial variability in the duration of dryspells for the three weather stations, the probability of a long dryspell lasting over a 21-day period is very low or insignificant (Navrongo - 2.1%, Zuarungu - 6.1% and Tamale - 0.0%) (Table 10). The probability of dryspells exceeding 14 days is more likely, although it was below 16% in all three weather stations. The probability of dryspells exceeding 7 days in a growing season is more than 80% in all three weather stations. Tamale has the highest probability (90%) of experiencing a dryspell exceeding 7 days.

TABLE 10: Probability of dryspells exceeding 7, 14 and 21 days in all three weather stations.

	Navrongo	Zuarungu	Tamale
7 days (%)	81.25	80.30	89.80
14 days (%)	4.17	15.15	12.24
21 days (%)	2.08	6.06	0.00

A similar study concluded that there is an 88-96% probability of dryspells of up to 7-8 days occurring in the rainy season in Nyankpala near Tamale (Gbedzi and Laryea 1999). The challenge of dryspells in the watersheds is exacerbated by poor soil water-holding capacity and high potential evapotranspiration (Fischer et al. 2013).

3.4 Water Quality Characterization

The concentrations of the measured parameters show, as expected, that generally the concentrations of the main cations (K^+, Na^+, Ca^+, Mg^{2+}) are higher in deeper wells (> 10 m) compared to the more shallow wells and reservoirs. Water in the reservoirs and shallow wells are often directly recharged by rainfall or runoff and therefore show relatively low concentrations of the same major cations, in comparison to deeper wells that are in contact with the underground for longer periods of time. One exception is the Zanlerigu Reservoir, which shows relatively high concentrations of the major cations compared to the Nyangua and Dimbasinia reservoirs. Similarly, the temporal wells in Zanlerigu are located downstream of the reservoir and the water quality in these wells is similar to that in the reservoir. It is, therefore, suspected that the two water sources are connected. As expected, concentrations at the end of the rainy season in October are lower than concentrations at the end of the dry season in April.

3.4.1 pH and Electrical Conductivity of Water Samples

Measurements of pH were used to estimate the acidity or alkalinity hazard of the irrigation water for crop production. Measured pH values for all the water bodies from all the sampling sites were fairly neutral with only a few deviations into the acidic pH. The pH levels for all the samples ranged from 5.9 to 8.3 (Figure 7), which (except for a few samples) falls within the range of 6.0-8.0 recommended by the Food and Agriculture Organization of the United Nations (FAO) (Ayers and Westcot 1994).

EC provides a measure of salinity potential of the irrigation water. Although none of the samples exceed the salinity levels at which crops are affected (>700 $\mu S\ cm^{-1}$; Abrol et al. 1988), there is a visible difference in EC in the different types of water sources. Except for Duko, wells, in general, show high EC values (Figure 8). However, these observations may be skewed, as temporal wells were only sampled in April as they were not functioning in October, and Duko wells were only sampled in October, which could have contributed to this observation. Zanlerigu Reservoir shows high EC values compared to Nyangua and Dimbasinia reservoirs.

3.4.2 Hydro-chemical Concentrations

Similar to the trend observed for the chemical parameters, the measured water quality parameters in the samples of the water bodies collected showed a general trend where most wells recorded higher levels than the surrounding water bodies (Table 11). Except for the Zanlerigu temporal wells, potassium (K^+) concentrations exceeded the FAO recommended level of 0-2 mg L^{-1} (Ayers

FIGURE 7. Variations in the pH levels of the water bodies of the different sampling locations.

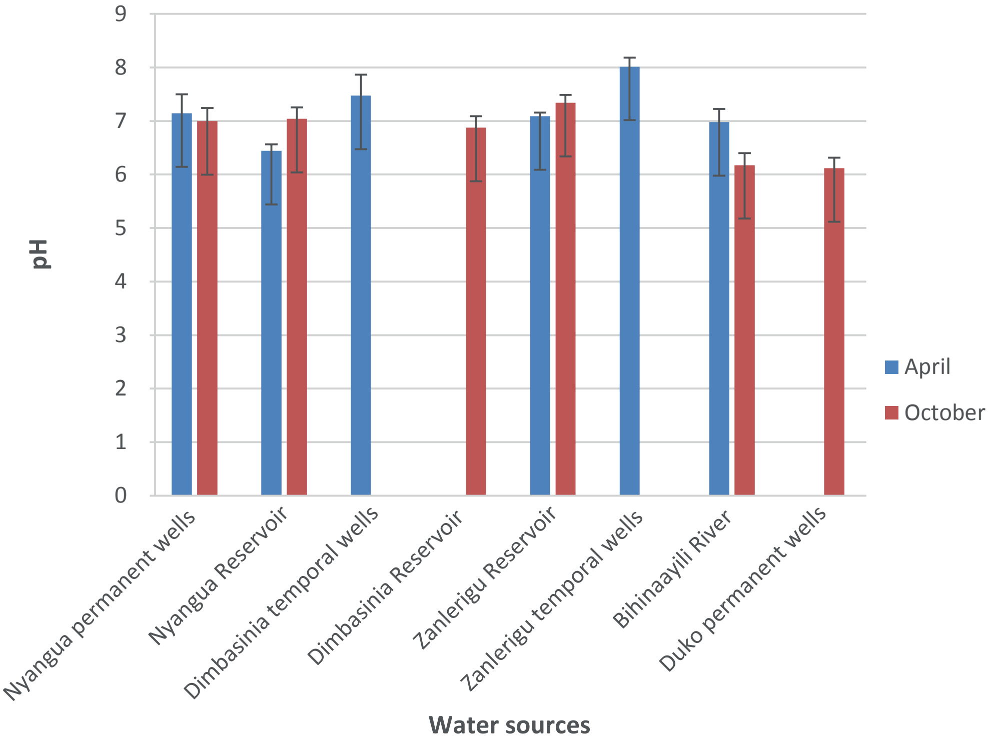


FIGURE 8. Variations in the electrical conductivity (μS cm^{-1}) levels of the water bodies of the different sampling locations.

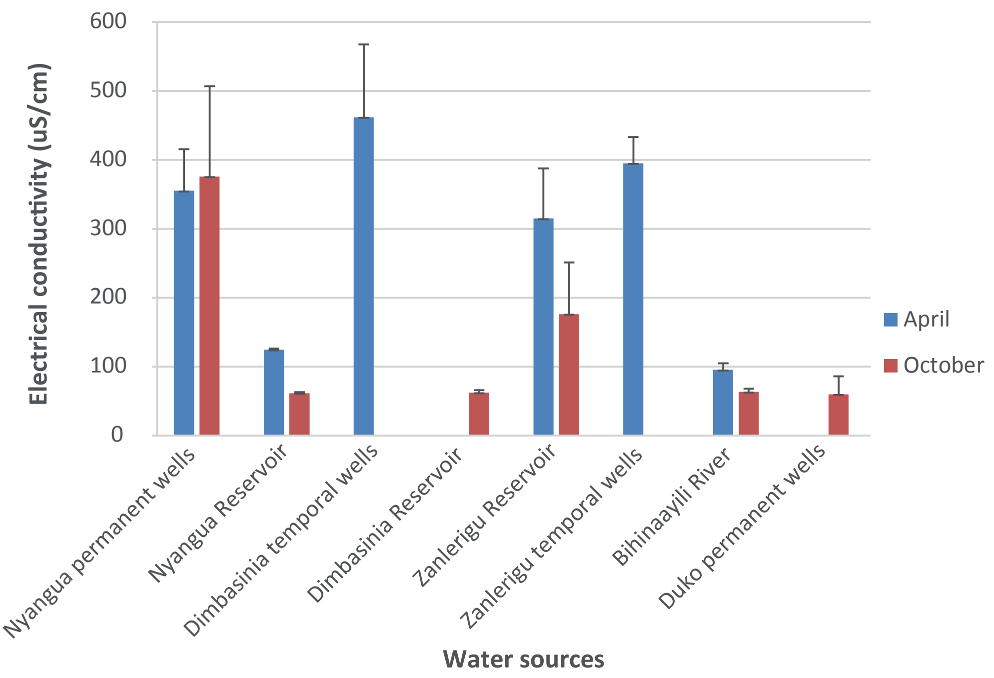


TABLE 11. Water characteristics for the water sources across the three watersheds§.

Watershed	Site name	Sampling month	pH	K^+	Na^+	Ca^{2+}	Mg^{2+}	F^-	Fe^{3+}	Al^{3+}
				mg L^{-1}						
Anyari	Nyangua Reservoir	Apr	6.44±0.13	**12.5±0.54**	14.5±4.12	8.8±3.06	3.4±0.58	<0.005	33.43±6.75	4.55±4.34
		Oct	7.04±0.22	**4.68±0.62**	6.05±0.06	5.20±0.80	2.43±1.25	<0.005	2.82±0.14	0.13±0.05
	Nyangua permanent wells (10-20 m)	Apr	6.44±0.13	**4.52±2.95§**	38.55±3.78	33.69±8.39	10.51±2.98	0.23±0.26	0.91±0.98	0.43±0.60
		Oct	7.00±0.24	**6.71±3.18**	56.32±27.33	31.98±20.18	5.99±2.73	0.02±0.07	1.80±1.50	0.20±0.04
	Dimbasinia	Apr	-	-	-	-	-	-	-	-
	Reservoir	Oct	6.88±0.22	**3.80±0.14**	4.05±0.05	5.33±0.83	2.40±0.55	0.01±0.00	2.98±2.51	0.18±0.02
	Dimbasinia	Apr	7.47±0.39	**2.52±1.02**	42.15±12.38	33.60±12.96	25.24±16.22	0.20±0.23	4.00±3.48	0.10±0.01
	temporal wells (8-12 m)	Oct	-	-	-	-	-	-	-	-
Zanlerigu	Zanlerigu Reservoir	Apr	7.09±0.07	**4.38±0.05**	24.25±6.5	25.25±1.58	13.6±0.82	0.20±0.35	5.31±1.31	1.08±0.78
		Oct	7.34±0.14	1.7±0.12	7.23±0.17	21.20±0.80	9.95±0.96	0.077±0.15	0.487±0.16	0.10±0.03
	Zanlerigu temporal	Apr	8.01±0.17	0.74±0.25	16.83±3.00	54.77±7.06	13.05±4.65	0.15±0.18	3.49±4.89	0.23±0.22
	wells (2-5 m)	Oct	-	-	-	-	-	-	-	-
Bihinaayili	Bihinaayili River	Apr	6.98±0.24	**6.08±1.54**	11.41±2.75	7.09±1.06	1.15±0.53	0.10±0.19	2.39±1.74	0.15±0.05
		Oct	6.18±0.23	1.72±0.35	8.42±0.75	4.80±0.75	1.82±0.53	<0.005	2.13±1.03	0.21±0.02
	Duko permanent	Apr	-	-	-	-	-	-	-	-
	wells (5-8 m)	Oct	6.12±0.20	**2.38±0.83**	6.42±2.09	4.16±3.12	2.32±1.11	0.06±0.13	1.37±0.93	0.20±0.02
FAO standard*			0-2	920	400	60	1.0	5.0	5.0	

Notes: § Mean ± standard deviation of more than 10 samples taken from many water sources across the site.

* Ayers and Westcot 1994.

and Westcot 1994). High levels of K^+ could be attributed to the slash and burn practices employed by the farmers (Brown et al. 1973) or natural dissolution of the bedrock. Other hydro-chemical parameters such as sodium (Na^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}) are all within the water quality guidelines for irrigation use (Ayers and Westcot 1994). Higher concentrations are observed in the deeper wells than in the dams and shallower wells.

Fluoride (F^-) concentrations are within the FAO recommended level of 1.0 mg L^{-1} for irrigation water (Ayers and Westcot 1994). Average concentrations for iron (Fe^{3+}) were within the acceptable range of 5 mg L^{-1}, except for Nyangua Reservoir, which recorded very high concentrations of iron (33.43±6.75 mg L^{-1}). Individual samples from other locations also exceed the acceptable limit. This could pose a threat to agriculture as it could limit availability of other nutrients such as phosphorus, and thus cannot be ideal for irrigating non-iron-tolerant crops. Average concentrations of aluminum (Al^{3+}) were within the acceptable range of 5 mg L^{-1}. Only individual samples at Nyangua Reservoir exceeded the acceptable limit.

3.5 Soil Texture and Quality

Table 12 presents the physical and chemical characteristics of the five sampling locations within the watershed in northern Ghana. In general, the soils from all the locations were deeply weathered up to the depth of 60 cm and more. This supports the growth of deep-rooted plants such as millet, groundnuts and sorghum. The soil in Zanlerigu was classified as clay loam with a sand content below 30%, silt 40% and clay content of 33% (Table 12). The silt content of the other four sites were, on average, below 30% with not much changes in the clay and sand content at an increasing depth of up to 60 cm (Table 12). In the soil in Dimbasinia, the sand content (49.6±10.3%) was higher in the deep layers (60 cm) compared to the top (45.1±9.9%) and subsoil (44.1±10.1%) layers, whereas there was a decreasing sand content with increasing depth in the soil in the other four sites. The phenomenon observed in the soil in Dimbasinia is possibly due to eluviation of fine silt material from the top layers into the deep layers of the soil. The texture of the soil is crucial for determining the type and growth rate of crops, moisture content, rate of evapotranspiration and hence the rate and the time of irrigation. From the soil texture classes shown in Table 12, the soils in Zanlerigu (clay) are therefore more prone to flooding and surface runoff compared to soils from the other sites, because the clay content does not allow fast and easy infiltration of water during rainfall or irrigation. On the other hand, the rate of evapotranspiration will be low in the soil in Zanlerigu compared to the other soils because of the clay content. This implies that, when implementing an irrigation project, the soils in Zanlerigu will need a slower flow rate to allow time for infiltration of the water, and once that is achieved, it will also take relatively more days before the next watering (USDA 1997). However, the other soils, especially the soils of Tekuru, with a sand content of over 64% (Table 12), will require more frequent watering because the sandy soil has more interlayer spaces for aeration. Based on the texture of the soil, the rate of infiltration can be illustrated as ‘Zanlerigu (ZN) < Dimbasinia (DM) < Bihinaayili (BH) < Nyangua (NY) < Tekuru (TR)’.

3.5.1 pH and Electrical Conductivity of Soil Samples

The pH of the soil was determined in water (pH_w 1:1). In general, the pH of all the four sites did not change significantly with increasing soil depths. The soil samples from Zanlerigu and Dimbasinia had a pH value between 6 and 8, while the pH value of the soils samples from Bihinaayili, Nyangua and Tekuru were between 5.4 and 5.8 (Table 12). From the cropping dynamics of the study area, the common crops grown were sorghum, early and late millet, groundnut, etc. (Table 8). These crops perform well under pH values between 6.0 and 7.0 (Barham et al. 1997). This might probably be the reason why farmers in these areas have adopted to the cultivation of such crops over years. The areas with a pH value below 6.0 show that the soils are moderately acid. From the data, it has been identified that the moderate acid soils also have relatively high amounts of available phosphorus compared to the soils with a pH value above 6 (Table 12). This is because, under a moderate pH value, the negatively charged anion of phosphate is attracted to the colloidal site of the soil, thus making it more available compared to the case of pH 6 soil. Minimizing the use of ammonium fertilizers, incorporating organic manures and plant residues and, where necessary, applying lime are needed to increase the pH value before native crops such as millet and sorghum can be grown well (Barham et al. 1997).

The EC of the soil is an estimator of the amount of total dissolved solids (TDS) or the total amount of dissolved ions in the soil. The EC also determines the rate at which water infiltrates through the soil during irrigation. The EC of soils from all the five sites were low (0.1-0.4 dS m^{-1}). According to FAO (2006), soils are non-saline with little or no effect on the soil organisms. They also suggest a standard of less than 1.5 dS m^{-1} for agricultural soils, and thus the EC from these soils are good for irrigation with less salt accumulation on the subsoil.

TABLE 12. Physical and chemical characteristics of the soil and hydraulic parameters of farmer plots in northern Ghana§.

Site	Depth	Sand	Silt	Clay	TX¶	pH_w	EC	OC	TN	AP	CEC
	cm	%				(1:1)	dS m^{-1}	%		mg kg^{-1}	cmol kg^{-1}
ZN	0-15	26.9±12.1	39.8±8.3	33.3±7.1	cl	7.1±0.2	0.4±0.3	**1.5±0.2**	0.11±0.03	1.9±2.6	20.7±11.1
	15-30	24.9±14.0	39.3±10.9	35.8±9.9	cl	7.1±0.2	0.3±0.1	**1.1±0.2**	0.09±0.02	1.9±2.8	20.5±8.9
	30-45	21.9±13.6	42.4±10.7	35.7±10.0	cl	7.1±0.2	0.3±0.2	**0.8±0.2**	0.07±0.02	1.8±1.7	20.3±10.1
	45-60	24.3±15.6	39.6±10.4	36.1±11.4	cl	7.2±0.3	0.3±0.2	**0.6±0.2**	0.05±0.02	1.5±1.6	21.6±13.1
DM	0-15	45.1±9.9	27.5±7.1	27.4±4.9	scl	6.7±0.8	0.3±0.1	**1.4±0.4**	0.06±0.02	3.9±2.9	18.0±5.4
	15-30	44.1±10.1	25.9±8.2	30.0±6.1	cl	7.0±0.5	0.2±0.1	**1.0±0.3**	0.04±0.02	2.6±1.4	15.6±2.8
	30-45	44.9±10.5	25.9±8.8	29.2±4.3	cl	7.1±0.5	0.2±0.1	**0.8±0.3**	0.03±0.02	2.1±1.4	14.6±2.8
	45-60	49.6±10.3	24.6±9.3	27.5±5.2	scl	7.1±0.4	0.2±0.1	**0.6±0.3**	0.03±0.02	1.8±0.7	13.9±1.4
BH	0-15	51.7±12.9	28.1±9.5	20.2±4.9	l	**5.4±0.4**	0.2±0.1	**0.7±0.2**	0.06±0.02	9.3±4.2	**7.2±2.8**
	15-30	48.7±16.4	29.8±12.3	21.4±5.9	l	**5.4±0.7**	0.1±0.1	**0.5±0.2**	0.06±0.02	6.6±3.4	**7.4±3.0**
	30-45	45.3±14.7	30.2±10.5	24.5±5.6	l	**5.5±0.5**	0.1±0.1	**0.4±0.2**	0.05±0.01	5.3±3.1	**7.6±3.7**
	45-60	44.1±14.7	27.6±9.8	28.3±7.6	scl	**5.6±0.5**	0.1±0.1	**0.2±0.1**	0.04±0.01	4.0±3.0	**8.8±3.1**
NY	0-30	58.5±10.3	20.3±7.5	21.3±7.1	scl	**5.4±0.8**	0.2±0.1	#	0.05±0.01	10.4±8.1	19.7±11.6
TR	0-30	64.1±9.1	16.8±7.5	19.1±4.7	sl	**5.8±0.6**	0.2±0.2	#	0.04±0.01	15.7±9.0	**8.0±3.9**
FAO standard*						6.0-8.0	<1.5**	4-10			>10

Notes:

§ Site description: ZN=Zanlerigu, DM=Dimbasinia, BH=Bihinaayili, NY=Nyangua, TR=Tekuru; Duko was not included as the wells are only used for domestic purposes.

¶TX = USDA textural soil classification: cl=clay loam, scl=sandy clay loam, l=loam, sl=sandy loam; EC=electrical conductivity; OC=organic carbon; TN=total nitrogen; AP=available phosphorus; CEC=cation exchange capacity

= not available

* FAO 2006

** Tanji and Kielen 2002 for pepper crop

3.5.2 Soil Fertility

The organic carbon (OC) content of the soils in all five sites were generally low (Table 11). This suggests that the soils are of low fertility and tentatively with low structural stability, affecting the available water-holding capacity of the plant as typical of highly-weathered tropical soils. Low organic matter also affects crusting at soil surface and siltation, which can cause problems in different irrigation applications such as drip irrigation. There might also have been overexploitation of the surface horizons leading to depletion in organic carbon. The FAO guidelines for the interpretation of soils suggest an organic carbon content of 4-10% for better crop performance (FAO 2006). The rates of soil carbon accumulation are inversely related to the sand content of the soil (Lugo et al. 1986). Similarly, soils in Bihinaayili and Nyangua, with high sand content, were also found to have a very low OC. The soil from Zanlerigu, with relatively high OC, also has the lowest sand content (Table 12). This implies that the soils cannot on its own support growth without any external inputs such as crop residues, organic manure or inorganic fertilizers. The soils, however, are not different from most tropical soils (Alley and Vanlauwe 2009). Tropical soils have been reported to generally have low organic carbon content below 4-10%, thus resulting in low yields per unit of cropland (Jones 1973; Bot and Benites 2005). The low organic carbon content is mainly due the high temperatures which increases the rate of microbial activities, facilitating decomposition and mineralization of any organic material input (Bashan and De-Bashan 2010). Management practices such as organic matter addition from residues and inorganic fertilizers can help increase the organic carbon content of the soil (Alley and Vanlauwe 2009).

The total nitrogen of the soils from all the five sites are generally below the recommended total nitrogen content for optimum plant growth. Total nitrogen content of less than 1.5 is considered too low for the requirement of all crops (McKenzie 1998) as in the case of the soils from the five sites (Table 12). To meet the crop nitrogen requirements for the growth of common cereals such as early and late millet, maize and sorghum in the watersheds, an external supply of nitrogen is recommended either with inorganic fertilizers or other organic management practices that improve nitrogen availability, such as the addition of compost.

The available phosphorus content is relatively higher (> 5 mg kg^{-1}) in soils from Bihinaayili, Nyangua and Tekuru, in comparison to soils from of Zanlerigu and Dimbasinia, with available phosphorus levels below 5 mg kg^{-1}. The available phosphorus is the amount of phosphorus available in the soil solutions and for plant uptake. Phosphorus is an essential plant nutrient required for protein synthesis and plant growth. It is required by microbes as an energy source (adenosine triphosphate [ATP]) for the activities of mineralization, and release of soil OC and TN in the soil.

3.5.3 Cation Exchange Capacity

The cation exchange capacity (CEC) of a soil is the maximum quantity of exchangeable total cation that a soil is capable of holding at a given pH value. These cations can either move into the soil solution or get absorbed into the colloidal soil surface depending on the change that occurs in the pH of the soil. According to the FAO recommended levels, the CEC (cmol kg^{-1}) of the soils from the Zanlerigu, Dimbasinia and Nyangua is considered high (>10 cmol kg^{-1}). On the other hand, the values from the other two sites (Bihinaayili and Tekuru) were considered low (<10 cmol kg^{-1}). The high CEC of Zanlerigu and Dimbasinia corresponds with high clay and silt content as shown in these two areas (Table 12). The low clay and silt content measured in the soils of Bihinaayili, Nyangua and Tekuru corresponds with the low CEC in these soils. The CEC of a soil will, therefore, have the following implications for agriculture and irrigation:

(a) Leaching of nutrients will be more prominent in soils with low CEC rather than in that with high CEC. Therefore, when applying fertilizers (inorganic) and soil conditioners to soils with low CEC, such as that in Bihinaayili, Nyangua and Tekuru (Ketterings et al. 2007a), it is recommended to spread the fertilizer over time and not apply the contents at once. This will help reduce leaching of the nutrients through the soil making it eventually unavailable to the plants but rather leached into underground water.

(b) Soils with low CEC will also require low, but frequent, watering. Soils with high CEC can accommodate relatively fast and less frequent watering. The CEC is also related to the clay and silt content of the soils as discussed above. This implies that soils in Zanlerigu and Dimbasinia will require less frequent watering compared to that in Bihinaayili, Nyangua and Tekuru (Ketterings et al. 2007a).

(c) Soils with high CEC are less prone to infiltration compared to soils with low CEC. As a result, when applying inorganic fertilizers to soils with high CEC, it is recommended that fertilizer be incorporated to reduce surface runoff due to the low infiltration rate (Ketterings et al. 2007b). Thus, when applying fertilizer to soils in Zanlerigu and Dimbasinia, the best practice is to incorporate fertilizer (Table 12).

(d) Most soils with high CEC do not need liming at all. However, when these soils become acidic then a large amount of lime is required to reach the optimum pH level (Ketterings et al. 2007a).

(e) The capacity to protect groundwater from cation contamination is improved under soils with high CEC compared to that with low CEC (Lewandowski et al. 2016). Thus, the soils in Zanlerigu and Dimbasinia have the potential to reduce cation contamination compared to that in Bihinaayili, Nyangua and Tekuru.

4. CONCLUSIONS

This biophysical characterization was aimed at collating hydrological and agricultural data at the three watersheds in northern Ghana (Anyari, Zanlerigu and Bihinaayili) to inform interventions in small-scale farming systems. The study also provided a description of the climatology of the watersheds as well as brief analyses of water availability, primarily with the purpose of developing opportunities for agricultural water management in smallholder farming systems.

Analysis of the climatology of the three weather stations shows increasing trends in annual rainfall in Navrongo and Zuarungu, and *PET* and a decreasing trend in annual rainfall in Tamale (although none being significant for rainfall). For *PET*, the increasing trend is significant only in the Bihinaayili watershed. The dryspell analysis shows that such dry periods exceeding 7 days are very common, where about 4 out of 5 years are affected by such a dryspell. For sustainable intensification, farmers need support in developing agricultural water management strategies to attain production and productivity. The water quality analyses indicate that all water sources are suitable for agricultural purposes. However, for most cases, the K^+ values exceed the recommended values.

The EC values across the study sites show that soil salinity is currently not a concern for irrigation development. On the other hand, OC in all the samples were below the recommended value of 4-10%. We, therefore, recommend that the soils require additional organic fertilizer to boost the low OC values found in these sites.

All three watersheds experience high annual water deficits on the basis of the total rainfall and higher deficit, considering reliable rainfall. Temporally, a water surplus occurs in 3 to 4 months in a year. The reservoirs and wells could be used to supplement irrigation during intermittent dryspells in the rainy season and for irrigation of short-duration crops in the dry season. Water management interventions are needed to eliminate crop failure and improve productivity. However, farmers have not been able to invest in mechanization and improved soil water management, and the viability and profitability of these interventions need to be investigated before further recommendations are made to the farmers.

REFERENCES

Abrol, I.P.; Yadav, J.S.P.; Massoud, F.I. 1988. *Salt-affected soils and their management*. FAO Soils Bulletin 39. Rome: Food and Agriculture Organization of the United Nations (FAO).

Akrasi, S.A. 2005. The assessment of suspended sediment inputs to Volta Lake. *Lakes & Reservoirs: Research and Management* 10(3): 179-186.

Alley, M.M.; Vanlauwe, B. 2009. *The role of fertilizers in integrated plant nutrient management*. Paris, France: International Fertilizer Industry Association (IFA); Nairobi, Kenya: Tropical Soil Biology and Fertilizer Institute (TSBF), International Center for Tropical Agriculture (CIAT). 59p.

Arnold, J.G.; Srinivasan, R.; Muttiah, R.S.; Williams, J.R. 1998. Large area hydrologic modeling and assessment part I: Model development. *Journal of the American Water Resources Association* 34(1): 73-89.

Asante, F. 2009. *Rethinking water storage for climate change adaptation in sub-Saharan Africa. Technical, economic and financial performance in Volta basin*. Unpublished report prepared for IWMI, Addis Ababa, Ethiopia.

Ayers, R.S.; Westcot, D.W. 1994. *Water quality for agriculture*. FAO Irrigation and Drainage Paper 29. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO). Available at http://www.fao.org/docrep/003/T0234E/T0234E00.htm (accessed on April 15, 2016).

Barham, P.; Begg, E.; Foote, S.; Henderson, J.; Jansen, P.; Pert, H.; Scott, J.; Wong, A.; Woolner, D. 1997. Guidelines for guidelines. *Disease Management & Health Outcomes* 1(4): 197-209. http://doi.org/10.2165/00115677-199701040-00003

Barron, J.; Rockström, J.; Gichuki, F.; Hatibu, N. 2003. Dry spell analysis and maize yields for two semi-arid locations in east Africa. *Agricultural and Forest Meteorology* 117: 23-37.

Bashan, Y.; de-Bashan, L.E. 2010. Microbial populations of arid lands and their potential for restoration of deserts. In: *Soil biology and agriculture in the tropics,* ed., Dion, P. Pp. 109-137.

Birner, R. 2008. *Can decentralization and community-based development reduce corruption in natural resource management? Insights from irrigation in Ghana and forestry in Indonesia*. Paper prepared for presentation at the 13th International Anti-Corruption Conference, Athens, Greece, October 30-November 2, 2008, International Food Policy Research Institute (IFPRI).

Blench, R. 2007. *Working paper: Agricultural production and the potential for commodity chain expansion in the three northern regions of Ghana in 2006*. Revised version. Cambridge, UK: McDonald Institute for Archaeological Research, Kay Williamson Educational Foundation.

Bot, A.; Benites, J. 2005. *The importance of soil organic matter: Key to drought-resistant soil and sustained food production*. FAO Soils Bulletin 80. Rome: Food and Agriculture Organization of the United Nations (FAO). Available at http://www.fao.org/3/a-a0100e.pdf (accessed on May 31, 2017).

Brown, G.W.; Gahler, A.R.; Marston, R.B. 1973. Nutrient losses after clear-cut logging and slash burning in the Oregon Coast Range. *Water Resources Research* 9(5): 1450-1453.

de Fraiture, C.; Giordano, M. 2014. Small private irrigation: A thriving but overlooked sector. *Agricultural Water Management* 131: 167-174.

Diao, X. 2010. *Economic importance of agriculture for sustainable development and poverty reduction: Findings from a case study of Ghana*. Paper presented at the Global Forum on Agriculture, Policies for Agricultural Development, Poverty Reduction and Food Security, OECD Headquarters, Paris, France, November 29-30, 2010. Reference: TAD/CA/APM/WP (2010)40.

FAO (Food and Agriculture Organization of the United Nations). 2006. *Guidelines for soil description*. Fourth edition. Rome: Food and Agriculture Organization of the United Nations (FAO). Available at http://www.fao.org/docrep/019/a0541e/a0541e.pdf (accessed on May 12, 2017).

FAO. 2016. AQUASTAT database. Rome: Food and Agriculture Organization of the United Nations (FAO). Available at http://www.fao.org/nr/water/aquastat/main/index.stm (February 20, 2017).

FAO; IIASA (International Institute for Applied Systems Analysis); ISRIC (ISRIC-World Soil Information); ISS-CAS (Institute of Soil Science, Chinese Academy of Sciences); JRC (Joint Research Centre, European Commission). 2012. Harmonized world soil database (version 1.2). Rome, Italy: Food and Agriculture Organization of the United Nations (FAO); Laxenburg, Austria: International Institute for Applied Systems Analysis (IIASA). Available at http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/ (accessed on November 17, 2015).

Fischer, B.M.C.; Mul, M.L.; Savenije, H.H.G. 2013. Determining spatial variability of dry spells, a Markov based method, applied to the Makanya catchment, Tanzania. *Hydrology and Earth System Sciences* 17: 2161-2170.

Gbedzi, V.D.; Laryea, P. 1999. Dry spell analysis for agricultural information in the Nyankpala area of Northern Ghana. In: *Proceedings of the Conference of the Ghana Soil Science Society*. Pp. 123-132.

Giordano, M.; de Fraiture, C. 2014. Small private irrigation: Enhancing benefits and managing trade-offs. *Agricultural Water Management* 131: 175-182.

Hargreaves, G.H.; Samani, Z.A. 1985. Reference crop evapotranspiration from temperature. *American Society of Agricultural Engineers* 1(2): 96-99.

Inkoom, D.B.; Nanguo, C.Z. 2011. Utilisation of irrigation facilities towards poverty reduction in the Upper West Region of Ghana. *Journal of Sustainable Development in Africa* 13(2): 335-351.

Johnston, R.M.; McCartney, M. 2010. *Inventory of water storage types in the Blue Nile and Volta river basins*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 40p. (IWMI Working Paper 140).

Jones, M.J. 1973. The organic matter content of the Savanna soils of West Africa. *European Journal of Soil Science* 24(1): 42-53.

Jung, G.; Kunstmann, H. 2007. High-resolution regional climate modeling for the Volta region of West Africa. *Journal of Geophysical Research* 112(D23108): 17.

Kadyampakeni, D.; Appoh, R.; Barron, J.; Boakye-Acheampong, E. 2017. *Water quality of selected irrigation water sources in northern Ghana*. 31p.

Kendall, M.G. 1975. *Rank correlation methods*. London: Charles Griffin. 4th edition.

Ketterings, Q.; Reid, S.; Rao, R. 2007a. *Cation Exchange Capacity (CEC)*. Agronomy Fact Sheet Series. Fact sheet 22. 2p. Available at http://nmsp.cals.cornell.edu/publications/factsheets/factsheet22.pdf (accessed on May 12, 2017).

Ketterings, Q.; Reid, S.; Rao, R.; Czymmek, K. 2007b. *Estimating CEC from Cornell Soil Test Data*. Agronomy Fact Sheet Series. Fact sheet 23. 2p. Available at http://nmsp.cals.cornell.edu/publications/factsheets/factsheet23.pdf (accessed on May 12, 2017).

Krautstrunk, M.L. 2012. *An estimate of groundwater recharge in the Nabogo River Basin, Ghana using water table fluctuation method and chloride mass balance*. MSc thesis. University of Nevada. 81p.

Lamptey, B.N.; Nyamadi, B.; Namara, R.; Barry, B.; Dittoh, S. 2009. *Ghana national consultation*. Project Stakeholder Consultation Summary Series. AgWater Solutions Project. Colombo, Sri Lanka: International Water Management Institute (IWMI).

Lemoalle, J.; de Condappa, D. 2009. *Water atlas of the Volta Basin*. Colombo, Sri Lanka: CGIAR Challenge Program on Water and Food; Marseille: Institut de recherche pour le développement. 96p.

Lewandowski, A.; Kelley, S.; Meinert, J.; Williams, C. 2016. *Review of the Minnesota Department of Health Contaminants of Emerging Concern Program: Process for selecting chemicals review*. Review conducted by the University of Minnesota Water Resources Center and Humphrey School of Public Affairs.

Liebe, J.; van de Giesen, N.; Andreini, M. 2005. Estimation of small reservoir storage capacities in a semi-arid environment: A case study in the Upper East Region of Ghana. *Physics and Chemistry of the Earth* 30(6-7): 448-454.

Lugo, A.E.; Sanchez, M.J.; Brown, S. 1986. Land use and organic carbon content of some subtropical soils. *Plant and Soil* 96(2): 185-196.

Mann, H.B. 1945. Non-parametric tests against trend. *Econometrica* 13: 245-259.

McCartney, M.; Rebelo, L.-M.; Xenarios, S.; Smakhtin, V. 2013. *Agricultural water storage in an era of climate change: Assessing need and effectiveness in Africa*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 37p. (IWMI Research Report 152).

McKenzie, R. 1998. *Crop nutrition and fertilizer requirements: Essential plant nutrients*. Agri-Facts Agdex 540-1. Lethbridge, Alberta, Canada: Alberta Agriculture, Food and Rural Development (AAFRD).

MoFA (Ministry of Food and Agriculture). 2011. *National irrigation policy, strategies and regulatory measures*. Ghana: Ghana Irrigation Development Authority (GIDA).

Molden, D. 2007. *Water for food, water for life: A comprehensive assessment of water management in agriculture*. London, UK: Earthscan; Colombo, Sri Lanka: International Water Management Institute (IWMI). 645p.

Monteith, J.L. 1965. Evaporation and environment. *19th Symposia of the Society for Experimental Biology* 19: 205-234.

Mul, M.; Obuobie, E.; Appoh, R.; Kankam-Yeboah, K.; Bekoe-Obeng, E.; Amisigo, B.; Logah, F. Y.; Ghansah, B.; McCartney, M. 2015. *Water resources assessment of the Volta River Basin*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 78p. (IWMI Working Paper 166).

Mul, M.L.; Kadyampakeni, D.; Salifa, F.; Sanon, A.; Haruna, S. 2017. *Agricultural water management practices as climate smart agricultural practices in West Africa*. Draft report CCAFS Water Storage in West Africa.

Namara, R. 2012. *Agricultural use of shallow groundwater in Ghana: A promising smallholder livelihood strategy*. AgWater Solutions Project Case Study. Colombo, Sri Lanka: International Water Management Institute (IWMI).

Namara, R.; Horowitz, L.; Nyamadi, B.; Barry, B. 2011. *Irrigation development in Ghana: Past experiences, emerging opportunities, and future directions*. GSSP Working Paper 27. Washington, DC, USA: International Food Policy Research Institute (IFPRI).

Namara, R.E.; Hope, L.; Owusu Sarpong, E.; de Fraiture, C.; Owusu, D. 2014. The adoption patterns and constraints pertaining to small-scale water lifting technologies in Ghana. *Agricultural Water Management* 131: 194-203.

Namara, R.E.; Horowitz, L.; Kolavalli, S.; Kranjac-Berisavljevic, G.; Dawuni, B.N.; Barry, B.; Giordano, M. 2010. *Typology of irrigation systems in Ghana*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 35p. (IWMI Working Paper 142).

Obuobie, E. 2008. *Estimation of groundwater recharge in the context of future climate change in the White Volta River Basin, West Africa.* Ecology and Development Series No. 62. Bonn, Germany: Zentrum für Entwicklungsforschung (ZEF), University of Bonn.

Obuobie, E.; Ofori, D.; Agodzo, S.K.; Okrah, C. 2013. Groundwater potential for dry-season irrigation in north-eastern Ghana. *Water International* 38: 433-448.

Oguntunde, P.G.; Friesen, J.; van de Giesen, N.; Savenije, H.H. 2006. Hydroclimatology of the Volta River Basin in West Africa: Trends and variability from 1901 to 2002. *Physics and Chemistry of the Earth* 31(18): 1180-1188.

Payen, J.; Faurès, J.-M.; Vallée, D. 2012. *Small reservoirs and water storage for smallholder farming: The case for a new approach*. AgWater Solutions Project. Agriculture Water Management Business Proposal Document.

Penman, H.L. 1963. *Vegetation and hydrology*. Technical Communication No. 53. Harpenden, England: Commonwealth Bureau of Soils. 125p.

Pettitt, A.N. 1979. A non-parametric approach to the change point detection. *Applied Statistics* 28: 126-135.

Rabus, B.; Eineder, M.; Roth, A.; Bamler, R. 2003. The shuttle radar topography mission - a new class of digital elevation models acquired by spaceborne radar. *Journal of Photogrammetry and Remote Sensing* 57: 241-262.

Stern, R.; Knock, J. 1998. *INSTAT Climatic Guide*. UK: Statistical Service Centre, University of Reading.

Tanji, K.K.; Kielen, N.C. 2002. *Agricultural drainage water management in arid and semi-arid areas*. FAO Irrigation and Drainage Paper 61. Rome: Food and Agriculture Organization of the United Nations (FAO).

Tinonin, C.; Azzarri, C.; Haile, B.; Comanescu, M.; Roberts, C.; Signorelli, S. 2016. *Africa RISING Baseline Evaluation Survey (ARBES) report for Ghana*. International Institute of Tropical Agriculture (IITA); International Food Policy Research Institute (IFPRI).

USDA (United States Department of Agriculture). 1997. Irrigation water management. Chapter 9 in: *Irrigation guide: National engineering handbook series Part 652*. Pp. 9.1-9.217.

Van de Giesen, N.; Kunstmann, H.; Jung, G.; Liebe, J.; Andreini, M.; Vlek, P.L.G. 2002. The GLOWA Volta project: Integrated assessment of feedback mechanisms between climate, landuse, and hydrology. In: *Climatic change: Implications for the hydrological cycle and for water management*, ed., Beniston, M. Springer Netherlands. Pp. 151-170.

WHO (World Health Organization). 1992. *GEMS/WATER Operational guide*. Third edition. GEMS/W. 92.1. Geneva: World Health Organization (WHO).

WHO. 2004. *Guidelines for drinking-water quality*. Third edition. Volume 1: Recommendations. Geneva: World Health Organization (WHO).

Zhang, X.; Yang, F. 2004. *RClimDex (1.0) User manual*. Downsview, Ontario, Canada: Climate Research Branch, Environment Canada.

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