UNIVERSITY OF GHANA

COLLEGE OF BASIC AND APPLIED SCIENCES

ASSESSING THE PERFORMANCE OF FLOOD RECHARGED AQUIFER STORAGE AND RECOVERY TECHNOLOGY FOR DRY SEASON IRRIGATION IN NORTHERN GHANA

BY

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THIS THESIS IS SUBMITTED TO THE UNIVERSITY OF GHANA, LEGON IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE AWARD OF DOCTOR OF PHILOSOPHY

INSTITUTE FOR ENVIRONMENT AND SANITATION STUDIES

JULY 2019

DECLARATION

This is to certify that this thesis is the result of research undertaken by Yaw Owiredu Mante towards the award of Doctor of Philosophy in the Institute for Environment and Sanitation Studies, College of Basic and Applied Sciences, University of Ghana.

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ABSTRACT

Bhungroo, a floodwater harvesting Aquifer Storage and Recovery technology, piloted in Northern Ghana for dry season irrigation, was assessed to determine its environmental and technical performance. The study evaluated the recharge, storage and recovery potentials of three Bhungroos, and their impacts on groundwater resources. Due to the limited time available for data collection, a multi-method approach was used. Water quality samples from rainwater, community boreholes, monitoring wells, Bhungroos and floodwater were characterized to determine the effect of Bhungroo artificial recharge on groundwater systems and irrigation water quality. Pump tests coupled with continuous water level monitoring were undertaken to determine aquifer storage characteristics and behaviour. Bhungroo aquifer recharge was estimated using chloride mass balance, water table fluctuation and infiltration rate methods, while end-member mixing analyses was used to estimate Bhungroo recovery potential. The sustainability of the Bhungroos were determined from sustainable yields and potential irrigable area. The findings indicated that artificial recharge had significantly changed Bhungroo groundwater from a shallow fresh water and deep groundwater character type of Ca-Mg-HCO_3 (67 %), Na-HCO_3 (31 %) and Ca-Mg-SO_4-Cl (6 %) with minimum anthropogenic influence towards floodwater character of Ca-Mg-HCO_3 (72 %) and Ca-Mg-SO_4-Cl (28 %) with a relatively higher anthropogenic impact. Microbiological differences between Bhungroos and surrounding groundwater systems, however, were found not be wholly attributed to the influences from floodwater recharge since E. coli had previously been observed in surrounding groundwater systems prior to Bhungroo operations. Generally, changes in Bhungroo groundwater character did not affect its suitability for dry season irrigation since all indicators showed no hazard; except for SAR, EC and bicarbonate which showed a slight to moderate effect of sodium hazard on soil water infiltration. Bhungroo recharge and recovery performances were found to be limited by available well/aquifer storage characteristics and behaviour. Hence, Bhungroos with transmissivities of 8.4 – 13.1 m^2/d, storativity of 0.0011 and specific capacities of 14.7 - 37.4 m^2/d increased mean annual recharge between 8 – 13 % but recovered between 0.17 – 0.41 for dry season irrigation due to the effect of well collapse and clogging. Thus, the loss of recharge proportion between 0.22 – 0.46 for Bhungroos with sustainable yields between 0.7 - 1.5 l/s implied a maximum of 14,000 m^2 (1.4 ha) of vegetable farm could be irrigated. However, considering the high costs of the Bhungroo technologies vis-a-vis the low potential irrigable area, it is recommended that the economics of the Bhungroo Irrigation Technology in Ghana should be carefully evaluated before upscaling to ensure sustainability.

DEDICATION

I dedicate this work to my wife Dr. Mrs. Afua Adobea Mante and my children Nana Obiribea Mante and Asa Asiedu Mante.

ACKNOWLEDGEMENT

I wish to acknowledge the support of the United States Agency for International Development (USAID) who funded this study and Dr. Marloes Mul who mentored me during my experiential learning at the International Water Management Institute (IWMI) and also hooked me up on the SecureWater project as a Doctoral student. Marloes, you have been a mother, a teacher, a counsellor and an invaluable supervisor to me.

I must acknowledge the great support and expertise of Professor Bruce Banoeng-Yakubo, an expert in hydrogeology, who proffered great ideas, and simple solutions when it mattered most. Many thanks to Dr. Daniel Nukpezah for your in-depth knowledge and excellent contribution to my work. I enjoyed your mentorship and splendid teamwork.

Let me also appreciate my field assistants, Mr Stephen Amankwa, Mr. Musa Kobina and Mr. Yaw Alhassan, staff of Water Research Institute, Tamale, staff of Ghana Atomic Energy Commission, Accra, and staff of International Water Management Institute, Accra, especially Richard Appoh and Benjamin Ghansah, for various roles played in assisting in my study.

Finally, I want to appreciate the spiritual and financial support given to me by my Dad, Ebenezer Owiredu Mante (deceased), my Mum, Esther Fianko and my siblings. Ms. Theresa Fianko, I remain indebted to you for your love and encouragement.

Finally, I appreciate the Praire Presbyterian Church, Winnepeg-Canada especially Erin Joy Whittaker, Terry Brunneau, Alicia Brunneau (deceased) and Rev. Mathew Borough who supported my family in Canada while I was undertaking this study in Ghana.

Thank you all.

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ACRONYMS

ASR	Aquifer Storage and Recovery
BGS	British Geological Survey
BIT	Bhungroo Irrigation Technology
CA	Conservation Alliance International
CBE	Charge Balance Error
CGIAR	Consultative Group on International Agricultural Research
CMB	Chloride Mass Balance
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
FAO	Food and Agriculture Organization
FTF	Feed the Future
GAEC	Ghana Atomic Energy Commission
GIDA	Ghana Irrigation Development Authority
HAP	Hydrogeological Assessment Programme
IFDC	International Fertilizer Development Cooperation
IWMI	International Water Management Institute
MCL	Maximum Contaminant Level

MOFA	Ministry of Food and Agriculture
NADMO	National Disaster Management Organization
SMOW	Standard Mean Ocean Water
UNICEF	United Nations International Children's Emergency Fund
USAID	United States Agency for International Development
WHO	World Health Organization
WRC	Water Resources Commission
WRI	Water Research Institute
WTF	Water Table Fluctuation

LIST OF SYMBOLS

Symbol	**Parameter Description**
R	Recharge
S	Storativity
T	Transmissivity
S_y	Specific yield
Q	Discharge rate
Q_{sus}	Sustainable yield
P	Annual Precipitation
S	Drawdown
K	Hydraulic conductivity
h_w	Capillary suction
l_f	Depth of wetting front
V_i	Infiltration rate
H_w	Water depth above soil
R	Radial distance
IR	Irrigation requirement
ET_c	Crop water requirement
ET_0	Reference evapotranspiration
K_c	Crop coefficient
I_{eff}	Irrigation efficiency

CHAPTER ONE

1. Introduction

1.1 Background

Flooding is a phenomenon triggered by excess rainfall leading to waterlogging and overflowing of drains/channels causing widespread damage. Floods occur naturally, influenced by geology, geomorphology, relief, soil, and vegetation conditions (Parker, 2000; Tehrany et al., 2015). But land use change, dam failures or landslides can aggravate floods as well as the impact of it. Floods can be as a result of fast or slow meteorological and hydrological processes producing highly unpredictable flash floods or easier predictable slow-developing floods, also called riverine floods (European Union, 2003). Globally, flooding causes deaths, diseases and destruction of property, which is reportedly increasing in intensity as a result of climate change (Milly et al., 2002; Demski et al., 2017). However, floods in agricultural landscapes lead to the loss of incomes, hunger and poverty. Particularly, for sub-Saharan Africa where vulnerabilities are high due to the absence of flood management technologies (like dams and levees), rural populations are at risk of losing their annual income.

Flooding is an annual recurring phenomenon in Ghana and has significant repercussions on livelihoods. Particularly, the Northern parts of Ghana are prone to flooding due to the relative flat terrain (Barry et al. 2005; Balana et al., 2015; Owusu et al., 2017a). Donkoh and Awuni (2011) estimates a total of 4,000 km^2 to be annually flooded as a result of overtopping of the main rivers, with even larger areas flooded due to localized floodings. Flooding in this environment is therefore a naturally recurring phenomena, which local communities have learned to live with. However, during extreme events, the National Disaster Management

Organization (NADMO) and other governmental agencies have been instrumental in organizing rescue operations and giving relief items. For example, the 2007 Northern floods affected 332,600 persons and caused the death of 56 people. Some 35,000 houses, 1,500 km of road and 1,000 ha of crops were destroyed (NADMO, 2008). Farmers were greatly affected as crops were destroyed in the middle of the growing season. The costs were largely borne by the local communities, although the Government of Canada through the Canadian High Commission assisted the flood victims with an amount of CAN $ 910,000 (UNCT Ghana, 2007). Managing the perennial or recurrent nature of floods in Ghana remains a challenge since the current approach is unproductive; and therefore calls for a more sustainable one geared at minimizing the impacts of floods while utilizing the availability of excess water to support the livelihoods of rural communities.

Despite widespread wet season flooding in many parts of Northern Ghana, water availability and accessibility in the dry season remains a challenge. High evapotranspiration drives high irrigation requirement, leaving many farmers unemployed due to inaccessibility of sufficient water resources to practice dry season irrigation. During this period, many households become food insecure, increasing vulnerability to nutritional deficiencies especially among children (Armah et al., 2010; UNICEF, 2015). In this regard, two scenarios define the seasonal water dynamics in Northern Ghana: abundance of water in the wet season and water scarcity in the dry season. To address these issues, the Naireeta Services together with the Conservation Alliance International (CA), a non-governmental organization, and with funding from the Consultative Group on International Agricultural Research (CGIAR) research program (Water Land and Ecosystems) introduced an Aquifer Storage and Recovery (ASR) technology from India called Bhungroo Irrigation Technology (BIT) into Northern Ghana (Owusu et al., 2017a). Additional funding was sourced from the United States Agency for International Development (USAID) Feed the Future initiative to evaluate the performance of the BIT in Northern Ghana.

A Bhungroo, which means ‘straw’ or ‘hollow pipe’ in Gujarati, is typically installed in floodprone areas where floodwater is collected through an infiltration bed and channeled into the underlying aquifer through a borehole piped system (Biplab, 2013). The pipe or borehole is also used to extract stored water from the aquifer during the dry season for irrigation. Structurally, a Bhungroo consists of a 3 m deep infiltration bed, a borehole (top 3 m is equipped with a screen pipe) and a recovery system (pump) (Figure 1-1).

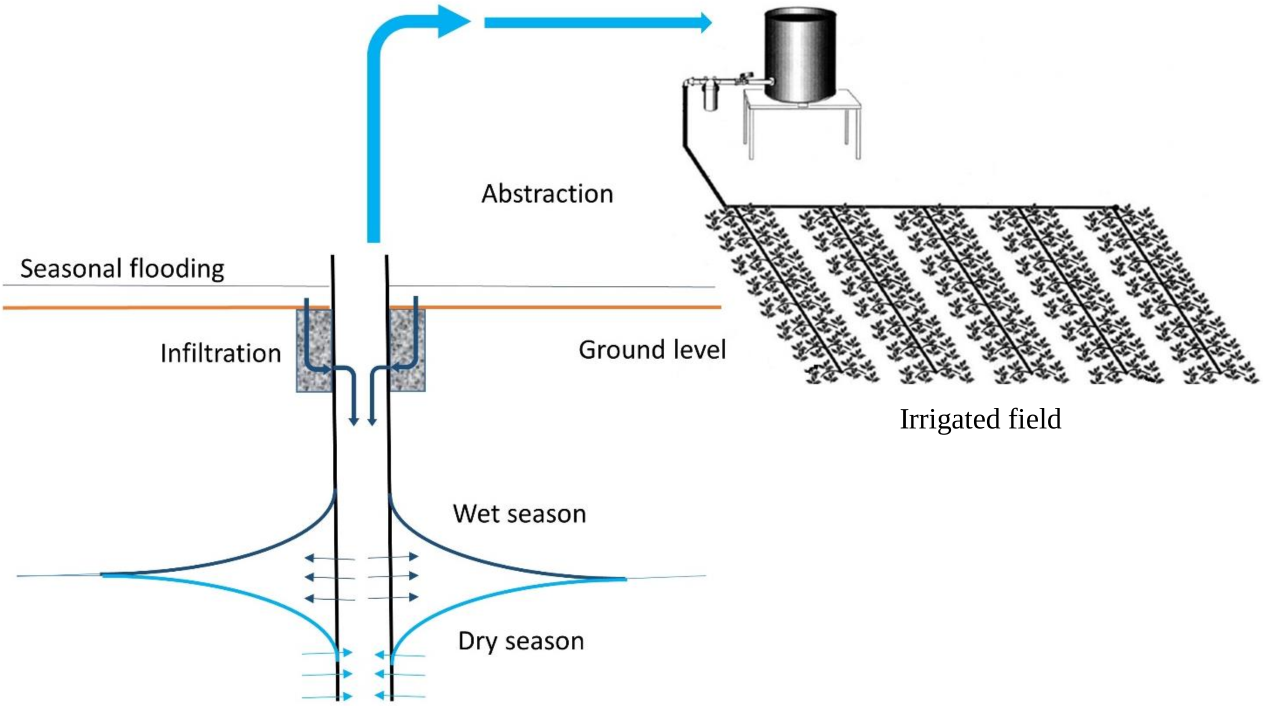

Figure 1-1. Schematic diagram of Bhungroo Irrigation Technology (Source: Owusu et al., 2017a)

The Bhungroo Irrigation Technology (BIT) has been tagged as a cost effective, decentralized water logging challenge solving technology capable of solving excess water in monsoon and no water in summer (Biplab, 2013). A Bhungroo can free five (5) acres of waterlogged land and has the capability to irrigate 8-12 ha (Biplab, 2013). The technology has also been recognized by the World Bank, hence, earned the World Bank India Development Market place 2007 award for water logging challenge solving technology (Biplab, 2013). The technology could be used for the next 20 years at near zero maintenance cost offering the possibility of dual season farming (Biplab, 2013). This translates into increasing family income by 150 % through increased farm productivity (CA, 2015) or increased annual family income from US \$200 - 1,000 within nine months (Biplab, 2013). Currently, it cost US \$24,000 to construct a BIT but has a net return of US \$5,000 - 10,000 per year. Injected water (4,000 - 40,000 m^3) into the Bhungroo can be stored for 3 to 12 months (Biplab, 2013). Through several partnerships with Naireeta Services, Bhungroo currently benefits farmers in Bangladesh, Burma/Myanmar, Cambodia, Laos, Pakistan, Sri Lanka, Vietnam, Togo, Zimbabwe and Madagascar (Christoff & Sommer, 2018; Trupti & Biplab, 2017).

In Ghana, different locations including the three Northern regions, Afram and Accra Plains have been identified as suitable for the construction of Bhungroo based on recorded incidence of flooding/waterlogging and drought (CA, 2015). Owusu et al. 2017b, however, has developed further a more detailed suitability map for Northern Ghana based on equally-weighted surface and subsurface characteristics (Figure 1-2). The current study therefore assesses the performance of three Bhungroos constructed in the Upper East and North East regions since 2015.

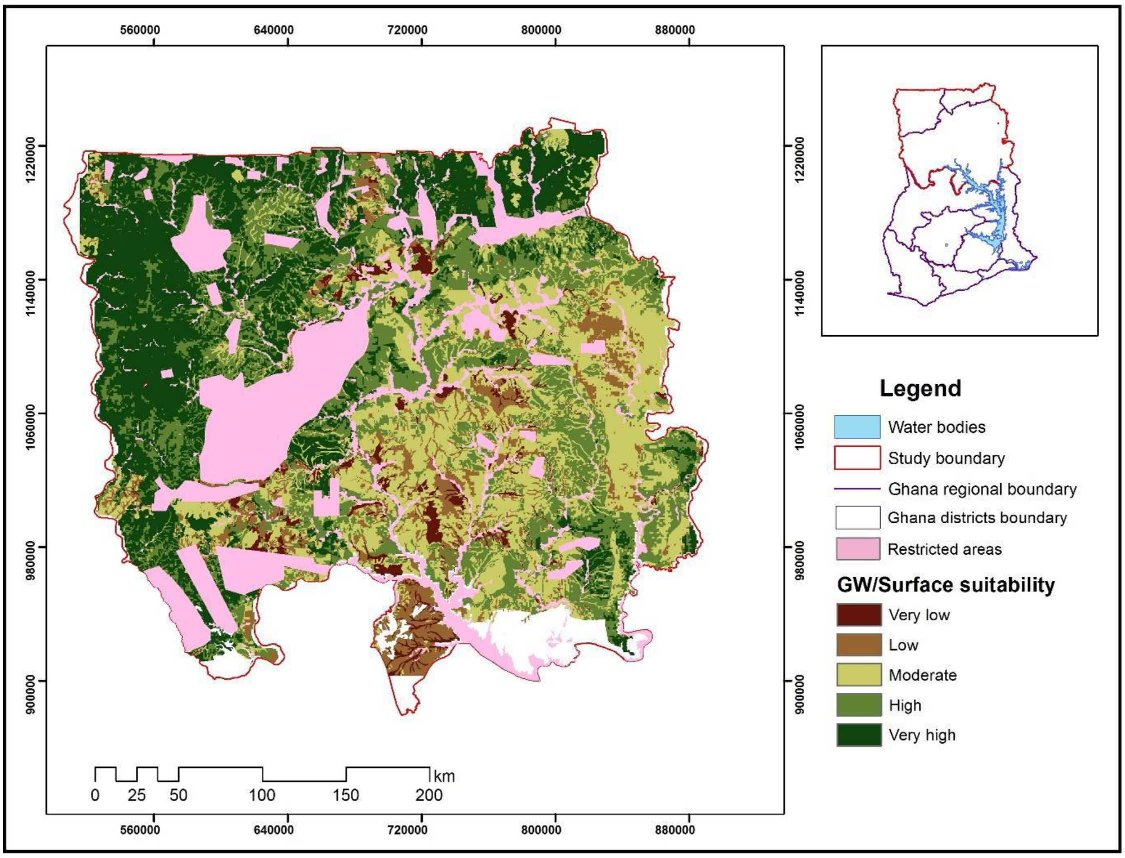

Figure 1-2. Suitability map for Bhungroo Irrigation Technology in Northern Ghana (Source: Owusu et al. 2017b)

1.2 Problem statement

Rainy season in Northern Ghana lasts for about six (6) months, during which period rural communities predominantly practice rainfed farming (Rademacher-Schulz, et al., 2014). Subsequently, at the peak of the rainy season, fertile lands are flooded, reducing the area available for cultivation. On the other hand, dry conditions during the other six months are characterized by high evapotranspiration rates (Obuobie, 2008; William et al., 2016), hence, require substantial water resources for dry season agriculture.

The introduction of the aquifer storage and recovery system (Bhungroo) in Northern Ghana was to drain flooded agricultural lands to reduce the impact of flooding as well as infiltrate floodwater into underground storage for dry season irrigation. The Bhungroo system has been reported to have worked well to the benefit of farmer across different climatic, geological and geographical environments. In India, for instance, the system is able to free 2 ha of land to irrigate 8-12 ha, inject about 4,000 - 40,000 m^3 into storage for 3 to 12 months and increase family income by 150 % (Biplap, 2013). This notwithstanding, very little information is available on the assessment of the Bhungroo in terms of recharge, storage or recovery apart from Inida. The operations of the Bhungroo as an ASR however brings to the fore related issues on the possibility of Bhungroo operations affecting groundwater. A study of 204 ASRs however concluded that problems associated with ASRs leading to its abandonment include well clogging, metals mobilization, low percentage recovery and poor water quality of recovered water (Bloetscher et al., 2014). There is however very little information regarding the performance of the Bhungroo in this regard. Thus, generally, empirical data on the performance of the Bhungroo apart from India in terms of quality and quantity is scanty. Hence, there was the need to assess the performance of the Bhungroo in terms of its influences on groundwater quality and quantity during recharge, storage and recovery. Particularly, in the context of a unique geographical, geological and hydrological environments with different floodwater characteristics, different design (with an infiltration system and minimum depth of 18 m) which somewhat different from what is common in India.

1.3 Justification for study

For more than 40 years, the purpose of ASR implementation has been varied, from drinking water supply through water storage to irrigation water supply; and so has led to the proliferation of several engineering designs to fit intended use. Experiences gained over the years in terms of hydrogeological studies, construction and implementation among others have contributed to a wealth of knowledge in the discipline (Bloetscher et al., 2014; Dillon et al., 2019). This notwithstanding, each system presents a unique opportunity to apply existing knowledge in ASR science to achieve purpose. This study therefore is intended to apply such knowledge in assessing the Bhungroo technology, while on the other hand, contributing to knowledge based on the uniqueness of the technology in the Ghanaian environment.

In the past, investments have been made into increasing food security through the introduction of agricultural technologies but some have ended in system failures. For instance, the World Bank funded Village Infrastructural Project implemented in the Northern Regions of Ghana, which was estimated to cost about US $30 million did not reap its full benefits, mainly due to inadequate technical knowledge for proper operation and maintenance (Namara, 2010). Currently, the average cost of a mechanized borehole for irrigation in Ghana is estimated at US $12,426 (Torbaghan & Burrow, 2019) while a Bhungroo costs US $24,000[1] to construct (personal communication from the Research Coordinator, Marloes Mul). The higher capital investment into the Bhungroo compared to the usual irrigation borehole makes the Bhungroo about twice more costly to construct. It is therefore imperative that a thorough performance assessment of the technology is done on a smaller scale before upscaling, so as to ensure value for money or a good return on investment.

Narratives on the need for Sustainable Development Goals (SDGs) indicate that 815 million people go hungry and 795 million people are estimated to be chronically undernourished as of 2014, due to among other things climate change (FAO et al., 2017). The demand for food and food security is pressing now than ever; especially for sub-Saharan African and particularly Northern Ghana where drought and floods significantly affect agricultural activities. Hence, efforts at applying agricultural technologies even on a local scale to increase food production and contribute towards achieving the Sustainable Development Goals (SDG) need to be supported. SDG 2 emphasizes the need to promote agricultural intensification using agricultural technologies to end hunger. This notwithstanding, the application of such technologies has to be sustainable in order not to jeopardize the ecosystem. For instance, applying technologies like the Bhungroo could potentially cause changes in groundwater

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[1] The breakdown of components making the BIT include: filter bed, mechanized borehole (diesel generator or solar panel), overhead tank, booster pump, distribution pipes and sprinkler/drip system.

quality and quantity (Bouwer, 2002; Herczeg et al. 2004; Owusu et al. 2017a). Hence, the need to assess the technology in order to minimize potential risks while ensuring sustainability.

The assessment of the water quality issues associated with the Bhungroo operations would enhance the understanding, description, and quantification of the source water for recharge, storage and recovery. The compilation and evaluation of water quality data would enhance the development of a monitoring program to collect additional data over time so as to use the data in modeling for predicting potential water quality problems for a specific, proposed recharge project.

1.4 Objectives

The main objective of the study is to assess the environmental and technical performance of the Bhungroo technology in addressing dry season communal irrigation farming. Specific objectives are to:

1. Determine the effects of Bhungroo artificial recharge, storage and recovery on groundwater characteristics
2. Assess the contribution of Bhungroo to groundwater recharge
3. Assess the performance of Bhungroo in aquifer storage and recovery
4. Determine the sustainability of the Bhungroo in addressing dry season irrigation farming.

1.5 Scope and Limitations

The research covered the North East and Upper East regions of Ghana where weathered and fractured aquifers have been located in consolidated sedimentary and crystalline basement rocks. Additionally, these areas have been known to experience flooding and long periods of drought. Generalizations of findings are therefore more appropriate to similar hydrogeological and climatic environments.

Again, though the Bhungroos were constructed in 2015, 2016 is considered as base year for analyses since field data collection started in that year. The use of secondary data in the analyses, however, was to fill gaps in the field (primary) data collected which included groundwater, floodwater and rainwater quality measurements.

This study only focused on the environmental and technical performances, and not the economic viability of Bhungroo operations, since enough primary or secondary economic data such as farmer incomes and expenditures, cost of farm inputs among others were not considered within the time frame of the study.

Inadequate data collection at the beginning of Bhungroo installation, and the irregular collection of data during monitoring resulted in the loss of very important information regarding recharge, storage and recovery.

The collapse or drastic reduction in the borehole depth of the Bhungroo wells before April 2016, meant the full potential of the Bhungroo could not be accessed.

CHAPTER TWO

2. Literature Review

The first three sections of this chapter describes groundwater occurrence, exploitation and quality in Ghana, while the next two sections followed with a description of irrigation governance and typology of irrigation systems in Ghana. The principles and concepts governing the performance of Aquifer Storage and Recovery Systems are discussed in subsequent sections, with examples of systems in other countries.

2.1 Groundwater occurrence in Ghana

Groundwater occurs in all geological formations in Ghana. The sedimentary and non-sedimentary formations cover about 43 % and 57 % respectively of the land area of Ghana (Mensah, 2010). The sedimentary rocks, belonging to the Voltaian system, are located mainly in the Volta basin and the central parts of the coastal areas. Occurrence of groundwater is controlled principally by local geology and other factors, such as topography and climate (Yidana et al., 2012; Obuobie et al., 2013). The non-sedimentary rocks mainly belonging to the Birimian super group are associated with Precambrian (Paleoproterozoic) cratonic supracrustal and intrusive rocks, generally trending North East - South West (Kortatsi, 1994; Obuobie et al. 2012).

Aquifers underlie almost all areas in the country but with high variations in yields. In the latest hydrogeological zonation, which is an improvement over previous works, Banoeng-Yakubo et al. (2010) determined five main hydrogeological provinces distinguished by their well yields, lithology, and groundwater quality. These consists of the Birimian Province, the Crystalline Basement Granitoid Complex Province, the Voltaian Province, the Pan African Province, and Coastal Sedimentary Province. The most prolific aquifers in the country are identified among the fractured and weathered zones within the non-sedimentary rocks. Aquifers of these rock formations also offer groundwater of the best quality for most uses in the country. However, yields of aquifers seldom go beyond 8 m^3/h (Kortatsi, 1994; Dapaah-Siakwan & Gyau-Boakye, 2000; USAID, 2011).

2.2 Groundwater Exploitation

The first record of groundwater exploitation dates back to when the first artesian well was successfully drilled in the 12th Century (Osiakwan, 2002). However, records of a more formal groundwater development programme could be traced to the 19th Century under the Gold Coast Survey Department, where due to intermittent droughts, population growth and congestion of larger communities, hand dug wells were developed to supply water to the urban and rural areas. Later in 1915, mention is made of a modern well located in Accra (Gyau-Boakye & Dapaah-Siakwan, 1999). Several boreholes sited in the country have been the collective efforts of government agencies, local and international donors, non-governmental organizations and individuals. Current data on the number of groundwater abstraction systems comprising boreholes, hand dug wells and dugouts in Ghana is still unavailable, though it was estimated to be more than 60,000 in 2004 (Agyekum, 2004). Groundwater development and distribution have not been evenly spread across the country due to uneven demand for domestic, irrigation and livestock. Thus, several boreholes have been sited in Northern Ghana with aquifers located between 3 and 60 m deep (HAP, 2006; USAID, 2011). Consequently, there have been concerns related to over exploitation in some parts of Northern Ghana (Anim-Gyampo et al., 2012) since aquifers are usually not extensive, restricted and occur in patches (Dapaah-Siakwan & Gyau-Boakye, 2000; Darko, 2015).

Groundwater for rural and urban water supply in Ghana has been largely towards agriculture, domestic and industry use. It is estimated that over 95 % of groundwater use is for domestic purposes (Gyau-Boakye et al., 2008) and about 50 % of the total number of borehole and hand dug wells are used solely for drinking and domestic water supply (Kortatsi, 1994). Overall, around 41 % of households in Ghana depend on groundwater for their water supply (GSS-GLSS 5, 2008) – this is generally much higher in rural areas (59 %) than urban areas (16 %). Less than 5 % of groundwater in Ghana is used for irrigation and watering of livestock and poultry (Laube et al., 2008; GSS, 2008; Agodzo et al., 2003). Increase groundwater consumption and subsequent agricultural production has often been limited by costs associated with the adoption of advanced groundwater irrigation technologies. For instance, in the Atankwidi-Anyare catchment area of the Upper East Region, farmers using buckets for irrigation cultivate an average farm size of 600 m^2 (0.06 ha), whereas those using pumps cultivate an average farm size of 2,000 m^2 (0.2 ha) (Laube et al., 2008).

Groundwater exploitation for irrigation in Ghana utilizes both shallow and deep aquifers. While shallow aquifers are often used in smallholder farms due to lower cost of construction, deep aquifers are used for large commercial or sponsored irrigation (borehole) schemes (Namara et al., 2011). The cost of mechanized boreholes in Ghana ranges from of about US $3,350 – 21,261 (Torbaghan & Burrow, 2019). Borehole irrigation systems such as the 1,500 wells within the Keta strip sponsored by the Agricultural Sector Investment Program (ASIP) (Namara et al., 2011) and the provision of 40 treadle pumps for farmers sponsored by the Food and Agriculture Organization through the Special Program for Food Security (SPFS), continue to support agricultural productivity (Adeoti et al., 2007). This notwithstanding, there has not been any major expansion of borehole-based irrigation systems in Ghana due to inadequacy of groundwater yield, cost of development, maintenance of the system, high construction and energy cost for water abstraction among others (Namara et al., 2010; Obuobie & Barry, 2010).

2.3 Groundwater quality

Groundwater quality refers to the physical, chemical and biological state of water beneath the surface of the earth. Groundwater quality can be influenced by groundwater chemistry, groundwater-rock interactions, local geology, and residence time in the aquifer among others. Hence, groundwater quality varies widely on spatial and temporal scales. In the development of ASR systems, the presence of chemical and microbial contaminants in the recharge water that could impair the use of the recovered water for its intended use at the time of operation or after project life is of utmost concern. The potential of contaminants introduced into an aquifer building up in the aquifer is also of concern. Hence, groundwater quality is among the most important parameters considered in groundwater monitoring and sustainability.

Assessing groundwater quality is generally based on a comparison of measured groundwater quality indicators against guideline values that usually relate to the potential use of the water (DSITI, 2017). Thus, the common indicators used to assess water quality relate to health of ecosystems, safety of human contact and drinking water. Indicators are selected based on, understanding, description and quantification of prevailing field conditions. Data collected from all indicators contribute to the compilation and evaluation of existing water quality data in addressing current and future water quality issues through monitoring, modelling and prediction. Due to the water-rock interactions, chemical, mineralogical and lithological data about the aquifer is useful in interpreting groundwater quality data. Physical groundwater quality indicators include temperature, pH, dissolved oxygen, conductivity and turbidity. Chemical groundwater indicators include nitrate, nitrites, ammonia, phosphates, chlorides, fluorides, bicarbonates, carbonates, arsenic, sodium, potassium, magnesium, manganese and iron. However, chemical constituents in groundwater can be categorized as major and minor. Major cations in groundwater are usually sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium ($Mg^{2+)}$ and the major anions are chloride (Cl^-), bicarbonate (HCO_3^-), sulphate (SO_4^{2-}) and nitrate (NO_3^-). Minor constituents (occur in minor amounts) include: iron (Fe; taste, staining), boron (B; toxicity to plants), fluoride (F; health risk), aluminium (Al; health risk), nitrate (NO_3^-; health risk). Biological constituents include bacteria (e.g. Salmonella, Yesinia, Campylobacter and Mycobacterium), viruses (e.g. Adenoviruses, Papovaviruses and Hepatitis A), protozoa and helminth (e.g. Gardia, Crptosporidium, Entamoeba Histolytica and Shistosoma) (WHO, 1996). However, indicators of microbiological contamination are general (process) microbial, faecal, index organism and model organism indicators. According to Strauss et al. (2001), using faecal indicator organisms particularly *Escherichia coli* (or thermotolerant coliform organisms) as the basis for microbiological contamination or pollution, is to make prudent use of scarce resources by using a simple test. Thus, unlike other indicators which may not give reliable detection limits, E. coli is universally present in large numbers in the faeces of humans and warm-blooded animals and so readily detected by simple methods. Again, they do not grow in natural waters but persist in water and can be removed by simple water treatment processes (WHO, 1996).

2.3.1 Groundwater quality in Ghana

Groundwater found in non-sedimentary rocks are generally soft with low total dissolved solids (TDS) (Mensah, 2010). Groundwater pH averages about 6.5 and is slightly acidic in the granitic terrain (Anku et al., 2009). In some instances, high iron and manganese concentrations give colour to the water when exposed to the atmosphere. Similarly, groundwater quality in the sedimentary formation is largely good for human consumption. Nonetheless, saline waters with TDS concentrations of 1,000 - 1,500 mg/l have been observed in the central portion of the Volta basin (Kortatsi, 1994; Barry et al. 2005).

Groundwater hydrochemistry is principally controlled by the silicate mineral weathering and cation exchange activity (Banoeng-Yakubo et al. 2010). These processes are pervasive throughout the country. Thus, chemical character of groundwater reflects the nature of the soil and rock media through which it passes enroute to the groundwater zone of saturation (Foster et al. 2000), and the residence time (MacDonald et al., 2002). Thus, the type and extent of chemical contamination of the groundwater is largely dependent on the geochemistry of the soil through which the water flows prior to reaching the Aquifers (Zhang et al., 2011). For instance, high fluoride concentrations in some parts of northern Ghana have been attributed principally to the dissolution of mineral fluorite in a type of granite locally known as the Bongo granite (HAP, 2006). Similarly, the report that 30% of all boreholes in Ghana have iron problem (Ayibotele, 1985), is partly attributed to the high iron proportion in bedrock of aquifers (Smedley et al., 1995).

Apart from natural factors influencing water quality, human activities such as domestic, industrial and agricultural practices impact negatively on groundwater resources. For instance, the high nitrate concentrations found in shallow groundwater have been attributed to anthropogenic sources including contamination from poorly sited and constructed sanitary facilities, surface runoff contamination of structurally defected wells and faecal contamination from poorly managed animal husbandries (Kortatsi, 1994; Duodu, 2014). Generally, cases of microbiological, chemical, agrochemical or industrial waste pollution (nitrate) of groundwater is not wide spread but few cases have been reported in isolated areas (Water Resource and Research Institute [WRRI], 1990; Ntow, 2001; Banoeng-Yakubo et al. 2010). Therefore groundwater quality is generally considered good for domestic and agricultural use in all aquifers in Ghana (Kortatsi, 1994: 2006: Darko *et al*, 2003; Amankona, 2010).

2.4 Groundwater irrigation governance

The use of water resources brings together very complex relationships among various actors in the management of the resource. In Ghana, key institutions such as the Water Directorate of the Ministry of Sanitation and Water Resources, Water Resources Commission (WRC), Council for Scientific and Industrial Research-Water Research Institute (CSIR-WRI), Ghana Water Company Limited (GWCL), Hydrological Services Department (HSD), Community Water and Sanitation Agency (CWSA) and the Environmental Protection Agency are responsible for the management of both surface and groundwater resources (Opoku-Ankomah et al., 2006; Obuobie et al., 2013). However, transboundary water resources are managed by countries which share the common resource. For instance, the Volta River Basin is managed by representatives of countries including Ghana, Benin, Togo, Cote d'Ivoire, Mali and Burkina Faso, under the Volta Basin Authority (Ampomah et al., 2008).

2.4.1 Institutional framework

Key agencies responsible for irrigation development include Ghana Irrigation Development Authority (GIDA), the District Assemblies, Environmental Protection Agency and Water Resources Commission (WRC) (Figure 2-1). GIDA, the lead agency, is responsibility for developing the country's water resources for irrigated farming, livestock watering and aquaculture (MOFA, 2011). Other responsibilities include (MOFA, 2011):

- Promote access to safer groundwater or safer irrigation practices where only marginal-quality water is available
- Promote good agricultural practice on all irrigation schemes
- Promote effective collaborations with appropriate agencies to ensure environmental compliance
- Promote effective research collaborations with other agencies and dissemination of information on safe irrigation practices for irrigated urban and peri-urban agriculture
- Assist District Assemblies in preparing responsive gender sensitive and pro-poor development plans to meet agricultural and water use related demands
- Encourage irrigation technology development and transfer
- Set national irrigation service delivery, design standards and operational guidelines

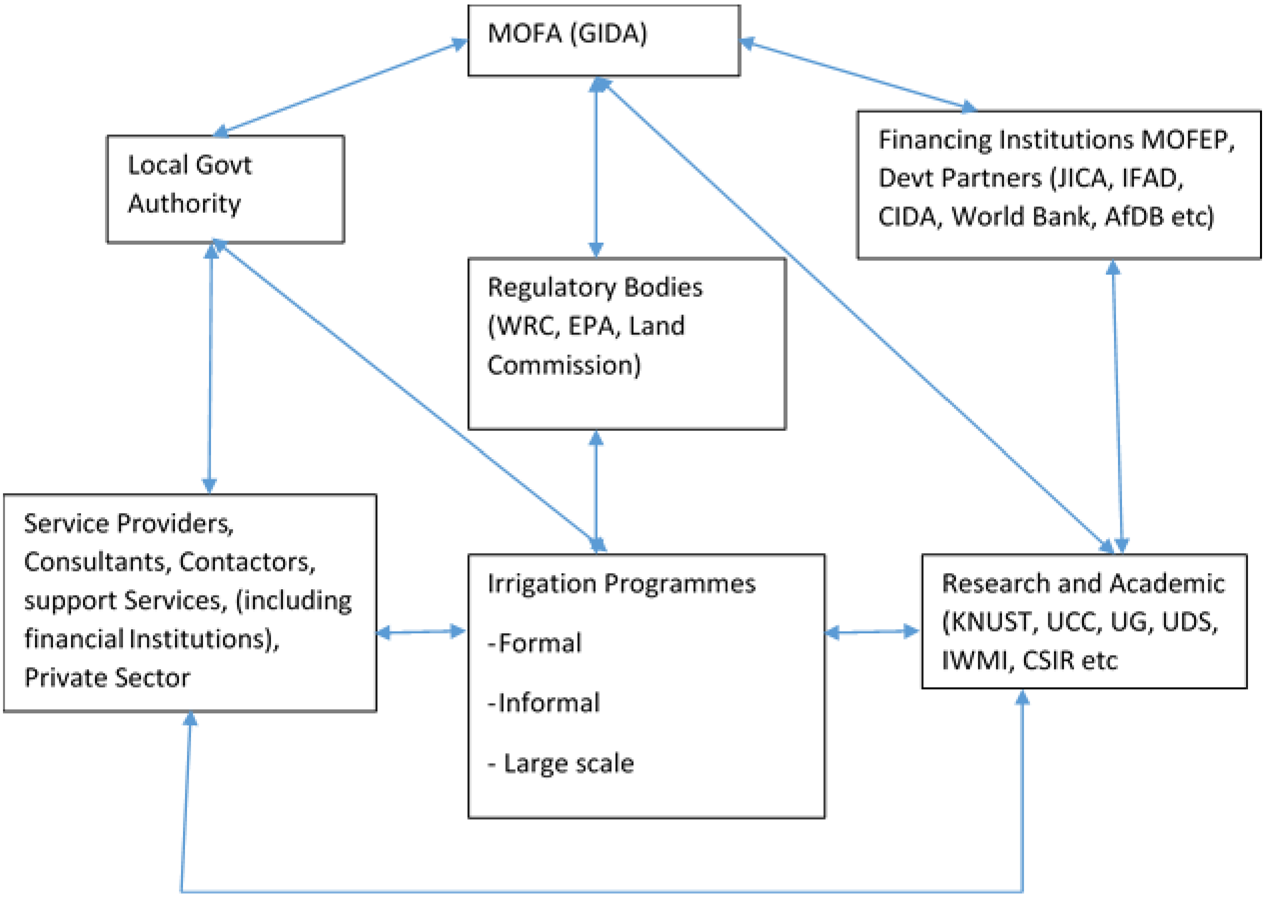

Figure 2-1: Actors and Institutions in the Irrigation sub-sector (Source: Ministry of Food and Agriculture [MOFA], 2011)

They also work in collaboration with the Department of Cooperatives, the private sector, field based Non-governmental Organizations (NGOs), and farmer associations. Over the years, GIDA had focused on the development of surface water especially dams for large scale irrigation. Hence, lack enough capacity for groundwater development. For instance the climate change adaptation report and Ghana's third national communication report to the United Nations Framework Convention for Climate Change (UNFCCC) emphasized lack of GIDA's capacity in identifying and harnessing the potential of groundwater for large scale irrigation during the 2010 extreme events in Northern Ghana (Government of Ghana [GoG], 2015).

2.4.2 Regulatory framework

Until recently, irrigation development and expansion in Ghana has been without any clear cut policy guide. Development has been dictated and affected by ad-hoc government agricultural strategies and programmes (MOFA, 2011). The launching of the National Irrigation Policy in 2010 was the beginning of streamlining irrigation activities in Ghana. The policy led by GIDA sets out to address:

1. Low agricultural productivity and slow rates of growth
2. Constrained socio-economic engagement with land and water resources
3. Environmental degradation associated with irrigated production
4. Lack of irrigation support services

Unfortunately, the policy is also silent on groundwater development for irrigation in Ghana and so has no design standards or guidelines for say borehole irrigation development. While awaiting a promulgation of this regulation, irrigation borehole developers could rely on standards or codes of practice, within Ghana and elsewhere. For instance, South Africa code of practice for Aquifer Storage and Recovery could be a good regulatory reference material for irrigation borehole development (SA EPA, 2004). Except for yield determination and specifics in terms of borehole development, regulations from the Community Water and Sanitation Agency (CWSA), under the Ministry of Sanitation and Water Resources (MSWR), provide some general guidelines on the processes for siting water supply boreholes to augment other documents on borehole irrigation development (MSWR, 2010). Though these codes of practice or guidelines may not be enough to meet the requirements for the development of an Aquifer Storage and Recovery system, it will serve as reference information for industry practitioners so as to improve practice.

2.4.3 Legal framework

Irrigation Development Authority (GIDA) established by Supreme Military Council Decree 85 performs its functions under Irrigation Development Authority Decree 1977 (S.M.C.D. 85) in the formulation and execution of plans and programmes for the development of irrigation, land use planning among others. Irrigation Development Authority Regulations 1987 (L.I. 1350) defines roles of project management, representation in the management of various Technical Departments and Farmers' Associations.

The Water Resources Commission derives its powers from Water Resources Commission Act 1996 (Act 552). WRC regulates Ghana's water resources and coordinates all related government policies. Acts 552 recognizes the President or anyone so authorized by him as holding all water resources in trust as there is no private ownership of water in Ghana. Thus, the trustee may grant rights for water use. Water Use Regulations 2001 (L.I. 1692) issued by the WRC stipulates the procedures to obtain water use permits (application, investigation, decision, objections, Environmental Impact Assessment requirements etc.) and modalities of administrative fees as well as raw water charges. In December 2001, however, parliament adopted some exemptions for water users to obtain permit. This include: where water abstracted is by manual means or by mechanical means, where abstraction level does not exceed 5 l/s, where subsistence water use for land areas not exceeding 1 hectare and where subsistence aquaculture water use not exceeding 1 hectare (Water Resources Commission 2003).

Local Governance Act 2016 (Act 936) empowers the District Assemblies with the responsibility to among other things develop, improve and manage the environment in the district. For instance, where substantial injury to the environment, amenity, public health or the economy is caused by a nuisance or is likely to result from the action or inaction of a person, a district planning authority may serve notice in the prescribed form on, and requiring that person to abate the nuisance within the time specified in the notice (Local Government Service, 2015). The districts assemblies and local authorities also assist the Water Resources Commission in giving water rights on behalf of the Water Resources Commission (Opoku-Agyemang, 2005). However, the Assembly is required to update the WRC on all water use rights approved (Opoku-Agyemang, 2005).

Environmental Protection Agency (EPA) plays regulatory and enforcement roles backed by Environmental Protection Agency Act, 1994 (Act 490). EPA, therefore performs its functions through Environmental Assessment Regulations 1999 (L.I. 1652). This LI stipulates the procedures, under EPA Act 490, for acquiring Environmental Permits and conducting Environmental Impact Assessments. Hence, dealings in the domains of agriculture, drainage and irrigation, construction, water supply among others which have or are likely to have adverse effects on the environment of public health are investigated under these regulations (Fuest et al., 2005).

The Office of the Administrator of Stool Land Act 1994 (Act 481) empowers the office to manage revenue drawn from stool lands under the overall control of the Lands Commission. According to State Lands Act 1962 (Act 125), the President has the power to acquire land for the public interest by activating the compulsory acquisition process or the state can acquire lands by powers of eminent domain with no compensation unless required to do so by a Court ruling.

2.5 Typology of Groundwater irrigation systems in Ghana

Irrigation systems in Ghana are classified as Conventional and Emerging. The conventional systems are mainly introduced and developed by the Government of Ghana and non-governmental organizations (NGOs), or are developed by communities or individuals over a number of years. These includes: public surface irrigation systems, small reservoir-based communal irrigation systems, domestic wastewater and storm water irrigation, recession agriculture or residual moisture irrigation and traditional shallow groundwater irrigation (Namara et al., 2010; Ofosu, 2011). The traditional shallow groundwater irrigation which is of interest (because it deals with groundwater usage) is practiced across Ghana particularly in the Volta region along the Keta strip and in the Northern Regions. This system has well been used for over 200 years but has transformed into other emerging groundwater systems due to the introduction of electric, diesel, petrol, solar and wind-powered engines (Namara et al., 2010; Ofosu, 2011).

The Emerging Irrigation Systems are those initiated and developed by private entrepreneurs and farmers, either autonomously or with little support from the government and/or NGOs. They also include groundwater irrigation systems, river lift irrigation system, public-private partnership-based commercial irrigation system, lowland/inland valley rice water capture system and small reservoirs/dugout-based private irrigation systems. Unlike the traditional shallow groundwater irrigation these systems have emerged but have not been widely used due to constraints such as drilling technology, costs of development and lack of energy. This notwithstanding, sub-typologies including seasonal shallow-well systems, permanent shallow-well systems, shallow-tube well systems and communal borehole systems are becoming dominant in specific agro-ecological socioeconomic and institutional setting (Namara et al., 2010).

2.6 Managed Aquifer Recharge (MAR) Systems

For the past 60 years the world has witnessed unparalleled groundwater extraction, over exploitation as well as development of new technologies for water treatment that together drive the advancement in intentional groundwater replenishment called Managed Aquifer Recharge (MAR) (Dillon et al. 2019). MAR technologies operate using different methods to maintain, enhance and secure groundwater systems under stress (Dillon et al., 2009 and 2019). Table 2-1 presents the different MAR methods.

Table 2-1. Variety of methods used in Managed Aquifer Recharge technologies

Type of MAR	**Method and Use**
Aquifer Storage and Recovery (ASR)	Well and borehole recharge: Useful in brackish or freshwater aquifers for water storage.
Aquifer Storage, Transfer and Recovery (ASTR)	Well and borehole recharge: Useful in achieving additional water treatment in the aquifer.
Infiltration ponds	Spreading method: Useful in diverting surface water sources, through an unsaturated zone, into underlying unconfined aquifer
Infiltration galleries	Spreading method: Useful in allowing infiltration from buried perforated pipes, through unsaturated zone into unconfined aquifer
Soil aquifer treatment (SAT)	Spreading method: useful in treating wastewater effluent or stormwater through the unsaturated zone into unconfined aquifer
Percolation tanks or recharge weirs	In-channel modification: To enhance storage in unconfined aquifers from dams built in ephemeral streams
Rainwater harvesting for aquifer storage	Runoff harvesting: To enhance water storage in unconfined aquifers
Recharge releases	In-channel modification: To enhance recharge (infiltration) into underlying aquifers

Type of MAR	Method and Use
Dry wells	Well and borehole recharge: To infiltrate high quality water into the unconfined aquifer at depth
Bank filtration	Induced bank infiltration: To induce infiltration from the surface water body
Dune filtration	Induced bank infiltration: Useful for improving water quality and balancing supply with demand
Underground dams	In-channel modification: To retain flood flows in saturated alluvium for stock and domestic use
Sand dams	In-channel modification: To enhance the creation of an aquifer to meet dry season water demand

Source: Dillon et al. (2009) and IGRAC (2016)

2.6.1 Aquifer Storage and Recovery (ASR)

ASR, sometimes referred to as artificial recharge (AR) or aquifer recharge and recovery (ARR), began around the 1960s in United States (Pyne, 2005). Typically, water is injected into an aquifer, stored and recovered for disinfection and use. In the process, injected water displaces ambient ground water and creating a ‘‘bubble’’ or a ‘‘bottle brush’’ or “upside-down Christmas tree” owing to aquifer heterogeneity (Missimer et al., 2002; Vacher et al., 2006). As of 2016 there were over 500 ASR wells operating in the United States, spread among at least 25 of the 52 States (Dillon et al. 2019). ASR technology has been applied in several countries including Australia, South Africa and Netherlands, however, there is no available record of its use in Ghana. Hence, the Bhungroo ASR system seems to be the first of its kind undertaken specially for agricultural use in Ghana.

2.6.2 ASR Concepts and Terminologies

Aquifer recharge is the addition of water to groundwater storage either through a natural or artificial process. Thus, recharge is defined as water that moves from the land surface or the unsaturated zone into the saturated zone (Meinzer, 1923; Heath, 1983). Aquifer storage, however, refers to the subsurface, reservoir or water bearing rock (confined, unconfined or semiconfined) receiving recharge water and recovery or abstraction refers to the pumped water from storage (Gale et al., 2002).

Different concepts in the fields of hydrology, hydrogeology, geochemistry and sustainability are relied on to explain the processes involved in aquifer recharge, storage and recovery. Generally, the analyses of ASR relies on the law of conservation of mass and Darcy's law to estimate the water balance and quantify the flow of water from source to recovery (Kovalevsky et al. (2004). Kovalevsky et al. (2004) further explains that the **water balance** equation is used to describe the flow of water in and out of a system. This follows the **law of conservation of mass** which states that mass can neither be created nor destroyed but transformed from one form to the other. Thus, typically the water balance equation is represented as:

Inflow = outflow + change of storage.

Darcy's law also explains the movement of groundwater through a porous medium and states that the rate of discharge (Q) is proportional to the gradient in hydraulic head (I) and the hydraulic conductivity (K) (Darcy, 1856). i.e.

$Q = KIA$

Q is discharge (L^3/T), K is hydraulic conductivity (permeability) (L/T),

I is hydraulic gradient, A is cross-sectional area through which flow occurs (L^2)

The macroscopic characteristics of the aquifer material in relation to the transmission behavior of water in the aquifer explains the hydraulic properties (hydraulic conductivity, transmissivity, storativity and specific yield) of the aquifer/recharge well. The zone of mixed water which interfaces the injected/recharged water and native groundwater called the buffer zone is a function of the recovery efficiency i.e. the percentage of recharged water recovered (Maliva and Missimer, 2010).

Other important concepts often used to explain the aquifer/rock-water interactions or the geochemistry of the ASR system relates to the hydrochemical properties of groundwater, mixing ratios, sediment transport, cation exchange, sorption and the water quality. For instance, hydrochemical analysis exposes the water quality by measuring the concentration of parameters and comparing them with the drinking, industrial and irrigation water standards and helps in understanding the change in quality due to rock–water interaction or any type of anthropogenic influence (Kelley 1940; Wilcox 1948).

The principle of **environmental sustainability** is another very important principle employed in the establishment and the operations of ASR. This is to ensure the wise use of limited groundwater resources to meet present needs without compromising the future generation to meet their own needs. Thus, issues such as groundwater overexpoitation, pollution, depletion, safe yield and sustainable yield are covered. The concept of Integrated Water Resources Management apart from requiring the careful monitoring of the water table elevation to avoid groundwater overexploitation (Rushton, 1994) also ensures that decision making on groundwater resources bring together all stakeholders (WRC, 2012).

The terminologies below are used to explain ASR concepts: Aquifers, regolith, confined aquifers, porosity, hydraulic conductivity, transmissivity, recovery efficiency, specific capacity and buffer zone.

A. Aquifers

An aquifer is a saturated bed, geologic formation, or group of formations from which significant amounts of groundwater can be pumped for domestic, municipal, or agricultural uses.

B. Regolith

It is a geologic term used to describe the loose and discontinuous blanket of decayed rock debris overlying solid bedrock. The term "soil" is sometimes used for this unconsolidated material, but soil is only the very uppermost part of the regolith, where the physical and chemical weatherings are the most active. Herein, the regolith includes the soil layer and the underlying loose material.

C. Phreatic water (Groundwater)

This is defined as water that enters freely into wells under both confined and unconfined conditions

D. Confined Aquifers

When a borehole is drilled through an overlying imperious layer into a water bearing formation and into another impervious basal bed, the aquifer is called a confined aquifer.

E. Porosity

The porosity of a sediment or rock formation is defined as the fraction of the material's volume that is not occupied by solids.

F. Hydraulic Conductivity

The property of a water bearing formation that relates to its pipeline or conduit function is called hydraulic conductivity (k) and is defined as the ability of a porous medium to transmit water.

G. Transmissivity

The transmissivity of an aquifer is defined as the hydraulic conductivity times the thickness of the aquifer: transmissivity = hydraulic conductivity x aquifer thickness Residence time

The residence time and flow path are determined by factors like aquifer thickness, permeability, porosity and amount of recharge.

H. Recovery efficiency

The percentage of recharged water recovered. It is a function of the hydraulic properties of the storage aquifer, native water chemistry, and buffer zone establishment

I. Specific capacity

The pumping flow rate per unit change in water level at the well. The units used in this report are gallons per minute per foot. Specific capacity during recharge is less than in recovery

J. Buffer zone

A zone of mixed water at the interface of the injected, or recharge, water and native groundwater. In most instances, the native groundwater is of lower quality than the recharge water and therefore undesirable for recovery. The volume of recharge water in the zone is called the buffer volume. More water is recharged than recovered during early aquifer storage and recovery operations to establish this zone.

2.6.3 Design of ASR

The viability of an ASR is dependent on the underlying geology of an area, topography, presence and nature of aquifers, local hydrology, land use, ambient groundwater quality and anticipated uses of the recovered water (Dillon et al. 2009; Karamouz et al., 2010). These factors also occasion the differences in ASR design. ASRs can differ with respect to the entire chain of system design, treatment processes and method of injection among others (Table 2-2). For instance, a comparison between Bhungroo and other ASR systems show that the former operates under gravity with no pretreatment whereas the latter requires pretreatment before injection of recharge water under pressure. It is however noted that clogging remains a general issue confronting ASRs irrespective of the design (Bouwer et al. 2008).

Though it could not be inferred from Table 2-2, Murray (2008) observes that two main physical characteristics determine whether or not an aquifer is suitable for accepting storing and recovering artificially recharged water. These are the aquifer's hydraulic conductivity and its storage capacity (Murray, 2008). A third significant factor is the aquifer's hydraulic gradient and the natural geological barriers to flow. These relate mostly to the recovery of the recharged water (Murray, 2008). Aquifers which have high hydraulic conductivity and which have high storage capacity are more suitable for receiving extra recharge water than those which have low conductivity and capacity (Dillon et al. 2019). Highly permeable aquifers, however, are not always ideal for artificial recharge if high quality water is stored in a saline aquifer, as this may result in undesirably high blending ratios (Dillon et al. 2009). Aquifers with high hydraulic conductivity and high hydraulic gradient may also be problematic, as water will flow rapidly away from the point of recharge and may be difficult to recover. This problem is greatest in fractured aquifers and can be averted either by placing recovery boreholes down-gradient of the recharge facility, or by reversing the hydraulic gradient during pumping so that water flows back towards the initial point of recharge.

Table 2-2. ASR Designs in India, Australia and USA

Parameters	**Bhungroo**		**ASR**		
	India-Gujarat	***India-***	***USA-Florida***	***Australia***	**USA-Florida**
Objective	Agriculture	Agriculture	Domestic	Landscape irrigation	Domestic
Population/Area served	8-12 ha	NA	NA	NA	NA
Source of Recharge	Floodwater, Run off from fields	Floodwater, Run off from fields	Surface runoff	Stormwater runoff	River
Pre-treatment	Not required	Not required	Required	Required	Required
Recharge rate	220mm/year	NA	NA	62500m^3/years	3800m^3/day (270 days)
Type of recharge	Gravity	Gravity	Injection (under pressure)	Injection (under pressure)	Injection (under pressure)
Aquifer storage	4000-40000m^3	NA	54000m^3	NA	NA

Parameters	**Bhungroo**		**ASR**		
Residence Time	90 days	NA	3 days	NA	9 months
Aquifer type	Limestone, alluvial, semiconfined	NA	NA	Limestone, unconfined	NA
Borehole depth	NA	Up to 50 m	NA	NA	NA
Recovery rate	***NA***	2590m^3/day	NA	NA	3800m^3/day
Recovery Efficiency	60 %	NA	51.2 % (36 days)		N/A
Issues	Clogging of wells	NA	NA	clogging	NA
Benefits	NA	High suspended loads (>2000 mg/l) removed	NA	NA	NA
Source	Hollander et al. (2009)	Malik et al. (2002)	Reese (2002)	Pavelic et al. (2006)	Eckman et al. (2004)

Although all type of aquifers i.e. unconfined, semi-confined and confined, are possible to use with ASR well, unconfined aquifers are less suited (Pyne, 2005; Dillon et al. 2019).

ASR is designed to meet these requirements (Pyne, 2005; Bloetscher et al., 2014; Dillon et al., 2019):

- Protect or improve groundwater quality
- Ensure that the required water quality is recovered
- Protect aquifers from damage either through recharge or recovery
- Avoid problems such as clogging or excessive extraction of aquifer sediments
- Ensure design is consistent with environmental flow requirements and catchment management strategy.

Additional design requirements may include source water diversion, treatment, conveyance, and injection to the subsurface through one or more wells, with subsequent pumping to recover stored water (Figure 2-2). The injection (artificial recharge), storage, and recovery process forms one cycle of ASR (Figure 2-2).

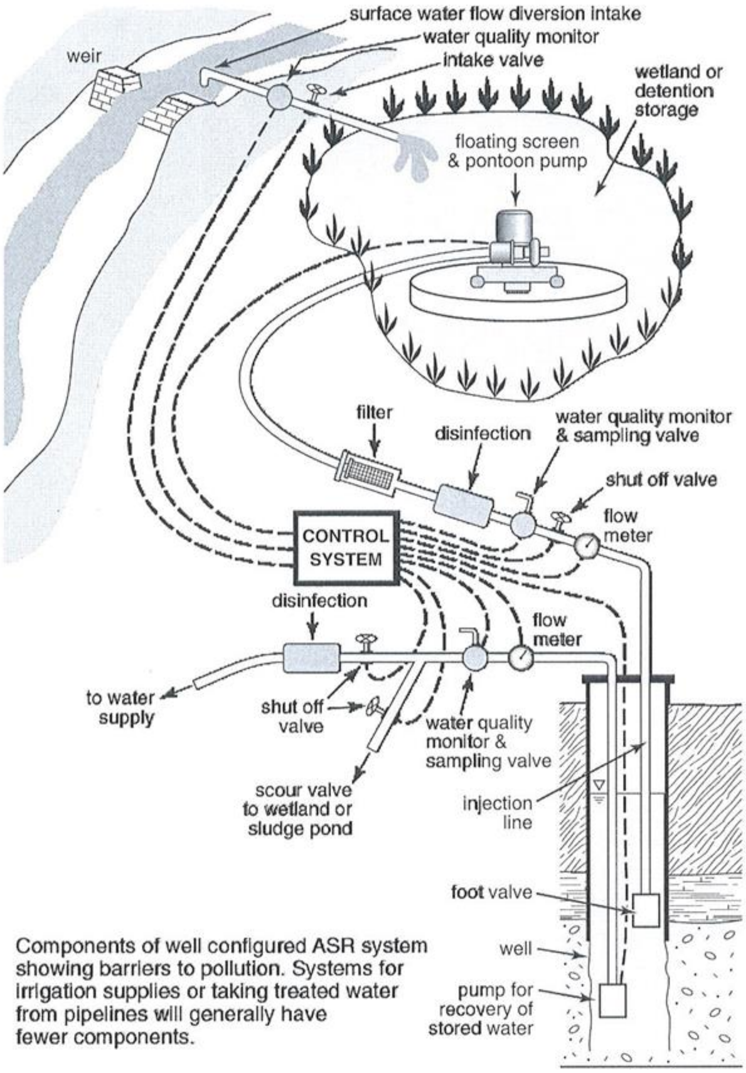

Figure 2-2. Components of a well-configured ASR system showing barriers to pollution

(Source: Martin and Dillon, 2002)

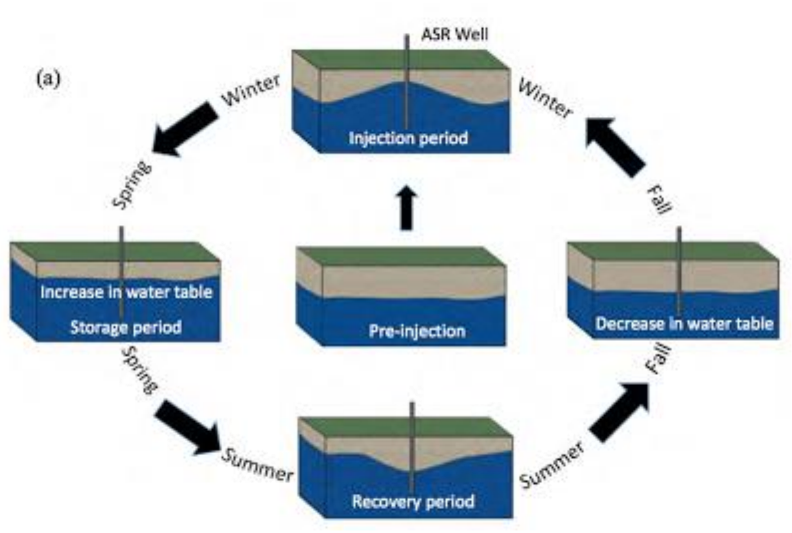

Figure 2-3. A typical ASR system cycle (Southwest Hydrology, 2008)

2.6.4 ASR performance assessment

ASRs go through thorough framework for assessing the feasibility of the system before full operations begin (Figure 2-4). Depending on design and use, all ASR systems are required to meet some performance standards to be regarded as feasible. An understanding of the local hydrogeology is primary to determining the technical feasibility of ASR projects (Gale, 2005; Murray, 2008; Dillon et al. 2009).

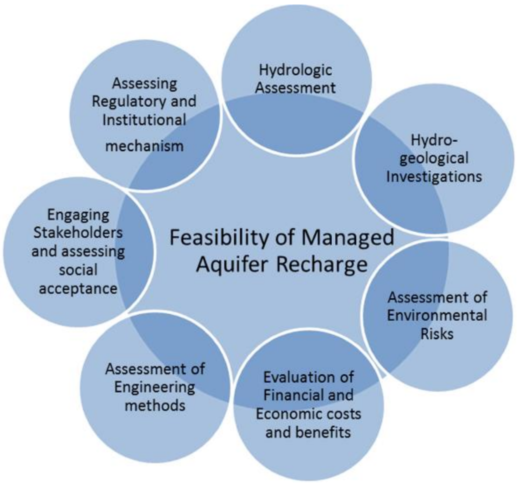

Figure 2-4. A framework for assessing the feasibility of aquifer storage and recovery (Source: Arshad et al., 2014).

Arshad et al. (2014) used a seven component approach in assessing the feasibility of aquifer storage and recovery systems. This approach mainly considers regulatory, economics, social, technical and environmental issues in its assessment framework. Hydrologic assessment, assessment of engineering methods and hydrogeological investigation, form the technical aspects of the framework dealing with the efficiency or functionality of the physical components of the system. On the other hand, environmental risk in the framework assessed the functionality of the system to mitigate against groundwater pollution. Similar documents such as the Draft Managed Aquifer Recharge Guidelines also provides a stepwise approach to determining the feasibility of an ASR (EPHC/NRMMC/NHMRC, 2008; Dillon & Arshad, 2016):

- Stage 1 considers the economic, social and environmental factors in project selection
- Stage 2 involves investigations into site specific conditions,
- Stage 3 involves commissioning trials
- Stage 4 is operations.

The elements for assessing ASR performance at Stage 3 which is also critical for the determination of Bhungroo performance include: the adequacy and suitability of source water for recharge, suitability of aquifer for storage and recovery, suitability and sufficiency of recovered water to meet demand and sufficient land to harvest and treat water (EPHC/NRMMC/NHMRC, 2008; Dillon et al., 2009).

2.6.4.1 Technical performance assessment of ASRs

A. Recharge system

The recharge performance of ASR is influenced by the availability of excess surface water and the efficiency of the recharge system to convey water underground (Bouwer, 2002; Maliva & Missimer, 2010). However, the quality of available excess surface water also influences recharge performance of the system. For instance, poor quality surface water reduces the recharge performance of ASR wells due to debris plugging well screens (Pyne, 1995; Barry et al., 2010; Bloestcher et al., 2014). Further, the nature or type of recharge system also influences the efficiency of recharge, since it limits the volumes of water conveyed underground (Bouwer, 2002; Bloestcher et al., 2014). For instance, the use of injection systems where recharge water is under pressure contributes larger volumes of water to storage than natural infiltration systems under gravity (Barry et al., 2010; Bloestcher et al., 2014). For artificial systems, such as the Bhungroo, infiltration rate and recharge volumes are a function of the filter bed/basin, hence, increasing the infiltration area, increases the infiltration rate and the recharge volume (Owusu et al., 2017a). Consequently, variations in recharge volumes which reflect in water level changes make the latter a useful indicator in assessing the recharge performance of ASR wells (Pavelic et al., 2008; Dillon et al., 2009; Pavelic et al., 2012).

Typically, overall ASR recharge performance is evaluated using recharge methods such as water table fluctuation, tracer techniques, water budget, Darcy’s law, empirical methods and groundwater models among others (Bouwer, 2002; Dillon et al., 2009; Dillion et al., 2018). The most appropriate choice depends on available data, local geographic and topographic conditions, spatial and temporal scale required and reliability of results obtained by different methods (Islam et al., 2015). This notwithstanding, the most widely used method is the water table fluctuation method (Allison et al., 1990; Healy & Cook., 2002; Obuobie, 2008).

B. Storage system

The storage performance of an ASR depends on hydraulic properties of the storage zone aquifer and the confining strata, the interaction of stored water with ambient groundwater and aquifer rock or sediment, aquifer storage size, permeability and connections with other aquifers (Bouwer, 2002; Maliva et al., 2006; Dillon et al., 2009; Bouwer et al., 2009). Aquifer heterogeneity and fluid-rock or fluid-sediment interactions also impact ASR storage performance (Maliva et al., 2005; Ward et al., 2009; Zuurbier et al., 2013). In evaluating the importance of various hydrogeologic factors on ASR system performance, Maliva et al. (2006)

observed that salinity of the ambient water and dispersivity of the storage zone aquifer had a great impact on recovery efficiency. Maliva et al. (2006) argues that as salinity increases, lesser amounts of mixing of ambient and stored water may occur before the stored water exceeds a water quality threshold. Higher salinities also result in greater convective movement of stored water in response to density gradients. The presence of high-transmissivity flow zones within the storage zone aquifer can result in excessive mixing and migration of stored water (Pavelic et al. 2002; Dillon et al., 2009; Ward et al., 2007 and 2009; Zuurbier et al., 2013). Where the storage zone contains water quality that has total dissolved solids (TDS) exceeding about 5,000 mg/l, the density difference between the stored water and the surrounding ambient groundwater can reduce recovery efficiency, particularly during extended storage periods (Maliva et al. 2006; Dillon et al., 2009).

Water level changes are indicative of changes in the physical storage of the aquifer (Bouwer, 2002; Obuobie, 2008). Hence, the amount of storage achieved is a function of the increase in head (Δh) above static water level. No net storage occurs if the water level returns to the pre-recharge static level. The problem with recharging ASR systems, therefore, is about achieving a useful storage (Maliva & Missimer, 2010; Dillion et al., 2009).

C. Recovery system

Recovery is a very important function which often defines the performance of an ASR system (Zuurbier et al., 2013; Ringleb et al., 2016). It is generally defined as the ratio of the amount of water stored that can be recovered without further treatment to the total amount of water recharged (Kimbler et al., 1975; Maliva et al. 2006; Dillon et al., 2009; Ringleb et al., 2016). It is not uncommon to have reduced efficiency because of mixing of original (ambient) ground and surface (recharge) water (Eastwood & Stanfield, 2001; Lowry & Anderson, 2006). Primary mechanisms that can influence the efficiency of ASR systems are those that can introduce or enhance mixing in the subsurface including density-gradient driven convection, dispersion and diffusion, heterogeneity of the aquifers and rate-limited mass transfer (Lu et al., 2011; Bloetscher et al., 2014). Additional factors such as salinity, aquifer thickness, hydraulic conductivity, hydraulic gradient, aquifer anisotropy, and hydrodynamic dispersion also influence aquifer recovery performance (Ward et al., 2007 & 2008; Maliva et al., 2005 & 2006). The first ASR cycle at a new site provides an opportunity to gather enough data on recovery efficiency and ASR performance. Initial cycle recovery water quality results for several ASR sites show very little mixing with surrounding water, however, mixing increases with subsequent cycles (Bouwer et al., 2009; Maliva & Missimer, 2010). This is because the residual water not recovered in one cycle becomes a transition or buffer zone of marginal quality surrounding the stored water in the next cycle (Bouwer et al., 2009; Barry et al. 2010). Frequent recovery increases the recovery efficiency of wells and vice versa since potential well clogging is reduced (Bloestcher et al., 2014). Wells which are not frequently recovered result in a 10-20 % loss in efficiency each year, rendering the wells unusable within 3-5 years (Bouwer et al., 2009).

2.6.4.2 Environmental performance assessment of ASRs

By design, the implementation of ASR implies that aquifers are vulnerable to the introduction of non-native waters resulting in leaching and mobilization of metals, such as As, Fe, Mn, among others due to differences in the oxidation-reduction potential of injected and receiving waters (Arthur et al., 2002; Vanderzalm et al., 2014; Dillion et al., 2018;). However, the treatment of water, near for example drinking standards, prior to recharge does not necessarily protect the aquifer from contamination due to the possible formation of chloroform in recovered water after chlorination (Dillion et al. 2009). Thus, aquifer interactions with recharged water could result in ineffective contaminant removal or the introduction of new contaminants (Dillon et al., 2009, Maliva & Missimer, 2010; Dillon et al. 2019). Other processes hampering aquifer performance include well clogging due to chemical precipitation reactions, increased turbidity and microbial growth, virus survival and transport, organic and inorganic colloidal transport (Bouwer et al., 2009; Barry et al. 2010; Dillon et al., 2019). For instance, infiltration water depth less than 3 m promote algae growth, clogging the voids of the soil, reducing infiltration and increasing the maintenance cost of the infiltration basin or filter bed (Hamdan & Jaber, 2001; Bouwer et al., 2009; Maliva & Missimer, 2010). This notwithstanding, aquifer interactions with recharged water could also result in pathogen inactivation, and biodegradation of some organic contaminants during the residence time of recharged water in the soil and/or aquifer within an attenuation zone (Maliva & Missimer, 2010; Dillon et al. 2019).

For the past 60 years, water quality evaluations using a more exact localized information on aquifer properties and source water quality (some of which are likely to require site-specific investigations as proposed in the Draft MAR Guidelines) have been used in assessing the environmental performance of ASR systems (EPHC/NRMMC/NHMRC, 2008). Specifically, the use of pathogens (viruses, protozoa and bacteria), inorganic chemicals, salinity, sodicity, nutrients (nitrogen, phosphorus, organic carbon), turbidity and particulates, and radionuclides have been very useful indicators in assessing ASRs (Vanderzalm et al., 2014; Dillion et al. 2009; Dillion et al. 2018).

CHAPTER THREE

3. Study Area

The chapter begins with a description of the demography, climate, geology and hydrogeology followed by a detailed description of Bhungroo construction, characteristics and potential socioeconomic impact in terms food security, health, employment and migration.

3.1 Brief description of project area

The study area is located in the Upper East and North East regions of Ghana within the White Volta basin (Figure 3-1). The White Volta River Basin is a sub-basin of the Volta River Basin in West Africa. It covers about 106,000 km^2, and the major riparian countries are Burkina Faso and Ghana (Obuobie, 2008).

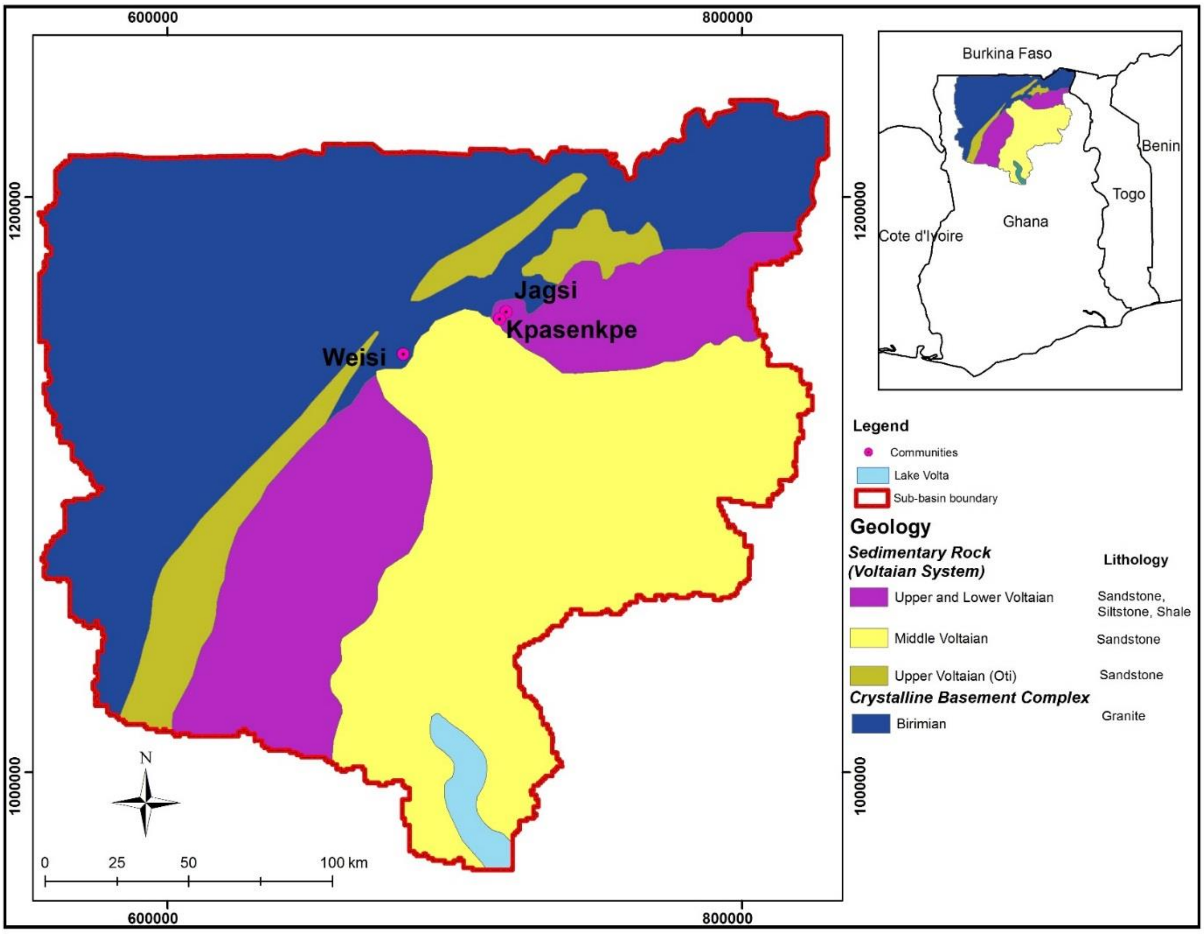

Figure 3-1. Study area map

The three communities under study; Kpasenkpe (West Mamprusi Municipality), Jagsi (West Mamprusi Municipality) and Weisi (Builsa South District) were located at 10^{o} 18’50.985”N longitude 0^{o} 58’20.662 W, 10^{o} 18’50.985”N longitude 0^{o} 58’20.662 W and 10^{o} 18’50.985”N longitude 0^{o} 58’20.662 W respectively. At the time of study, these were the communities with installed Bhungroo boreholes. Thus, all communities with Bhungroos were selected. These communities also have very similar demography and environmental setting. The land is generally flat with a few undulating areas and slope less than 2 % (HAP, 2011; Owusu et al., 2017b). The major land cover type in the study area is savannah (Mul et al., 2015). These are grassland interspersed with shrubs and trees covering about 86 % of the basin (World Resources Institute, 2003). Crop production is generally on subsistence basis where farmers produce to feed their households and then sell the rest. Staples cultivated include yam, beans, groundnuts, maize, millet, rice, sorghum, tomatoes, onions and pepper. Fuel wood is regarded as a major source of domestic fuel, hence, deforestation or falling of trees for firewood is contributing to changes in vegetation as well as threatening the climate.

3.2 Demography

The major occupation of the population is farming, with about 80 % of households into agriculture (Ghana Statistical Service [GSS], 2010). This include more than 60 % of the economically active persons above 15 years (GSS, 2010). Predominantly, farming is rainfed with farm sizes usually less than three acres (Barry et al., 2005). Rainfed agriculture is highly dependent on adequate and well distributed rainfall, however, erratic climatic conditions have contributed to lower agricultural outputs. Apart from a few farmers practicing dry season irrigation, dry season unemployment is high since there are virtually no ongoing farming activities; driving the men and youth to seasonally migrate to urban centres. Sanitation in these communities is poor since a high proportion of households (more than 80 %) defecate in the open/bush with public dump (open space) as the most widely used means of disposing solid waste (refuse) (GSS, 2010). Household liquid waste is just disposed off into the street/outside.

3.3 Climate

Northern Ghana has a tropical climate characterized by low altitude and dry conditions driven by three air masses: the Southwest Monsoon, the Northeast Trade Winds and the Equatorial Easterly (Hess, 2011). As the moist Southwest Monsoon encounters the dry Tropical Continental Air Mass, together they form the Inter Tropical Convergence Zone (ITCZ) (Gyau-Boakye, 2001). The movement of the ITCZ is the driving force of the wet and dry seasons in Ghana.

The annual average potential evapotranspiration is about 2500 mm/yr (Amisigo, 1996) with actual evapotranspiration amounting to 70-90% of the total rainfall (Andreini et al., 2000; Martin, 2005). For most part of the year, from 6 to 9 months, potential evapotranspiration exceeds rainfall (HAP, 2011).

Average monthly temperatures vary betweem 36 - 27 ^{o}C from March to August (Oguntunde, 2004). Maximum daily temperatures from March to April vary from 32 - 44 ^{o}C; while minimum daily temperatures from December to February can drop to its lowest at about 14 ^{o}C in January (FAO, 1997).

3.3.1 Flooding within the Bhungroo catchment

Flooding is considered a major water management problem in the study area (WRC, 2008), but it is the main source of water for Bhungroo recharge. Floods in the basin can be very devastating, especially for the years 1994, 1999 and 2007 (Anayah & Kaluarachchi, 2009). In September 2007 for instance, approximately 2,600 km^{2} of lands nearer to the main White Volta river and its tributaries became flooded, equivalent to some 5 % of the entire White Volta Basin area (WRC, 2008). Over 12,000 ha of farmlands were destroyed in the Upper East Region alone (WRC, 2008), reducing annual food production by 66% in the region (Biederlack and River, 2009). There are price hikes with persistent food insecurity during such periods due to high demand for the little food available.

Since most road networks are destroyed, transporting food supplies into the area or salvaging the crops left on the farm become a challenge. Thus, the disproportionate impact of floods and droughts reduce the resilience of many households resulting in outcomes such as the limited access to sufficient and nutritious food (Biederlack and River, 2009).

Generally, flooding at the Bhungroo site is caused by runoff collected from several agricultural fields accumulating in flat areas and valley bottoms. Flooding usually begins in June till ending of September resulting in water logging from a couple of weeks to months. Flood water depths at the Bhungroo sites range from 10 -50 cm (Owusu et al., 2017b).

Water logging at the Weisi site is affected primary by flooding from Weisi pond (100 m away from Bhungroo) which is connected to the Sisili floodplains. Similarly, the Jagsi Bhungroo is also affected by a river channel (50 m away from the Bhungroo) connected to the Duu River (tributary to the White Volta River) flood plains. However, unlike the Jagsi and the Weisi Bhungroo sites, flooding at the Kpasenkpe site is highly influenced by its location in a valley.

3.4 Geology and Hydrogeology

The Volta Basin is dominated by the Basement crystalline rocks of Precambrian age and the Consolidated Sedimentary rocks of the Paleozoic age with the study area lying largely within the later. Thus, Jagsi and Kpasenkpe are in the consolidated sedimentary formation commonly categorized as the Voltaian system whereas Weisi is in the crystalline formation categorized as Birimian system (Figure 7).

Basement crystalline rocks consist of granite-gneiss-greenstone rocks, anorogenic intrusions and strongly deformed metamorphic rocks (Key, 1992). The crystalline formation of Precambrian age consists of different categories such as the Tarkwan group, Buem formation, Birimian super group (with associated granitoid intrusion), Togo formation and Dahomeyan formation. The Birimian system consists of metamorphosed volcanic and sedimentary rocks divided into Lower Birimian and Upper Birimian (Junner 1940). Rock types in the Lower Birimian sedimentary belt are greywackes with turbidite features, phyllites, slates, schists, weakly metamorphosed tuffs and sandstones. The Upper Birimian is characterized by lava flows and dyke rocks of basaltic and andesitic composition have mostly metamorphosed to hornblende-actinolite schists, calcareous chlorite schists and amphibolites (Kesse, 1985). Pillow structures, signifying subaqueous eruption of the original basaltic lavas, and felsic volcanic rocks occur in this succession (Junner 1940; Kesse 1985). Stratigraphically, Manganese-rich horizons have been observed at the lower level in the Upper Birimian and the uppermost Lower Birimian. The granite and gneiss, which form part of the Birimian System overly extensive and very well populated areas and are therefore very important in the rural water delivery system (Junner 1940; Kesse 1985).

The other dominant geological formation in the Volta basin is the Palaeozoic consolidated sedimentary formation known as the Voltaian system. This system consists mainly of limestones, sandstones, mudstones, shales, sandy arkose and pebbly beds (MWH, 1998). However, based on the lithology and field relationships, the Voltaian system can be grouped as the upper, middle and lower Voltaian (Junner & Hirst, 1946). The Upper Voltaian, is thickest and coarsest in the southeast. The conglomerates contain pebbles of granite and other igneous rocks, as well as quartzite fragments. Rocks of the Middle Voltaian (Obusum and Oti Beds) comprise interbedded mudstones/siltstones, sandstones, arkose and conglomerate (Dapaah-Siakwan & Gyau-Boakye 2000). These are generally flat-lying and inherently impermeable, except in a few locations. The lower Voltaian consists of massive quartzite sandstone and grit (MWH, 1998). The Voltaian strata are nearly horizontal beds of sandstones, shale, mudstones and conglomerates thought to be of Late Precambrian to Palaeozoic age (Kesse 1985). In most places, the flat lying Voltaian strata overlie the Birimian rocks.

The geological formations in the White Volta sub-basin are overlain by a regolith characterized by a weathered layer varying in thickness and lithology (Martin, 2005; HAP, 2006). Thus, the Birimian system varies widely in regolith up to 140 m but averages between 10 - 40 m (Palacky et al., 1981; Groen et al., 1988; Smedley, 1996) whereas, the regolith of the Voltaian system generally has a lesser thickness than the Birimian and averages between 4 - 20 m (HAP, 2009; Forkuor et al., 2013). Hydrogeological formations occurring in most parts of the study area have little or no primary porosity. Hence, the two main aquifers systems, the weathered zone and the fractured zone aquifer develop from secondary porosities due to weathering, jointing, fracturing and shearing (MWH, 1998; HAP, 2009). The weathered zone aquifer, usually of high porosity and low permeability due to high clay content is found at the base of the weathered mantle of the Birimian system whereas the fractured zone aquifer developed in fractured bedrocks, particularly in the sedimentary formations has low porosity and high permeability. Aquifer yields differ and are generally low with the different geological formations in the study area. Studies suggest that borehole yields range from 2.1 to 5.7 m^3/h in the Volta basin with mean yields seldom exceeding 6 m^3/h (MWH, 1998).

Table **3-1** gives some information on aquifer characteristics in the Volta Basin.

Table 3-1. Hydrogeological characteristics of aquifers in the Volta basin

Sub-basins	Run-off coefficient (%)	Borehole Yields (m^3/h)	Mean Borehole Yields (m^3/h)	Specific capacities (m^2/h)	Depths to Aquifer (m)	Mean Depth to Aquifer (m)	Depth of boreholes (m)	Mean Depth of Borehole (m)
White Volta	10.8	0.03-24.0	2.1	0.01-21.1	3.7-51.5	18.4	7.4-123.4	24.7
Black Volta	8.3	0.1-36.0	2.2	0.02-5.28	4.3-82.5	20.6		
Oti	14.8	0.6-36.0	5.2	0.06-10.45	6.0-39.0	20.6	25.0-82.0	32.9
Lower Volta	17.0	0.02-36.0	5.7	0.05-2.99	3.0-55.0	22.7	21-129.0	44.5

Source: Adapted from MWH (1998)

3.5 Bhungroo Borehole Construction and Development

The procedures for Bhungroo borehole drilling are quite similar to guidelines provided by CWSA for community water supply in Ghana. A summary of the Bhungroo construction process can be found in Abdul-Ganiyu & Gbedzi (2015).

A. Drilling Process

The drilling method is chosen by the driller, however, Direct Rotary Drilling is recommended (

Figure 3-2). The borehole depth penetrates below the shallow aquifer and tap into aquifers with confined/semi-confined conditions. Boreholes are expected to go beyond the regolith for a good yield. But no decision has been taken on the required yield and action to be taken in the event borehole yield is below a certain yield.

Figure 3-2. Rotary Drilling machine

B. Screen and Casing pipe

The borehole is fully cased to the bottom but screen and casing are positioned at appropriate depths to intercept the aquifer (s). U-PVC (unplasticised polyvinyl chloride) casing pipe is the preferred material (Figure 3-3).

Figure 3-3. U PVC Screen for borehole

C. Graving packing and grouting

The annular space between the casing and borehole wall is filled with filter packing materials in the screen intervals and back filling materials. The grouting is done with a concrete mix.

D. Pump Depth Setting

Borehole pump depth (intake) setting is determined using the safe/sustainable yield of borehole, maximum allowable drawdown and 1 m above main water zone screen.

E. Bhungroo Maintenance

There is no proposed maintenance but for CWSA guidelines the maintenance for boreholes are: 2-yearly pumping test to assess specific capacity variation, 2-yearly camera inspection for checking depth and siltation levels and then 4-5 yearly appropriate rehabilitation which includes well redevelopment for clogged borehole and screens.

F. Development and determining the yield

The borehole shall be developed for a period of at least three hours in order to obtain a maximum yield of water that is free of suspended matter. A pump test is conducted for a minimum of eight (8) hours to determine the borehole yield and other hydraulic properties such as transmissivity, storativity and specific capacity.

3.6 Construction of infiltration bed

A 3 m deep blockwork is constructed around the borehole making sure the borehole is situated in the middle of the constructed box. A wire mesh containing sand and/or activated charcoal is bundled around the screen pipe to serve as an additional barrier to prevent particles or sediments from falling into the pipe and remove toxins (dos Santos & Daniel, 2020). The constructed box is then filled with gravel at the bottom and river sand on top (Figure 3-4).

Figure 3-4. Infiltration bed showing constructed blockwork and screen with mesh

3.6.1 Characteristics of Jagsi, Kpasenkpe and Weisi Bhungroos

Bhungroos have very similar features especially with respect to how they function. Thus, all Bhungroos go through recharge, storage and abstraction. Bhungroos are also made of different designs and construction materials, as shown in Figure 3-5, to meet the needs of the farmer or user (Singh, 2016). These differences are however influenced partly by purpose, cost, surface and sub-surface characteristics. For example, since Bhungroos constructed in the study area are expected to drain large areas with potentially high suspended solids, the infiltration bed design has river sand on top and gravel at the bottom which is somewhat different from the local context in India where some Bhungroo have no filtration system.

Figure 3-5. Different types of Bhungroo (CA, 2018)

Typically, the Bhungroos in Ghana can be described as having first, the infiltration system which consists of an artificial infiltration bed and a borehole with pipes (screen and plain) connecting the aquifer. Another feature is the storage medium (confined or unconfined aquifer) which has a minimum depth of 45 m. The third feature is an abstraction unit, which consist of a submersible pump powered through solar or diesel generator. Lastly, a distribution unit consisting of a drip or sprinkler system connected to an overhead tank with a supplementary generator to augment the head during water distribution and application. The whole system, from water infiltration, storage, abstraction, distribution and application is the Bhungroo Irrigation Technology (BIT).

3.6.2 Infiltration bed design

The infiltration bed is made up of gravels at the bottom with river sand particles on top. The infiltration box is about 9 m^2 with the screen or perforated pipe in the middle. A wire mesh packed with river sand envelopes the screened pipe to ensure that larger suspended particles are filtered/screened. A large particle bed supports the filter media to prevent fine sand from escaping into the pipe system. For any specific filter design, the most desirable media size depends on the suspended solids characteristics as well as the effluent quality requirements (Figure 3-6) (Huisman and Wood, 1974; Sherard et al., 1984; Bouwer et al., 2008).

Figure 3-6. Typical grades of sand and gravel for filter bed (Source: Neumann Group, 2010)

However, no such considerations was given in the case of the Bhungroo, since river sand by default has highly rated effective particle size and uniformity coefficient (Prochaska & Zouboulis, 2006). The effective size is the minimum size of most of the particles. Thus approximately 10 % of the total grains by weight are smaller and 90 % are larger. The uniformity coefficient describes how similar in size the sand particles are. Hence, generally river sand has good uniformity coefficient values i.e. below 1.5 (Huisman and Wood, 1974). Table 3-2 shows the characteristics of the Bhungroo infiltration bed at each location.

Table 3-2. Characteristics of the Bhungroo infiltration bed

Parameter	**Jagsi**	**Kpasenkpe**	**Weisi**
Filter bed Area (m^2)	4.97	5.43	6.25
Depth of infiltration bed (m^2)	3.0	3.0	3.0
Length of screen (m)	3	3	3
Gravel normal size (mm)*	3-25	3-25	3-25
Gravel layer thickness (m)	0.5	0.5	0.5
Sand normal size (mm)*	0.5-1.2	0.5-1.2	0.5-1.2
Sand effective size (mm)*	0.45-0.7	0.45-0.7	0.45-0.7
Sand layer thickness (m)	2.5	2.5	2.5

*Adapted from Neumann Group (2010)

The design of the infiltration bed, where the screen pipe covers the entire section of the bed, defeats the principles behind providing a filter bed for the Bhungroo. An effective filtration system would require that a particle which enters the filter bed would move through the entire section before it enters the pipe system (Yao et al., 1971). However, for the current design, the pipe serves as an alternative pathway for floodwater to enter the borehole without being fully treated. This observation would likely affect the floodwater (recharge water) treatment process of the Bhungroo leading to issues of clogging (Pavelic et al., 2006). Clogging occurs as a result of interaction between the source water and the media. It is the commonest and prime operational challenge with ASRs since it restricts recharge volume (Pavelic et al., 2008). This challenge can be solved or minimized by providing a screen at the bottom of the infiltration bed.

3.6.3 Water treatment processes in the Bhungroo infiltration bed

The main Bhungroo groundwater treatment process is filtration. This is usually considered a simple mechanical process, involving the mechanisms of adsorption (physical and chemical), straining, sedimentation, interception, diffusion, and inertial compaction (Bouwer, 1978; Asami et al., 2016; Camprovin et al., 2017). During filtration suspended particles are removed by course media penetrating 5-10 cm into the bed (Huisman and Wood, 1974; Blazejewski & Murat-Blazejewski, 1997; Bouwer et al. 2008). Thus, suspended solids trapped deep into the bed minimizes pressure drop, allowing for the media to remove more suspended solids thereby reducing surface clogging (Blazejewski & Murat-Blazejewski, 1997; Bouwer et al. 2008). Several pretreatment processes aimed at removing colloidal matter and key bio-available nutrients from the recharge water have been applied in ASR projects especially the use of roughing filtration (Lin et al., 2006) and biofiltration (Page et al., 2006). These methods have been suitable for their simplicity, low cost and potentially low maintenance requirements (Segalen et al., 2005; Pavelic et al., 2006).

3.7 Aquifer characteristics at Bhungroo sites

3.7.1 Lithology of monitoring well and Bhungroo aquifers

Table 3-3 illustrates the lithological characteristics of monitoring wells (CA, 2015) and Bhungroos sited 100 m apart.

Table 3-3. Lithology of the monitoring well and Bhungroo aquifers

Jagsi/Kpasenkpe	Weisi
1-4 m (clayey)	1-5 m (Clayey- hardpan)
4-25 m (highly weathered light grey shale with water strike at 23 m)	5-20 m (Highly weathered pinkish granite)
25-50 m (Moderately weathered grey shale)	20-56 m (Moderately weathered pinkish granite with water strike at 25 m)

Source: CA (2016)

It is assumed that due to inadequate data on Bhungroos compared to monitoring wells, lithological information provided for the latter are same for Bhungroos based on the closeness of the two systems. Thus, Kpasenkpe Bhungroo and monitoring well, as well as Weisi Bhungroo and monitoring well have the same lithology. Similarly, due to the closeness (approximately 1 km apart) of the Jagsi and Kpasenkpe sites, the Bhungroos and monitoring wells are also assumed to have the same lithology.

Generally, the lithology of the wells indicate that the Kpasenkpe/Jagsi aquifers located in the consolidated sedimentary rock system consists largely of grey shales whereas the Weisi aquifers located in the crystalline basement complex rocks consist of pinkish granite. With the upper part of the aquifer bounded by impervious clay material, wells located at Jagsi, Kpasenkpe or Weisi could exhibit semi-confined to confined aquifer conditions depending on the extent of enhanced secondary permeability (Barry et al., 2005; Banoeng-Yakubo et al.

2010). The presence of the weathered rocks in each formation (>4 m) also indicate an increased permeability and therefore serve as better water bearing zones suitable for development into water supply schemes (Akudago et al., 2007; Banoeng-Yakubo et al. 2010; Yidana et al. 2012

3.7.2 Characteristics of Bhungroo Boreholes

Table 3-4 presents the characteristics of the Bhungroo borehole. The Table indicates that the original Kpasenkpe Bhungroo borehole was fully cased and screened up to a depth of 45 m; with Jagsi and Weisi Bhungroos up to a depth of 70 m and 55 m respectively. Hence, cases and screens covered the full depth of the Bhungroo boreholes. Screens were fixed where aquifers were intercepted and in the infiltration bed.

Table 3-4. Bhungroo Borehole characteristics

Parameter	Jagsi	Kpasenkpe	Weisi
Original depth (m)	70	45	55
Current depth (m)*	32.5	38.9	18
Water strike at construction (m)	45	20	45
Static Water level (m)*	7.2	10.0	6.7
Number of screens	5	10	6
Number of plains	19	5	12
Screen position (m)	45-50, 65-70	20-45	40-55
Length of screen (m)	3	3	3
Pipe diameter (cm)	12.7	12.7	12.7
Slot size of screen (mm)	0.5 – 1.0	0.5 – 1.0	0.5 – 1.0
Type of plastic casing	uPVC	uPVC	uPVC

*As at April 2016

The Bhungroo borehole characteristics indicate that since construction, borehole depths have significantly reduced. For instance, Jagsi Bhungroo borehole has reduced from 70 m to 32.5 m

(37.5 m reduction) in depth. Kpasenkpe Bhungroo reduced from 45 m to 38.9 m (6.1 m reduction) and Weisi Bhungroo from 55 m to 18 m (37 m reduction). Due to this, the screened section of Kpasenkpe Bhungroo at depth 20 – 45 m below ground level has reduced to 20 – 38.9 m below ground level, whereas that for Weisi (40 – 55 m below ground level) is completely blocked or lost.

Although the cause of well collapse is unknown, this could be due to improper well design and construction, incomplete well development, damaged casing and screens, borehole wall collapse, corrosion and excessive water velocities into the well (Government of Alberta, 2020). For instance, high water velocity could cause formation particles like sand and suspended solids to flow into the well leading to the eventual collapse of the wall.

The changes in Bhungroo well depths has the potential to alter the storage and recovery potential of the well/aquifer, since the connection of the well and the weathered zone represented a significant control over the productivity of aquifers (Graham, 2008).

According to BGS (2007), comparisons of water strike to rest water level can be used to identify perched water table (strike>level) or confined conditions (strike > level). Thus for the Jagsi Bhungroo well with water strike (15 m) > level (7.2 m) and Kpasenkpe Bhungroo well with water strike (20 m) > level (9.97 m), they can be described as tapping from a confined aquifer.

CHAPTER FOUR

4. Methodologies of Research and Data Interpretation

This chapter presents a framework detailing the approaches, data requirement and tools needed to undertake the assessment of the Bhungroo performance. It discusses how the framework was executed in terms of field sampling, laboratory analysis, groundwater monitoring and data analyses. Additionally, the chapter indicates how a one-time pump test was carried out on the Bhungroos to assess aquifer hydraulic characteristics.

4.1 Bhungroo performance assessment framework

The Aquifer Storage and Recovery feasibility assessment approach proposed by Arshad et al. (2014) and EPHC/NRMMC/NHMRC (2008) were adopted, modified and applied to the Bhungroo as seen in **Error! Reference source not found.**. The Bhungroo performance assessment framework was categorized as technical and environmental. The technical assessment approach considered the evaluation of the physical components (design) of the Bhungroo technology in relation to its behaviour or functionality during recharge, storage and recovery. Technical indicators used for assessment included recharge amount, mixing ratios, sustainable yield among others (Missimer et al., 2002; Reese, 2002). On the other hand, environmental assessment approach considered evaluation of the susceptibility of the physical components (design) of the Bhungroo technology to cause groundwater quality changes or pollution during recharge, storage and recovery. Thus, environmental indicators generally monitored and measured changes in drinking and irrigation water quality parameters and water levels (Martin & Dillion, 2002; Missimer et al., 2002; Reese, 2002; Taranik, 2014).

Table 4-1. Bhungroo performance assessment framework

Indicator	**Measure**	**Method of Evaluation**	**Materials/Tools**
Environmental			
1. Groundwater characteristics	1.Water quality ***(BW, FW, RW, GW)***	Physicochemical, Microbiological, $\delta^{18}O$, $\delta^{2}H$ analysis, Irrigation water suitability indices	Spectrophotometer, Turbidity meter, pH/TDS/EC meter, Titration apparatus, Membrane Filtration apparatus
	2.Hydrochemical water type	Piper plots	GW Chart Software
	3. Static/Dynamic water level	Water level measurement	Water level indicator/Pressure transducer (daily at 1 hour interval)
Technical			
2. Groundwater Recharge Potential	Recharge amount i.e. natural and artificial	1.Chloride Mass Balance 2.Water Table Fluctuation 3. Infiltration rate	Rainwater collectors Pressure transducers/Water level indicators Mini Disk Infiltrometer
3. Groundwater Storage Potential	Well/aquifer hydraulic properties e.g. Transmissivity, Storativity, Specific capacity	Pump test analysis	Submersible pump, generator, water hose, flow meter, water level indicator, stop watch
4. Groundwater Recovery Potential	1. End-member water	Isotope and Chloride end-member mixing analysis	Light Water Isotope Analyzer, Rainwater collector
	2.Sustainable yield	Pump test analysis	Submersible pump, generator, water hose, graduated bucket, timer, water level indicator, stop watch
	3. Irrigable area	Irrigation water requirement and Sustainable yield	

BW – Bhungroo Water; FW – Floodwater; RW – Rainwater; GW - Groundwater

4.2 Water sampling and standard laboratory methods of analyses

Water sampling took place between April 2016 and June 2017, with a sampling interval of approximately 3 months. This ensured that the sampling captured and reflected the different seasonal conditions. The samples collected in April 2016, January 2017 and April 2017 were classified as dry season samples, whereas samples from August 2016, October 2016 and June 2017 were classified as wet season samples. In all, there were three sampling events for each season spanning April 2016 to June 2017. Information on the sample location and number of samples for each water source is presented in Annex 1. Additionally, Figure 4-1 and Figure 4-2 show the images obtained from Google Earth satellite data for the sample locations at Jagsi, Kpasenkpe and Weisi sites.

Figure 4-1. Weisi sampling locations (Source: Google Earth)

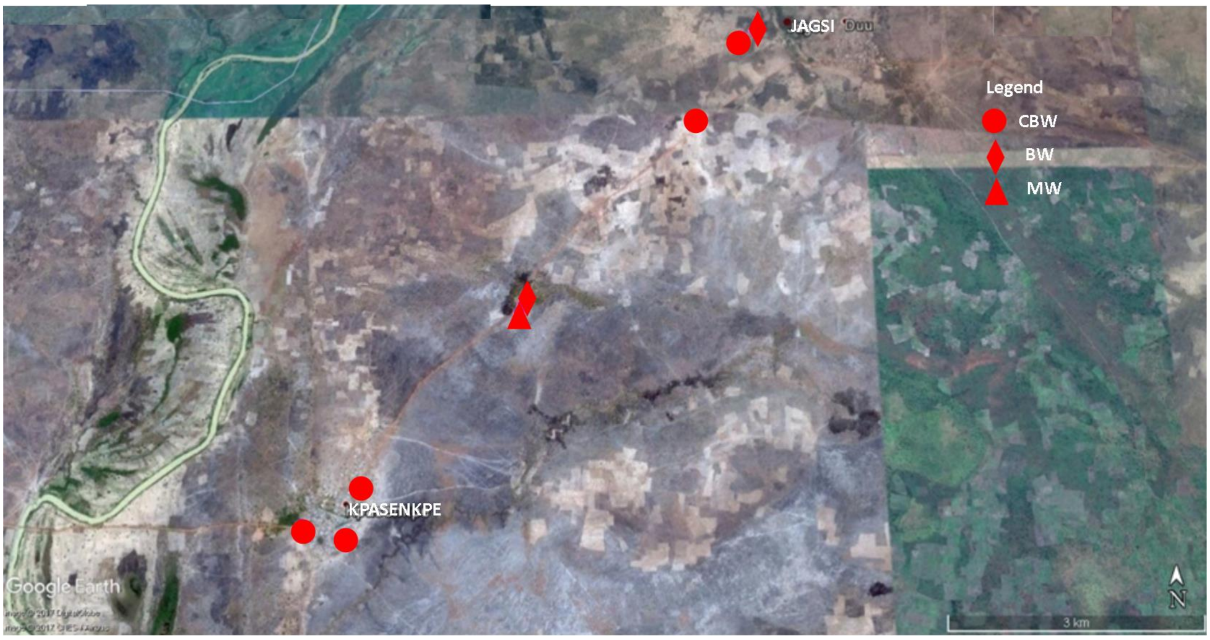

Figure 4-2. Jagsi and Kpasenkpe sampling locations (Source: Google Earth)

Groundwater samples were taken from three sources including community boreholes (CBW), Bhungroos (BW) and monitoring wells (MW); in addition to floodwater (FW) and rainwater (RW) samples. Groundwater samples were collected by purging the boreholes for about five (5) minutes to remove stale water in the pipe before sampling. Flood waters around the Bhungroos were sampled whereas rainwater samples were collected from 2 m high rainwater collectors (4.5 L container equipped with a funnel) mounted on metal bars at all the three Bhungroo sites (Figure 4-3).

Figure 4-3. Rainwater collector

4.2.1 Microbiological and physicochemical method of analyses

All groundwater and flood water samples for physicochemical analyses were collected into 1.5 L high-density polyethylene (HDPE) bottles. Nonetheless, microbiological samples were collected into 500 ml pre-conditioned HDPE sampling bottles. These volumes ensured that each samples was enough to analyze 22 physicochemical and 1 microbiological parameter. All samples were placed in ice chest containing ice blocks in order to keep sample below 4 ^{0}C for transfer to Water Research Institute laboratory in Tamale for analysis within 48 hours. Standard laboratory methods, described in American Public Health Association (APHA, 2012) for the different parameters listed

Table 4-2 were analyzed. These standard methods are developed by the largest public health and water associations in the world. In situ analysis of pH, TDS, EC and turbidity were not done due to unavailability of portable field meters. However, precautions including the use of pre-cleaned sample bottles and preservation of water samples in ice, were intended to reduce the potential for bacterial action and the formation of oxides resulting in possible changes to water quality (APHA, 2012; Beatrice et al., 2019).

Table 4-2: Summary of Laboratory methods of analyses

Parameter	**Method of Determination**
Physicochemical	
Total Dissolved Solids (TDS), pH and Electrical Conductivity	Determined using portable meters i.e. pH/TDS/EC meter
Turbidity	Turbidity meter
Phosphate -phosphorus (PO_4-P),	Reaction with ammonium molybdate and stannous chloride and measurement at an absorbance of 690 nm
Nitrate-N (NO_3-N),	Hydrazine reduction followed by diazotization and colour intensity measured at an absorbance of 520 nm
Nitrite-N (NO_2-N),	Diazotization
Ammonia-Nitrogen (NH_3-N)	Direct Nesslerisation
Sulphate (SO_4^{2-}),	Reaction with barium chloride and measurement at an absorbance of 420 nm
Fluoride (F^-),	SPADNS Method
Total Alkalinity	Strong acid titration Method
Total Hardness	Titration using EDTA Method
Cations and Anions: Sodium (Na^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), potassium (K^+), carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-).	Titrimetric Method
Chloride (Cl^-),	Argentometric Method using silver nitrate
Heavy metals	
Trace Metals: Manganese (Mn) and total iron (Fe)	Atomic Absorption Spectrophotometry
Microbiological	
E. coli	Membrane filtration

Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, HCO_3^{-} and CO_3^{2} were used in determining the hydrochemical facies of the source water using piper diagram. Alkalinity is a measure of the ability of the water to neutralise acids. The contributing substances are bicarbonate and carbonate.NO_3-N, NO_2-N, PO_4- and NH_3 were considered to assess the impact of anthropogenic activities on the source water. NO_3-N is reduced to NH_3-N under the anaerobic aquifer conditions found in flooded lands or confined aquifers. It is also commonly associated with recent impacts of decomposing plant, animal and human waste. NH_3-N is a useful indicator of the previous existence of nitrogen as nitrate. The presence of heavy metal, Mn, was an indicator for soil erosion, leaching from landfill sites or from industrial sites into water (Florence et al. 1994; Francis and White, 1987). The Fe and Mn are good indicators for monitoring the potential clogging of filters and water distribution networks. Their presence in water could, increase turbidity of water, stain laundry and plumbing fixtures, confer bitter taste and colour (Appelo & Postma, 1994). Fluoride has been found in several boreholes in the study area with cases of Dental fluorosis making it a public health concern (Harvey, 2004). E.coli was the only microbiological parameter i.e. the only indicator for faecal contaminant considered based on practice of free range and open defecation in the area. While the presence of faecal coliforms is often indicative of faecal pollution, more specific tests could detect which coliforms are present. E. coli are bacteria normally found in the intestines and feces of humans and warm blooded animals indicating the likelihood of disease-causing organisms being present. This has resulted in the almost universal use of E. coli as the standard indicator for faecal contamination (Francis et al., 1999). The physical parameters including odour, colour, taste, pH, total dissolved solids (TDS), electrical conductivity (EC), Turbidity were measured to monitor the amount of solutes dissolved in the water, salinity and the combined effect of chemical and microbiological activities on the physical character of the water. Overall, all parameters chosen compared to

WHO and FAO guidelines indicated the suitability of source water for domestic or agricultural use.

A total of about 23 parameters were analyzed for all sampling locations covering both dry (November to April) and wet (May to September) seasons. While all samples were analyzed in the laboratory for physicochemical and microbiological characterization, rainwater samples were analysed only for Chloride (Cl^-). Thus, together with the chloride concentrations already determined in the Bhungroo and the community borehole samples, the rainwater chloride was used to compute the natural and artificial recharge potential of the study area using the Chloride Mass Balance Method (Obuobie, et al., 2010; Carling et al. 2012; Ping et al., 2014) and the proportion of floodwater in the recovered water or the recovery efficiency (Sakakibara et al., 2017; Robinson, 2018).

4.2.2 Isotope tracer method of analyses

A 100 mL polyethylene isotope bottle was completely submerged into a bucket full of sample water (community borehole water, Bhungroo groundwater and flood water) and filled completely; making sure the sampling container had no bubbles and was air tight (Clark & Fritz, 2013). For rainwater, monthly composites were prepared into well-sealed 100 mL polyethylene isotopic bottles and transferred to the Ghana Atomic Energy Commission Isotope Hydrology laboratory in Accra for analysis. Duplicate samples were prepared in all cases, labelled and stored in ice chest before transporting to the Ghana Atomic Energy Commission Isotope Hydrology laboratory in Accra with caution to avoid evaporation of the sample. These duplicates were to be used in case there are bubbles detected in the original sample container.

All stable isotope data were reported in δ notation using the equation:

$$\delta = [R_{sample} / R_{vsmow} - 1] \times 1000 \qquad 4\text{-}1$$

In terms of $\delta^{18}O$ and $\delta\ ^2H$, equation 4-1 becomes

$$\delta^{18}O = (^{18}O/^{16}O - ^{18}O/^{16}O_{SMOW}) \times 1000 \qquad 4\text{-}2$$

$$\delta^{2}H \text{ or } \delta D = (^{2}H/^{1}H - ^{2}H/^{1}H_{SMOW}) \times 1000 \qquad 4\text{-}3$$

Thus, R is either $^{18}O/^{16}O$ or $^{2}H/^{1}H$ ratio of the sample, and R_{vsmow} is the isotope ratio of the V-SMOW, a reference standard (Craig, 1961).

Isotope sampling spanned different periods from January to June 2017. Bhungroo wells and community borehole sampling spanned January to June, rainwater sampling spanned April to June and floodwater sampling occurred only in June. The results from laboratory analyses were used in source water isotope characterization to monitor the extent of isotopic changes in water due to temporal patterns, evaluate source of groundwater recharge and also to evaluate the extent of mixing between floodwater and ambient groundwater in the Bhungroo aquifer (Freeze and Cherry, 1979; Chapman, 1996; Izbicki, 2002; Jeelani & Deshpande, 2017; Hamdi et al., 2018).

4.3 Groundwater level monitoring

Water level measurements were continuously taken for two Bhungroo wells and two monitoring wells sited at Kpasenkpe and Weisi. These measurements were undertaken to identify trends in water level variations and also establish the existence or otherwise of a hydraulic connection between Bhungroo wells and monitoring wells (Fuentes-Arreazola et al., 2018; Bhanja et al., 2018). Jagsi Bhungroo was not monitored due to financial constraints.

Hourly water levels were measured in the Bhungroos using automated pressure transducers with accuracy of ±0.5 cm pressure head. In addition, daily water levels of the monitoring wells (100 m apart from Bhungroo) were taken manually using a dip meter. Bhungroo groundwater level measurements started in August 2016 whereas monitoring well measurements started

January 2017. Data on Bhungroo abstractions for dry season irrigation spanned January to April 2017.

4.4 Pumping tests

In order to ascertain the suitability of Bhungroo well/aquifer for enhancing water storage and recovery, key hydraulic characteristics of Bhungroo wells and aquifers were obtained through a sixty (60) minute and eight (8) hours of step-drawdown and constant rate pumping test (Kruseman & de Ridder, 1994; Adul-Ganiyu et al., 2017). An initial 60 minute step-drawdown test with 20 minutes interval and discharge rates of 55, 65 and 75 l/min was done to estimate the discharge rate for the constant rate pumping test. The choice of discharge rates for the step-drawdown test was based on the information that boreholes yields in the study area range between 50 - 80 l/min (personal communication from West Mamprusi District Works Officer, 2016). Subsequently, a constant rate pumping tests were performed on the Bhungroos under controlled conditions of known pumping rates and pumping duration, while measuring water level changes with time. The Jagsi, Weisi and Kpasenkpe Bhungroos were pumped at 75 l/min, 75 l/min and 60 l/min respectively. Recovery duration for Weisi was two hours whereas Jagsi and Kpasenkpe recovered in an hour. During pumping tests, changes in drawdown reveal confined or unconfined aquifers and also identify recharge and no-flow boundaries that limit the lateral extent of aquifers (Fuentes-Arreazola et al., 2018; Zhang et al., 2018; Bhanja et al., 2018).

4.5 Data Analyses and Interpretation

This section describes the various methods used in assessing the performance of the Bhungroo as prescribed in **Error! Reference source not found.**.

4.5.1 Source water characteristics

The different water sources were analyzed according to their physicochemical, microbiological, hydrochemical and isotopic characteristics, in order to evaluate the changes imposed on groundwater systems leading to impairment in its use for drinking and agricultural purposes. A major assumption to the analysis in this section was that the initial Bhungroo groundwater character before operation was same as the ambient groundwater character.

4.5.1.1 Physicochemical and microbiological characteristics

A. Validation of water quality data

Using the principle of electroneutrality which states that aqueous solutions must be electrically neutral, the water quality results was validated using Charge Balance Error (CBE) approach (Freeze & Cherry, 1979; Appelo & postma, 2005). CBE equation could only be applied to potable waters since non-potable waters have high suspended solids which affects the total charge of the water (Fritz, 1994; Murray & Wade, 1996; Li et al., 2018). CBE was therefore only applied to community borehole samples using equation 4-4.

$$\mathbf{CBE} = \frac{\sum \mathbf{cations} - \sum \mathbf{anions}}{\sum \mathbf{cations} + \sum \mathbf{anions}} \ \mathbf{x\,100} \qquad \text{4-4}$$

Where CBE is less than [+ or -] 5 % for all samples.

A check on the charge water balance for community borehole samples indicated a CBE = + 4.8.

B. Data Analysis

Three water sources including community boreholes, Bhungroos and floodwater were analyzed following the approach used in case-control clinical research design (Bogalusa, 2012), where the floodwater being recharged is the intervention, Bhungroo is the test, community borehole is the control and the monitoring well is the measure showing the spread of the influence from the intervention or the extent to which the test differed from the control (i.e. active comparator). This approach has also been applied in assessing the performance of several ASR projects undertaken in the United States and Australia (Martin & Dillon, 2002; Reese & Avarez-Zarikian, 2007; Dillon et al., 2010).

SAS statistical software (SAS 9.0) was used to present the descriptive statistics of the water quality data (comprising 40 community borehole samples, 18 Bhungroo groundwater samples and 6 floodwater samples), in order to identify parameters which exceeded the WHO/FAO Maximum Contaminant Level (MCL). Analysis of Variance (ANOVA) at significant level 0.05 was employed to identify significant differences in water quality among different water sources i.e. flood, community borehole and Bhungroo (Zar, 2009; Bhat et al., 2014). Further, post-hoc test (Tukey test) was conducted to identify significantly different specific group (water source) means (Da Silva & Sacomani, 2001; Deng et al., 2018; Bouaroudj et al., 2019). Based on the results, a comparison between Bhungroos and monitoring wells was undertaken using t-test at significant level of 0.05 to identify significant water quality differences between the two sources (Zar, 2009; Bhat et al., 2014; Powers et al., 2019). This was to confirm the spread of Bhungroo influence or otherwise on nearby groundwater resources after two years of Bhungroo operation.

4.5.1.2 Hydrochemical characterization

Water quality data comprising major ions determined for community borehole samples, Bhungroo groundwater samples and floodwater samples were inputted into the GW Chart software[2] to determine the *water type* or hydrochemical facies of groundwater in the study area (Ganyaglo et al., 2010; Singh & Singh, 2018; Alfaifi, 2019. This was useful in providing a preliminary idea about the complex hydrochemical processes in the subsurface (Appelo & Postma, 2005; Anku et al., 2009; Kumar, 2013; Hosseinifard and Aminiyan, 2015). Piper diagrams provided a graphical way of presenting the relative concentrations of major ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, HCO_3^{-} and CO_3^{2-}) in water (Piper, 1944; Edjah et al., 2017). The cations and anion fields were projected to show a single point in a diamond-shaped field,

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[2] https://water.usgs.gov/nrp/gwsoftware/GW_Chart/GW_Chart.html

from which inferences were drawn on the hydrogeochemical facies of groundwater. Basic conclusions derived from the Piper diagrams include water types, precipitation or solution, mixing and ion exchange (Piper, 1944; Hounslow, 1995; Ravikumar et al., 2015). From Figure 4-4, the top quadrant of the diamond field, represent calcium, magnesium sulphate waters (gypsum groundwater and mine drainage) which are known to exhibit permanent hardness. The left quadrant is calcium bicarbonate water (shallow fresh ground water) which are also known for temporary hardness. Water lying at the right hand side of the diamond is sodium chloride waters (marine and deep ancient ground water) which may be considered saline. The bottom quadrant is sodium bicarbonate waters (deep ground water influenced by ion exchange) or primary alkali carbonates.

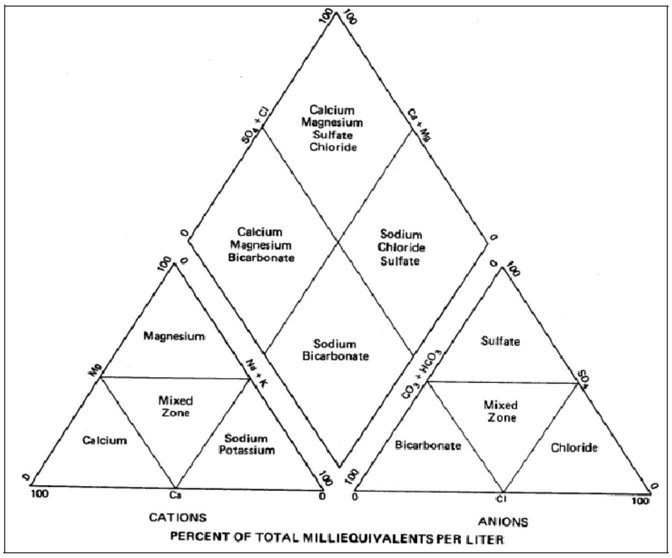


Figure 4-4. A diagram showing the water types of the piper plot

4.5.1.3 Isotopic characterization

Isotopic characterization was used to evaluate the signature similarities or differences between different water sources, the plausible processes driving these changes and the source of aquifer recharge (Eastoe et al., 2010; Meredith et al., 2013; Kanduc et al, 2014).

Thus, δD and $\delta^{18}O$ were plotted to determine the local meteoric water line (LMWL), flood water line (FWL), Bhungroo groundwater line (BWL) and Community borehole water line (CBWL) for rainwater, Bhungroo and community borehole respectively. The LMWL was compared to the Global Meteoric Water line (GMWL), Akiti's line and Pelig-ba's line to determine isotopic signature similarities or differences and source of recharge for the study area (Ganyaglo et al. 2010; Gibrilla et al., 2010; Saka et al., 2013; Su et al., 2018).

On the basis of large numbers of meteoritic water collected at different latitudes, it has been shown that $\delta^{18}O$ and δD values of meteoritic water are linearly related and can be represented by (Craig, 1961):

$$\delta D = 8\ \delta^{18}O + 10 \tag{4-5}$$

Data plotted on the best fit regression line also known as the Global meteoric water line suggests that such water is of meteoritic origin whereas large deviations imply either enrichment or depletion.

The LMWL is the concentration of all the points that fall in a $\delta^{2}H$ - $\delta^{18}O$ plot with the slope reflecting, approximately, the equilibrium fractionation associated with hydrogen and oxygen, and the intercept reflecting the kinetic fractionation within the study area (Glover, et al. 2013). Deviation of the slope and intercept gives useful information regarding secondary processes related to surface-groundwater interaction. The use of Akiti (1986) and Pelig-ba (2004) meteoric water lines served as reference lines developed for Southern and Northern Ghana respectively whereas the GMWL is also an average of many LMWL controlled by local climatic parameters and gives clues about the origin of the vapour mass, re-evaporation during rainfall and the seasonality of precipitation (Clark & Fritz, 2013).

4.5.2 Analyses of temporal variations in water quality and level

4.5.2.1 Bhungroo groundwater quality variations

Water quality data for the Bhungroo's major operational phases i.e. recharge and recovery, defined the seasonal character of the Bhungroo water. The wet season recharge period spanned between May and October whereas the dry season recovery period spanned between November and March. A t-test at significance level of 0.05 was applied to the seasonal water quality data to identify significant differences between the seasons. Additionally, water quality was compared to the WHO/FAO to identify parameters that exceeded the Maximum Contaminant Level (MCL) and to ascertain the suitability of the water for drinking and agricultural use (WHO, 2004; Ayers and Wescot, 1985). Further, analysis was performed on the dry season data to classify its suitability for irrigation and to anticipate with some assurance the effect of the water on crops and soils using indicators such as electrical conductivity (EC), total dissolved solids (TDS), sodium adsorption ratio (SAR), residual sodium carbonate (RSC), soluble sodium percentage (SSP), bicarbonate concentration, specific ion toxicity and pH (Ayers & Wescot, 1985; Singh et al., 2006; Bhat et al., 2013). SAR evaluated the alkali (sodium) hazard of irrigation water using equation 4-6.

$$\mathrm{SAR} = \frac{\mathrm{Na}^{+}}{[(\frac{\mathrm{Ca}^{2+}+\mathrm{Mg}^{2+}}{2})]^{1/2}} \qquad \text{4-6}$$

Where Na^+, Ca^{2+} and Mg^{2+} concentrations are expressed in terms of meq l^{-1}.

RSC determined the hazardous effect of carbonate and bicarbonate on irrigation water quality using equation 4-7 and subsequently classified the water based on the RSC index in Table 4-3 (Raju, 2007).

$$\mathrm{RSC} = (\mathrm{HCO}^{-} + \mathrm{CO}_3^{2-}) - (\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}) \qquad \text{4-7}$$

Where HCO^-, CO_3^2, Ca^{2+} and Mg^{2+} concentrations are expressed in terms of meq l^{-1}.

Table 4-3. Bhungroo irrigation water quality based on RSC index (Eaton 1950)

RSC (meq L^{-1})	Remark on Quality	Hazard
<1.25	Good	Low, with some removal of calcium and magnesium from irrigation water.
1.25-2.5	Doubtful	Medium, with appreciable removal of calcium and magnesium from irrigation water.
>2.5	Unsuitable	High, with most calcium and magnesium removed leaving sodium to accumulate.

SSP, also referred to as sodium percent or percentage sodium, was used to estimate and classify sodium hazard of the Bhungroo groundwaterusing Equation 4-8 and Where Na+, K+, Ca2+ and Mg2+ concentrations are expressed in terms of meq l-1.

Table 4-4 respectively.

$$\%Na = \frac{\mathrm{Na^{+}\ x\ 100}}{\mathrm{Ca^{2+}{+}Mg^{2+}{+}Na^{+}{+}K^{+}}} \qquad 4\text{-}8$$

Where Na^+, K^+, Ca^{2+} and Mg^{2+} concentrations are expressed in terms of meq l^{-1}.

Table 4-4. Classification of Bhungroo irrigation water based on soluble sodium percent (Wilcox, 1955)

Sodium (%)	**Water Class**
<20	Excellent
20-40	Good
40-60	Permissible
60-80	Doubtful
>80	Unsuitable

The salinity status of irrigation water were also determined by the water's EC (electrical conductivity) and total dissolved solids (TDS). Bicarbonates concentration in irrigation waters was evaluated in relation to calcium (Ca^{2+}) and Magnesium (Mg^{2+}) ions since the precipitation of these ions as carbonate salts increase the relative proportion of sodium which directly raises the sodium hazard rating of the water. pH was used as a measure of the acidity or alkalinity of water with scale from 0 (strongly acidic) through 7 (neutral) to 14 (strongly alkaline).

4.5.2.2 Groundwater level variations

Haven taken data on groundwater level responses on Bhungroos from October 2016 to June 2017 and monitoring wells from January 2017 to June 2017, temporal trends in water level data were analyzed to established hydraulic connection between Bhungroos and monitoring wells (Fuentes-Arreazola et al., 2018; Bhanja et al., 2018; Kumar et al., 2018). The effects of water abstraction and rainfall on changes in water levels were however inferred.

4.5.3 Recharge estimation using the Water Table Fluctuation (WTF) method

This approach relies on groundwater level variations in time and space to estimate recharge (Healy & Cook, 2002). It is applicable in shallow unconfined aquifers or fractured rock systems where groundwater levels respond to precipitation (Sibanda et al., 2009). The method requires detailed description of the underlying aquifer and its parameters in order to equate changes in saturated volume to recharge (Rushton, 1987). Difficulties in applying the method are related to determining a representative value for specific yield and ensuring that fluctuations in water levels are due to recharge and are not the result of evapotranspiration, changes in atmospheric pressure, presence of entrapped air ahead of a wetting front, extraction or injection of water by pumping, temperature effects, and tidal effects (Todd, 1980). WTF method uses the following equation:

$$\boldsymbol{R = S_Y \Delta h} \qquad \text{4-9}$$

Where R is recharge in mm yr^{-1}; S_y is the specific yield of the aquifer (dimensionless); and Δh is the measured increase of groundwater level (peak rise in water level attributed to the recharge period in mm) (Sibanda et al., 2009).

Assumptions for WTF method include (Acheampong & Hess, 2000; Healey & Cook, 2002; Pelig-Ba, 2009):

1. Application only over periods of water-level rise (i.e. Δh is positive).
2. Recharge occurs only as a result of transient events
3. Recharge occurring under steady flow conditions cannot be estimated.

The main limitations of the WTF technique include (Beekman & Xu, 2003):

1. The determination of the specific yield of the saturated aquifer at a suitable scale
2. The fact that the accuracy of method is based on the knowledge and representativeness of data on water table fluctuations since the method is designed for natural rather than artificial water level fluctuations.

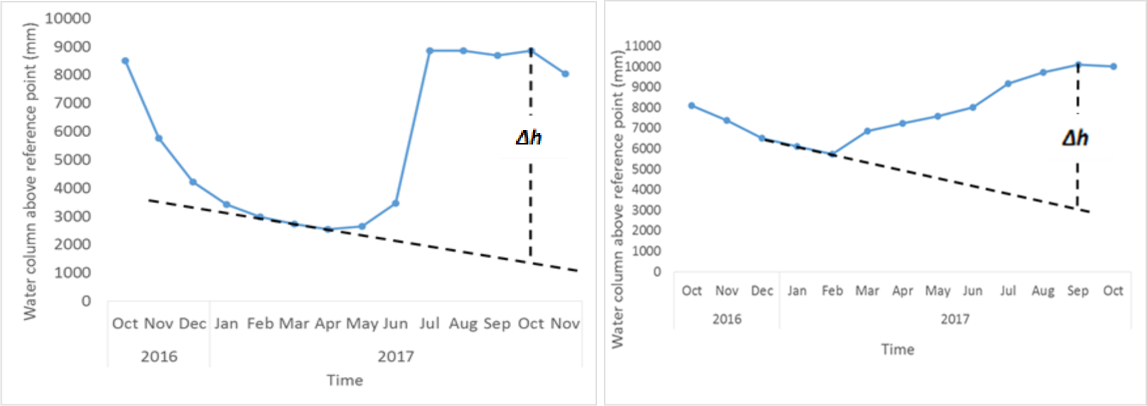
4.5.3.1 Specific yield

Specific yield, Sy, is a dimensionless storage term that accounts for the release of water by gravity from the aquifer (Healy, 2010). Values of Sy vary according to depth of groundwater geological material, soil, and fracture size in the case of fractured aquifers (Diluca, & Muller, 1985). For instance, in fractured rock aquifers, specific yield values can change as the degree and connectivity to fractures decreases with depth (Cunningham & Daniel, 2001). Sy is estimated using laboratory methods, field methods, water-budget methods, and empirical methods, but all of these have a degree of associated uncertainty (Robson, 1993; Healy & Cook, 2002).

In the absence of, or very few, reliable estimates of aquifer storage for the study area, specific yield studies conducted in similar hydrogeological environments were adopted from other studies (Taylor, et al. 2009; Oboubie et al. 2012). Specific yield values of 0.02 - 0.05 used in Shahin (2002) and Oboubie et al. (2012) for weathered zone material in Burkina Faso and Ghana were adopted. Hence, these values generated a low-end and a high-end recharge estimates. Based on the characteristics of the Weisi aquifer, in Section 4.5.2.2, to drain easily compared to Kpasenkpe aquifer, the former was given a higher low-end specific yield value of 0.03 compared to 0.02 for Kpasenkpe.

4.5.3.2 Measured increase in groundwater level (Δh)

Δh was determined as the difference between a hydrograph peak and the recession curve at the time of that peak (Diluca & Diagana, 1988) using the graphical extrapolation method (Figure 4-5). Hence, from the Bhungroo and monitoring well hydrographs, Δh were determined for Weisi and Kpasenkpe sites where continuous monitoring was done. It is worth noting that, since no real time monitoring of Bhungroo or monitoring well was done at Jagsi, results from Kpasenkpe were assumed to be applicable to Jagsi.



(a) (b)

Figure 4-5. Recharge estimated using the graphical WTF method for Weisi and Kpasenkpe Bhungroos

4.5.4 Recharge estimation using the Chloride Mass Balance (CMB) Method

CMB is a technique widely used to estimate recharge in unsaturated and saturated zones (Eriksson & Khunakasem, 1969; Brunner et al., 2004; Carling et al. 2012). Recharge is premised on the assumption that the source of chloride into the aquifer is only by direct precipitation on the soil surface and subsequent recharge through the vadose zone (Ping et al., 2014). There is no flow from underlying or adjacent aquifers. CMB techniques assumes that chloride behaves as a conservative tracer; it is not absorbed by the plant roots and soil, and does not react with any mineral, mineral surfaces or organic materials along the recharge flow path (Carling et al. 2012; Ping et al., 2014). Hence, chloride concentration in groundwater shows the extent to which the chloride in precipitation has been affected by evaporation, transpiration or sublimation (Carling et al. 2012; Ping et al., 2014).

The CMB method, requires three primary data sets: the amount of precipitation, the concentration of chloride dissolved in precipitation, and the concentration of chloride dissolved in groundwater (Obuobie et al., 2010).

Recharge is estimated according to the equation:

$$\boldsymbol{R = \frac{Cl_P}{Cl_{gw}} P} \qquad 4\text{-}10$$

Where R is recharge flux, P is average annual precipitation, Cl_p the weighted-average Chloride concentration in precipitation, Cl_{gw} is the average Chloride concentration in groundwater.

Since CMB gives recharge rates as spatial and temporal averages, it is ideal for water resources planning. It also provides a higher level of certainty than recharge rates obtained for certain years or certain locations. Unlike other recharge methods, CMB captures the long term recharge rate (Martin, 2005). Further, CMB is mostly preferred to WTF since the application of the latter are costly and time demanding. Additionally, using WTF demands more time for the monitoring and collection of reliable data (Lerner et al., 1990). Thus, generally, the use of natural tracers are commonly applied.

4.5.4.1 Chloride in rainwater, community boreholes and Bhungroos

A descriptive statistics on chloride concentration for the different water sources was analyzed. Subsequently, seasonal chloride trends for the Bhungroos and community boreholes were plotted to show variations (seasonality) within the sampling period. Bhungroo and community boreholes representing artificial and natural recharge rates were determined for 2016 and 2017 using mean 2016 and 2017 precipitation data from the Navrongo synoptic station as inputs.

Due to gaps in data collection during the 2017 sampling period, chloride concentration in precipitation from other SecureWater Project sites at Gorogo, Sepaat and Baare in the Talensi District of the Upper East region were used together with data from the study communities to determine the mean chloride concentration in the study area. Again, since there was no data collected for 2016, the 2017 data on chloride concentration in precipitation was used for 2016.

A source of error is the assumption that measured atmospheric input of chloride from the short term data is assumed to be representative for a long period, as rainfall and chloride deposition during the past may be different from today (Beekman and Xu, 2003). Again, there are uncertainties in the measured chloride content of rainfall and rainfall amount, depending on the type of rain gauge used, pollution and analytical errors when measuring relatively low chloride contents (Beekman & Sunguro, 2002; Adams, 2002).

4.5.5 Recharge estimation using the Infiltration Rate Method

Infiltration rate is the rate of movement of water into the soil under the driving forces of gravity and capillarity, and limited by viscous forces involved in the flow into soil pores as quantified in terms of permeability or hydraulic conductivity (Tarboton, 2003). The infiltration capacity declines rapidly during the early part of a storm and reaches an approximately constant steady state value of saturated hydraulic conductivity after a few hours.

Darcy's Equation was applied to a soil after it has been flooded with water, yielding Equation 4-11, which is the Green-and-Ampt equation for infiltration into flooded soil or under ponded conditions, which is based on the piston flow (Bouwer, 2002). The method assumes evaporation is negligible on the surface being flooded so the infiltration rate equals the infiltration capacity of the media.

$$V_i = K\frac{H_w + L_f - h_{cs}}{L_f} \qquad 4\text{-}11$$

Where, V_i is the infiltration rate per unit of time [mm/day], K is the hydraulic conductivity of wetted zone [m/s], H_w the water depth above soil [m], L_f the depth of wetting front [m], and h_{cs} the capillary suction or negative pressure head at setting front [m]. Typical h_{cs} values for sandy loam (Kpasenkpe and Weisi), sandy clay/loams (Jagsi), silt/ fine sand (filter bed) used were -25 cm, -35 cm and -15 cm, respectively (Bouwer, 2002). The water depth above the soil, H_w was solicited from the local community experiences of flooding in the study area over the last 5 years. The average depth of ponding for the three sites was assumed 0.3 m. Hydraulic conductivities were obtained from the field soil infiltration test at the three sites (Mante et al., 2017). An average of three infiltration tests in the area surrounding the Bhungroo were used. When the soil is first flooded, L_f is small and V_i is high, but as the wet front moves downward and L_f increases, the ratio in Equation 15 approaches a value of unity making the infiltration rate numerically equal to K of the wetted zone. As the area is flooded for a long period, the wetting front for the filter bed was estimated to cover the full depth of the infiltration bed, being 3m deep. For the field estimates, L_f was estimated from Equation 4-12 (Tarboton, 2003):

$$L_f = \sqrt{\frac{2Kh_{cs}t}{\eta}} \qquad 4\text{-}12$$

Where, L_f the depth of wetting front, K is the hydraulic conductivity of wetted zone, h_{cs} is the capillary suction, t is the time, η is the porosity. The porosity values used for silt is 0.501, sandy clay is 0.43 and sandy loam is 0.453 (Tarboton, 2003). The infiltration through the Bhungroo system was compared to an equivalent area of the surrounding fields to estimate the added contribution of the Bhungroo to the aquifer recharge. The analyses assumes that there is free flow below the wetting front.

4.5.6 Analyses of pumping test data to determine aquifer storage potential

Parameters such as specific capacity, transmissivity and storativity or storage coefficient of the Bhungroo wells and aquifers were determined using Flow Characteristic Programme (FC programme) (Van Tonder et al., 2001). The Specific capacity of the Bhungroo well is a function of the well construction and the capacity of the aquifer to yield water. It is the amount of water that is available per unit drawdown (Bouwer, 1978; MacLay et al., 1980; Graham et al., 2009). The storativity is the volume of water that an aquifer releases from or takes into storage, per unit surface area of the aquifer, per unit drop in hydraulic head (Todd, 1980). It is a dimensionless quantity. The transmissivity of the aquifer is the rate of flow under a unit hydraulic gradient through a cross-section of unit width over the whole saturated thickness of the aquifer.

The FC programme which functions in Excel received inputs in terms of pumping test results, static water levels, discharge rates, borehole depths and depth to water strike with default aquifer thickness of 20 m and effective borehole radius of 0.98 m. These default values were acceptable since the Voltaian and Basement aquifers are generally confined and vary in thickness from 2-20 m, depending on the thickness of the weathered zone (HAP, 2006; BGS, 2007). Using the Cooper-Jacobs straight line method, the FC programme plotted drawdowns and residual drawdowns on the (linear) y-axis against time and time ratio on the (logarithmic) x-axis. From the line of best-fit, the difference in water levels over one log cycle (Δs) were determined and used in equation 4-13 and 4-14 to calculate for transmissivities and storativities respectively.

$$T = \frac{0.183Q}{\Delta s} \qquad 4\text{-}13$$

$$S = \frac{2.25Tt_0}{r^2} \qquad 4\text{-}14$$

Where T is the transmissivity (m^2/day), Q is the discharge (m^3/day) and Δs is the drawdown per one log cycle of time (m), S is the storativity, r is the radial distance to the pumping well, and t_o is the time where the straight line intersects the zero-drawdown axis (t_0 is converted from minutes to days before it is used in equation 4-7).

Assumptions underpinning cooper Jacob method include (Cooper and Jacob, 1946):

1. The pumping well and all observation wells are screened only in the aquifer being tested.
2. The pumping well and the observation wells are screened throughout the entire thickness of the aquifer.

Further, the specific capacity was also determined using equation 4-15;

$$SC = \frac{Q}{s} \qquad 4\text{-}15$$

Where SC is specific capacity (m^2/day), Q is discharge rate (m^3/day), s is final drawdown (m). Specific capacity assumes that (Bouwer, 1978; MacLay et al., 1980; Graham et al., 2009):

1. The well is pumped at a constant rate long enough to establish an equilibrium drawdown
2. Drawdown within the well is a combination of the decrease in hydraulic head (pressure) within the aquifer, and a pressure loss due to turbulent flow within the well.

4.5.7 Analyses of Chloride and Isotope tracers to determine aquifer recovery potential

Chloride, deuterium and oxygen-18 are natural tracers for monitoring recharge, storage and recovery of ASRs. The chemical constituents of chloride forms a major part of the water cycle but where remarkable differences in altitude exist deuterium and oxygen 18 can also be used (Behrens, 1983). The use of chlorides or isotopes as tracers in the mixing of different water sources can often be applied in circumstances where there are no evaporite minerals within an aquifer and where there can be assumed to be conservative behaviour i.e. neither addition nor removal during mineral solution interaction (Bear & Jacob, 1965; Herczeg & Edmunds, 2000; Adelana & MacDonald, 2008). In this study, a two end-member mixing system was employed. End-member mixing analysis (EMMA), exclusively uses water chemical and isotopic composition to identify contributions of components in a hydrological budget (Tardy et al. 2004; Robinson, 2018). Thus, EMMA was used to identify specific component contributions to the Bhungroo water. The relative proportions of floodwater and ambient groundwater in the Bhungroo groundwater were estimated from equation 4-16 (Katz et al., 1998; Herczeg et al., 2002; Sakakibara et al., 2017).

$$X = \frac{[\mathrm{BW}]-[\mathrm{CBW}]}{[\mathrm{FW}]-[\mathrm{CBW}]} \qquad 4\text{-}16$$

Where the concentration of Cl^-, $\delta^{18}O$ or δ^2H in the Bhungroo groundwater is denoted as [BW], floodwater as [FW] and community borehole water as [CBW]. X is the fraction of floodwater in the Bhungroo groundwater recovered.

The error margin (E_{BW}) in equation 4-16 is estimated based on the square root of the sum of the squares of the respective standard deviation (E_{FW} and E_{CBW}) as in equation 4-17 and it ranges from 7 % to 11 % (Snedecor & Cochran, 1980; Barthold et al., 2011; Tubau et al., 2014).

$$E_{BW} = \sqrt{\{(E_{FW})^2 + (E_{CBW})^2\}} \qquad 4\text{-}17$$

Where E_{FW} and E_{CBW} are the standard deviation of the respective end-members. The bigger the isotopic or chloride difference, the better the separation and the lower the statistical error in mixing calculations between analyzed waters (Payne, 1988; Kortelainen, 2011).

The two component mixing approach is based on the assumptions that (Ogunkoya & Jenkins, 1993):

1. The chemistry (solute and isotopic) of the waters from the various sources are distinguishable, i.e. each source has its own chemical identity
2. The chemical identity is only changed during mixing in the system, there is spatial and temporal uniformity in the identity of each end-member

Similar to limitation discussed in section 4.5.4.1, mean floodwater isotope and chloride values were computed for 2017. These values were thereafter used in evaluating the proportion of floodwater in the Bhungroo during 2016 recharge and 2017 recovery period. Thus, there was insufficient data to determine correctly the error within the floodwater sample data for each Bhungroo site accounting for the use of a mean value to represent chloride and isotope concentration for all Bhungroo sites while computing for the proportion of floodwater in the Bhungroo.

4.5.8 Analyses of pumping test data to evaluate Bhungroo sustainable yield

The determination of sustainable yields in the management of groundwater recovery systems contribute to the management of over exploitation and its consequence of aquifer depletion. Sustainable yield, defined as the discharge rate that will not cause the water level in a borehole to drop below a prescribed limit, is a moving target with no single or best approach applicable at all times and in all cases (Hahn, et al., 1997; Van Tonder et al., 2000; NGC, 2004; Ponce, 2007). Thus, with the ultimate goal of meeting the needs of the present without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development, 1987), three approaches i.e. Flow Characteristics (FC) programme, Lee

(1915) and USEPA (1994) were adopted to ensure a more reliable and representative value is determined (Harvey 2007; Anim-Gyampo et al., 2012; Diabene & Gyamfi, 2012).

4.5.8.1 Flow Characteristics programme

The determination of sustainable yield using the FC programme is commonly applied in areas where aquifers are predominantly fractured (Van Tonder et al., 2002). FC programme quantifies the effects of no-flow boundaries as well as the uncertainties in the values of transmissivity, storativity and distances to the boundaries using the Cooper-Jacob method together with equations 4-18, 4-19 and 4-20 in the determination of sustainable yield (Van Tonder et al., 2001; Barker, 1988; Cooper-Jacob, 1946).

$$\frac{s\,(t=t_l)}{Q} = const_{well}\,(T, S) \qquad 4\text{-}18$$

$$\frac{s(t=t_l)}{Q} = \frac{s_{av}(t=t_l)}{Q_{sus}} = const_{well}\,(T, S) \qquad 4\text{-}19$$

Equation 4-16 can therefore be rearranged as:

$$Q_{sus} = Q\,\frac{s_{av}(t=t_l)}{s(t=t_l)} \qquad 4\text{-}20$$

Where T is transmissivity (m^2/d), S is the Storativity, Q is the pumping rate (l/min), t_l is the maximum operation time (years) in which the drawdown (s in meters) shall not exceed a maximum drawdown (S_{av}) i.e. the position of main water strike in the borehole, Q_{sus} is the sustainable yield (l/min).

From Table 4-5, data inputted into the FC programme using pumping test results comprised static water levels, swl (m), discharge rates Q (l/min), Bhungroo depths BH (m) and available drawdown S_{av} (m), with default aquifer thickness of 20 m, maximum operation time of 2 years and effective borehole radius of 0.98 m. S_{av}, was defined as the difference between static water level and the water strike or prescribed limit.

Table 4-5. Input data for FC programme

Bhungroo	*Q* (l/min)	BH depth (m)	swl (m)		S_{pt} (m)	S_{av} (m)
Jagsi	1.25	32.5	7.2		2.89	7.8
Kpasenkpe	1.25	38.9	9.97		3.59	7.8
Weisi	1.0	18	6.67		5.88	8

*S_{pt} is the drawdown during pumping test

For the Weisi aquifer, available drawdown was defined as 2/3 of the distance between the base of the aquifer and the static water level (or 2/3 or the saturated thickness) (AENV, 2003). On the other hand, the available drawdown for Kpasenkpe and Jagsi were determined from the well logs as the difference between static water level and the water strike. A major drawback in applying the Cooper-Jacobs method was its reliance on knowing the depth of the main aquifer water strike. Consequently, it is not applicable to boreholes with no well logs.

In this study, the FC programme simulated four scenarios to determine the sustainable yields of the Bhungroo aquifer systems. These included:

1. An open aquifer system that is not restricted by any boundaries
2. An aquifer bounded by a single no-flow boundary
3. An aquifer restricted by two no-flow boundaries
4. A closed aquifer system

For each Bhungroo, the average value from the four scenarios was chosen due to the heterogeneity of aquifers at each Bhungroo catchment.

4.5.8.2 Lee (1915) approach (Transmissivity method by Murray, 1996)

Lee (1915) defined sustainable yield as the limit to the quantity of water which can be withdrawn regularly and permanently without causing dangerous depletion of the storage reserve. This approach was applied by Diabene and Gyamfi (2012) in determining the sustainability of boreholes in the Bawku municipality of Northern Ghana. Using equation 4-21.

$$\boldsymbol{Q_{sus} = TS_{av}} \qquad 4\text{-}21$$

Where T is transmissivity (m^2/d) and S_{av} is available drawdown (m)

With the transmissivity method, sustainable yield is quite sensitivity to available drawdown compared to transmissivity especially in fractured zone aquifers (Murray 1996). For example, where two wells intercept a fractured aquifer at different depths, the estimated sustainable yields are different due to differences in available drawdown but with same transmissivity value. Table 4-6 is used for the determination of sustainable yield.

Table 4-6. Input data for Lee (1915) approach

Bhungroo	T (m^2/d)	S_{av}(m)
Jagsi	13.1	7.8
Kpasenkpe	9.7	7.8
Weisi	8.4	8

4.5.8.3 USEPA approach

According to USEPA (1994), the maximum rate at which a borehole can be pumped without lowering the water level to the screen is defined as safe yield based on equation 4-22 (USEPA, 1994):

$$\boldsymbol{Q_{sus} = (AW)(SC)} \qquad 4\text{-}22$$

Where AW is available water and SC is the specific capacity.

SC is defined as the yield per unit drawdown (equation 4-23).

$$\boldsymbol{SC = Q/S_{pt}} \qquad 4\text{-}23$$

But AW is further elaborated in equation 4-24;

$$\boldsymbol{AW = S_{av}f} \tag{4-24}$$

Where factor of safety (f) = 0.6 - 0.9 (USEPA, 1994). The introduction of the factor of safety in the determination of the maximum drawdown introduces a fundamental difference between the Lee (1915) and USEPA (1994). For higher safety margin f = 0.9. Thus, data in Table 4-7 was inputted to determine Q_{sus} using equation 4-25:

$$\boldsymbol{Q_{sus} = 0.9S_{av}\left(\frac{Q}{S_{pt}}\right)} \tag{4-25}$$

Table 4-7. Bhungroo sustainable yields (l/s) from USEPA (1994) approach

Bhungroo	*f*	S_{av}(m)	*Q (l/s)*	S_{pt}(m)
Jagsi	0.9	7.8	1.25	2.89
Kpasenkpe	0.9	7.8	1.25	3.59
Weisi	0.9	8	1	5.88

4.5.9 Analyses of the sustainability of Bhungroo irrigation potential

The sustainability of the Bhungroo irrigation potential was evaluated based on the sustainable yields determined from Bhungroo wells and irrigation water requirements for leafy vegetable and cash crops. Irrigable area (A_i) for each of the Bhungroo sites was estimated using equation 4-26:

$$\mathrm{A_i = \frac{Q_{sus}}{IR}} \tag{4-26}$$

Where A_i is potential irrigable area in m^2

Q_{sus} is sustainable yield in m^3/d

IR is irrigation water requirement in mm/d

The determination of Bhungroo irrigable area (potential irrigable area) set the basis for farmers to plan for the season in terms of securing and repaying loans, purchasing farm inputs, hiring labour among others. Again, based on expected revenues a self-financing model can be instituted to support the upscaling of Bhungroo concept.

4.5.9.1 Irrigation water requirement (IR)

The amount of irrigation water to be supplied was calculated based on the crop water requirement; defined as the depth of water needed to meet the water loss through evapotranspiration (ET_c) of a disease-free crop, growing in large fields under non-restricting soil conditions including soil water and fertility and achieving full production potential under the given growing environment (FAO, 2012).

IR was estimated using Equation 4-27:

$$\mathrm{IR} = \frac{\mathrm{ET_c}}{\mathrm{I_{eff}}} \qquad 4\text{-}27$$

Where;

ET_c represents crop water requirement in mm/d

IR represents irrigation requirement in mm/d

I_{eff} represents irrigation efficiency

4.5.9.2 Estimation of Crop Water Requirement (ETc)

A critical part of growing crops is determining the right quantity of water and time to supply to the crops. The net quantity of irrigation water to be applied to a field depends on the magnitude of moisture deficit in the soil, leaching requirement and expected quantity of rainfall. When no rainfall is likely to be received as in the case for dry season irrigation, and the soils are not saline, net quantity of water to be applied is equal to the moisture deficit in the soil, which is the water quantity required to fill the root zone to field capacity. Therefore crop water requirements refer to the amount of water required to compensate for evapotranspiration losses from a cropped field during a specified period of time (Todorovic, 2005).

The ET_c was estimated using Equation 4-28:

$$ET_c = ET_o \times K_c \qquad 4\text{-}28$$

ET_o represents reference evapotranspiration in mm d^{-1}

K_c represents maximum crop coefficient

Doorenbos & Pruitt (1977) explains the above equation further by stating that the factors determining the crop water requirement for an area include effect of climate and its variability over time and. area, effect of soil water availability together with agricultural and irrigation practices and relationship between ETc and level of crop production.

Leafy vegetables and cash crops adopted for the study included Corchorus and Amaranthus, and Onions and Tomatoes respectively. Corchorus and Amanranthus are known for good nutritional value, with a ready market since they are staple foods in Northern Ghana. Additionally, Onions and Tomatoes are also known cash crops with high market value, with a history of contributing immensely to the local economy of Northern Ghana. However, the non-availability of data specific for each of the sites on crop water requirement (ET_c), implies this study relied on ET_o from Navrongo weather station using Hargreaves formula to estimate ETc (Kadyampakeni et al., 2017). Additionally, K_c of 1.00 reported for herbs, salad greens and leafy vegetables from Texas A&M Agrilife Extension studies was adopted and used (Allen et al., 1998; Masabni et al., 2013; Kadyampakeni et al., 2017) as shown in

Table 4-8.

Table 4-8. Crop growth stages and crop coefficients and growth days per stage

Crop		Initial stage	Development stage	Mid-season stage	Late season stage	Total
Corchorus/Amaranthus	Days	20	30	40	10	100
	K_c	0.7	1.0	1.0	1.0	-

Onions/Tomatoes	Days	20	45	20	10	95
	K_c	0.7	1.0	1.0	1.0	-

To ensure better irrigation water management, crops water requirement was estimated taking into consideration the growth stages (Tan & Lanye, 1981). For the analyses, the first cropping period began from November to February and the second cropping period began same month after land preparation till May. Corchorus/Amaranthus for the first cropping season spanned November to February and with the second cropping season beginning in March to May. For Onions/tomatoes, on the other hand, the first cropping season spanned November to January and the second cropping season began from February to June.

The estimation of crop water requirements was fed into irrigation water requirements and water management practices during the first and second cropping season.

4.5.9.3 Irrigation efficiency

Based on Table 4-9, irrigation methods with high efficiencies i.e. drip and sprinkler were used to estimate the irrigation water requirements.

Table 4-9. Irrigation efficiencies for different irrigation methods (after Brouwer et al. 1989)

Methods	Field application efficiency
Surface irrigation (border, furrow, basin)	60%
Sprinkler irrigation	75%
Drip irrigation	90%

CHAPTER FIVE

5. Results and Discussion

The chapter analyzed and discussed the characteristics of rainwater, floodwater, Bhungroo water, borehole water and monitoring well water to ascertain the effect of Bhungroo artificial recharge on groundwater characteristics. Methods used for the analyses included physicochemical and microbiological characterization, oxygen-18 and deuterium isotopic analysis, hydrochemical analyses and water level monitoring. Natural and artificial recharge amounts were also compared to ascertain the performance of Bhungroo system. The chapter also discussed the Bhungroo storage potential using pump test results and finally concluded on what the Bhungroo recovery potential and sustainability in terms of the proportion of recharge water recovered, sustainable yield and potential irrigable area would mean to the smallholder farmer.

5.1 Source water characterization

5.1.1 Physicochemical and microbiological characterization

Table 5-1 shows the mean concentrations of community borehole water, floodwater and Bhungroo groundwater quality for the study area. It identifies the significant differences between the different water sources and compares measured water quality parameters to WHO/FAO maximum contaminant level (MCL).

Table 5-1. Physicochemical and microbiological quality of water sources in study area

Parameter	**Unit**	**WHO**	**FAO**	**CBW**	**BW**	**FW**
N=23				**N = 40**	**N =18**	**N = 6**
Physical						
EC Mean SD Range	µS/cm	-	-	**488.92a** **220.5** **46.79-1030**	**162.07b** **94.1** **32.08-349**	**69.21b** **75.6** **8.91-210**
Turbidity Mean SD Range	NTU	5	-	**14.63b** **55.4** **1-366**	**46.29ab** **55.2** **2-195**	**80.7a** **37.3** **39-131**

Parameter	**Unit**	**WHO**	**FAO**	**CBW**	**BW**	**FW**
N=23				**N = 40**	**N =18**	**N = 6**
pH Mean SD Range	pH Units	6.5 – 8.5	6 – 8.0	**7.73a** **0.3** **7.26-8.5**	**7.43b** **0.3** **6.96-8.19**	**7.52ab** **0.4** **7.14-8.21**
TDS Mean SD Range	mg/l	1000	2000	**303.37a** **136.5** **31.24-531**	**103.78b** **60.9** **20.57-233**	**104.58b** **137.5** **6.81-371**
Chemical						
Ammonia Mean SD Range	mg/l	0.00 – 1.5	0-5	**0.17b** **0.3** **0.001-1.166**	**0.37ab** **0.4** **0.001-1.371**	**0.94a** **0.4** **7.14-8.21**
Nitrate Mean SD Range	mg/l	10	10	8.91a 15.3 0.008-78.09	7.15a 13.3 0.001-48.9	4.24a 7.6 0.481-19.70
Nitrite Mean SD Range	mg/l	10	<5.0	0.06a 0.1 0.001-0.322	0.11a 0.1 0.001-0.377	0.26a 0.31 0.00-0.81
Phosphate Mean SD Range	mg/l	-	0-2	**0.07b** **0.1** **0.001-0.426**	**0.10a** **0.1** **0.001-0.377**	**0.06ab** **0.04** **0.01-0.12**
Sulphate Mean SD Range	mg/l	250	960	21.64a 25.4 1.61-148.3	19.69a 26.2 1-112.7	36.39a 19.30 9.21-63.92
Fluoride Mean SD Range	mg/l	1.5	1	**1.23a** **1.0** **0.005-4.54**	**0.21b** **0.3** **0.005-0.889**	**0.154b** **0.2** **0.005-0.437**
Total Alkalinity Mean SD Range	mg/l	-	-	**251.48a** **127.7** **26-492**	**89.56b** **60.8** **22-216**	**50.0b** **36.3** **12-116**
Calcium Mean SD Range	mg/l	200	400	25.81a 17.1 3.21-76.15	24.36a 12.8 8.82-58.52	10.82a 10 2.4-27.3
Chloride Mean SD Range	mg/l	250	350	10.38a 4.1 3.97-19.9	7.31a 3.18 2.93-14.89	4.49a 0.55 3.9-5.0
Total hardness Mean SD Range	mg/l	500	-	168.22a 117.6 22.4-518	104.78a 50.5 44-216	69.67a 58.2 20-156
Magnesium Mean SD Range	mg/l	150	60	24.69a 20.3 2.39-82.5	11.47a 9.8 2.9-44.2	11.37a 7.4 3.89-21.4
Potassium Mean SD Range	mg/l	30	0-2	3.02a 3.0 0.4-16.7	4.54a 4.0 0.8-13.2	2.12a 1.8 0.3-5
Sodium Mean SD Range	mg/l	200	920	**63.82a** **53.3** **2.3-178**	**7.54ab** **4.4** **1.9-16.1**	**5.65b** **4.2** **1.7-13.3**
Bicarbonate Mean SD Range	mg/l	-	610	**300.3a** **155.0** **31.7-600**	**109.22b** **74.2** **26.8-264**	**64.34b** **4.2** **1.7-13.3**
Ca hardness Mean SD Range	mg/l	-	-	569.5a 48.8 8.02-240	63.67a 35.7 22-146.3	27.03a 25.1 6-68.1

Parameter	**Unit**	**WHO**	**FAO**	**CBW**	**BW**	**FW**
N=23				**N = 40**	**N =18**	**N = 6**
Mg hardness Mean SD Range	mg/l	-	-	101.62a 3.6 9.83-340	48.56a 39.8 11.9-182	42.63a 34.2 8-87.9
Manganese Mean SD Range	mg/l	0.4	0.2	0.43a 2.2 0.005-15	1.42a 2.7 0.022-9.412	0.58a 0.8 0.072-2.136
Total Iron Mean SD Range	mg/l	0.3	5	0.25a 0.3 0.003-1.428	1.46a 1.7 0.063-5.988	0.99a 0.9 0.066-2.219
Microbiological						
E.coli Mean SD Range	cfu/100ml	0	100	1.42a 2.4 0-10	30.72a 105.2 0-450	953.83a 2325.1 0-5700

*Community borehole water is CBW, BW is Bhungroo groundwater and Floodwater is FW

**Means with the same letters are not significantly different

***Figures in bold are significantly different

Generally, the mean levels of turbidity (80.7±37.3 NTU), manganese (0.58 ±0.8 mg/l), total iron (0.99 ±0.9 mg/l), potassium (2.12 ±1.8 mg/l) and E.coli (953.83 ±2325.1 cfu/100 ml) in floodwater exceeded the WHO/FAO MCL. Similarly, mean levels of turbidity (14.63 ±55.4 NTU), potassium (3.02 ±3.0 mg/l), fluoride (1.23 ±1.0 mg/l), manganese (0.43 ±2.2 mg/l) and E.coli (1.42 ±2.4 cfu/100 ml) were above the WHO/FAO MCL in community borehole water. However, the Bhungroo groundwater which has a blend of ambient groundwater and floodwater (recharged water) showed similarities to floodwater character; with mean levels of turbidity (46.29 ±55.2 NTU), manganese (1.42 ±2.7 mg/l), total iron (1.46 ±1.7 mg/l), potassium (4.54 ±4.0 mg/l) and E.coli (30.72 ±105.2 cfu/100 ml) exceeding the WHO/FAO MCL in both sources. Parameters which exceeded the WHO/FAO MCL for the Bhungroos were less contaminated compared to floodwater. For example, levels of turbidity (80.7±37.3 NTU), manganese (0.58 ±0.8 mg/l), and E.coli (953.83 ±2325.1 cfu/100 ml) in floodwater reduced to 46.29 ±55.2 NTU, 1.42 ±2.7 mg/l and 30.72 ±105.2 cfu/100 ml respectively in Bhungroo water.

The results from the Tukey test which indicated significantly different water sources confirmed the similarities (means with same letters) between floodwater and Bhungroo groundwater character compared to community boreholes. Thus, from Table 5-1 only ten (10) out of twenty three (23) water quality parameters including EC, turbidity, pH, TDS, ammonia, phosphates, fluoride, sodium, total alkalinity and bicarbonate, showed significant differences between Bhungroo groundwater and community borehole water. Further, t-test analyses presented in Table 5-2 compared the Bhungroo groundwater quality to the monitoring well in order to evaluate the extent of Bhungroo operational influences on surrounding groundwater systems. The results indicated that six out of the ten parameters i.e. EC, TDS, pH, total alkalinity, bicarbonate and sodium, remained significantly different as observed between Bhungroos and community boreholes in Table 5-1. On the other hand, ammonia, phosphate, fluoride and E.coli did not show significant differences between Bhungroos and monitoring wells, hence need to be monitored.

Table 5-2. Monitoring well and Bhungroo groundwater quality

Parameter	**Unit**	**WHO**	**FAO**	**Mean MW**	**Mean BW**	**T-Test**
				N= 6	N= 18	
Physical						
EC	µS/cm	-	-	440.50 (±123.7)	162.07 (±94.1)	**0.009**
Turbidity	NTU	5	-	9 (±6.9)	46.29 (±55.2)	0.857
pH	pH Units	6.50 – 8.5	6 – 8.0	7.59 (±0.1)	7.43 (±0.3)	**0.019**
TDS	mg/l	1000	2000	284.25 (±79.5)	103.78 (±60.9)	**0.009**
Chemical						
Ammonia	mg/l	0.00 – 1.5	0-5	0.25 (±0.3)	0.37 (±0.4)	0.670
Phosphate	mg/l	-	0-2	0.03 (±0.1)	0.10 (±0.1)	0.384
Fluoride	mg/l	1.5	1	1.72 (±1.4)	0.21 (±0.3)	0.125
Total Alkalinity	mg/l	-	-	241 (±104.3)	89.56 (±60.8)	**0.027**
Bicarbonate	mg/l	-	610	294 (±127.5)	109.22 (±74.2)	**0.027**
Sodium	mg/l	200	920	46.13 (±20.5)	7.54 (±4.4)	**0.012**

Parameter	**Unit**	**WHO**	**FAO**	**Mean MW**	**Mean BW**	**T-Test**
Microbiological						
*E.coli	cfu/100ml	0	100	2.67(±2.3)	30.72 (±105.2)	0.276

Figures in bold are significantly different, MW is monitoring well

Generally, parameters which exceeded the WHO/FAO MCL in floodwater and Bhungroo, such as turbidity and E.coli, were influenced by the presence of dissolved geological materials, suspended solids and feacal matter in the environment. However, restoration processes of the Bhungroo infiltration bed and the effect of Bhungroo recovery among others contributed to reducing the levels of contamination in the Bhungroo groundwater compared to floodwater (Bouwer et al., 2009). Thus, whereas the presence of E.coli in floodwater ranged from 0 - 5700 cfu/100 ml, count in Bhugroo water reduced between 0 - 450 cfu/100ml.

Further, due to the geochemical processes influencing natural recharge into aquifers, factors such as soil or rock-water interactions and the leaching of aquifer material, could have influenced the excess concentration of iron, manganese and fluoride found in the community boreholes (Pyne, 1995; nkel, 2015). Additionally, community borehole water parameters such as E. coli, which exceeded the WHO/FAO MCL suggested possible preferential flow paths into the borehole. Poor sanitation around community boreholes which raised some health concerns, coupled with the development of cracks along boreholes could have also contributed to presence of E. coli in community boreholes (Figure 5-1).

Figure 5-1. Poor sanitation around community borehole

From the study, the significant differences between the Bhungroo and community borehole water quality, influenced by anthropogenic and geochemical interactions, can be attributed to the physicochemical and microbiological water characteristics of floodwater recharged into the Bhungroo. Also, the significantly high concentrations of EC and TDS influenced by the high levels of bicarbonate, sodium and total alkalinity explains the significant increase in Bhungroo pH compared to the monitoring well. This notwithstanding, physicochemical and microbiological differences between the monitoring wells and Bhungroos cannot be wholly attributed to the influences from floodwater recharged or Bhungroo operations, since for example E. coli contamination in ambient groundwater had already been observed in community boreholes.

5.1.2 Hydrochemical Characterization

Figure 5-2 presents piper plots showing the different water types for Bhungroo and community borehole water sources sampled in the study area. From the study, community boreholes exhibited three water types including calcium magnesium bicarbonate ($Ca\text{-}Mg\text{-}HCO_3$), sodium bicarbonate ($Na\text{-}HCO_3$) and calcium magnesium sulphate chloride ($Ca\text{-}Mg\text{-}SO_4\text{-}Cl$), with proportions as 67 %, 31 % and 6 % respectively. $Ca\text{-}Mg\text{-}HCO_3$ water type is typical of shallow fresh groundwater with temporal hardness, $Na\text{-}HCO_3$ water type also suggests a deep alkaline carbonate groundwater with permanent hardness influenced by ion exchange and $Ca\text{-}Mg\text{-}SO_4\text{-}Cl$ water type signifies evolutionary processes characterized by permanent hardness (Kumar 2013; Cloutier et al., 2006; Loh et al., 2012).

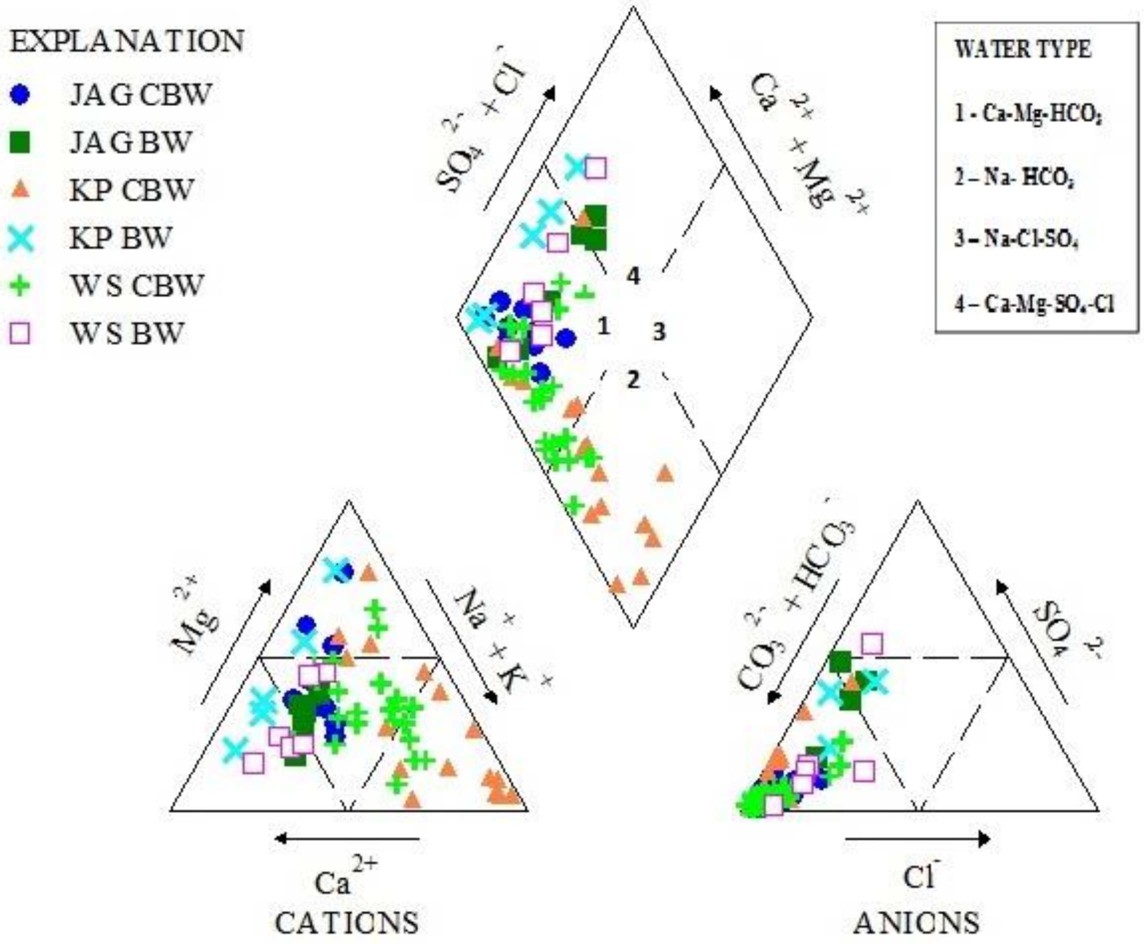


Figure 5-2: Piper plot for Bhungroos and community boreholes

Specifically, the Jagsi community boreholes (JAG CBW) were of the Ca-Mg-HCO_3 water type (100 %), whereas the Weisi community boreholes (WS CBW) were of both the Na-HCO_3 (27 %) and Ca-Mg-HCO_3 (73 %) water types, with the latter being dominant. The Kpasenkpe Community boreholes (KP CBW) exhibited all three water types i.e. Ca-Mg-SO_4-Cl (6 %), Ca-Mg-HCO_3 (29 %), and Na-HCO_3 (65 %), but with Na-HCO_3 being dominant. On the other hand, the Bhungroos were of the Ca-Mg-SO_4-Cl (28 %) and Ca-Mg-HCO_3 (72 %) water types, with the each Bhungroo exhibiting different proportions and dominance. For instance, the Jagsi Bhungroo (JAG BW) exhibited a co-dominance situation of Ca-Mg-HCO_3 water type (50 %) and Ca-Mg-SO_4-Cl (50 %) water type, the Weisi Bhungroo (WS BW) showed Ca-Mg-SO_4-Cl (17 %) and Ca-Mg-HCO_3 water type (83 %) and the Kpasenkpe Bhungroo (KP BW) also showed Ca-Mg-SO_4-Cl water type (17 %) and Ca-Mg-HCO_3 water type (83 %). Each Bhungroo (a single water source) exhibited two water types with dominance different from its community boreholes. For instance, Weisi Bhungroo exhibited Ca-Mg-HCO_3 and Ca-Mg-SO_4-Cl water type whereas the community boreholes exhibited Na-HCO_3 and Ca-Mg-HCO_3 water types during the sampling period.

The dominant water type (Ca-Mg-HCO_3) associated with the Voltaian sedimentary rock at Jagsi and the crystalline basement rock systems at Weisi, suggests carbonate mineral weathering processes in the aquifers (Yidana et al., 2012; Bartos & Ogle, 2002).This reflects the effects of short duration water-rock interaction and dissolution of carbonate aquifer in the lithologic environment (Bajjali, 2006). Also, it indicates groundwater recharge zones, characterized by groundwater of young and meteoric origin (Yidana et al., 2012). The Na-HCO_3 water type associated with crystalline basement rocks and the Voltaian sedimentary rocks suggests Ca^+-Na^+ cation exchange reactions where Ca-HCO_3 evolve to Na-HCO_3 water type (Yidana and Yidana, 2010; Cloutier et al., 2010). The presence of Ca-Mg-SO_4-Cl water type associated with community boreholes within the sedimentary rocks, and Bhungroos wells (located in both crystalline and sedimentary rocks) suggest contact with evaporites such as calcium, magnesium, sulphates and chlorides (Yidana et al., 2008). Thus, the low lying topography, prolonged waterlogging and slow flow rate of infiltrating water in a predominantly clay lithologic environment, provides large surface area for ion exchange, and enhance the precipitation and formation of evaporites (Jalali, 2007; Yidana 2008; Yidana et al., 2012; Cloutier et al., 2006; Loh et al., 2012). The Bhungroos and floodwaters having the same water types of Ca-Mg-SO_4-Cl and Ca-Mg-HCO_3 as in Figure 5-2 and Figure **5-3** suggest that floodwater and ambient groundwater mixing within the Bhungroo well/aquifer is quite minimal. Thus, confirming similarities between Bhungroos and floodwater as observed under physicochemical source water characterization in Section 5.1.1.

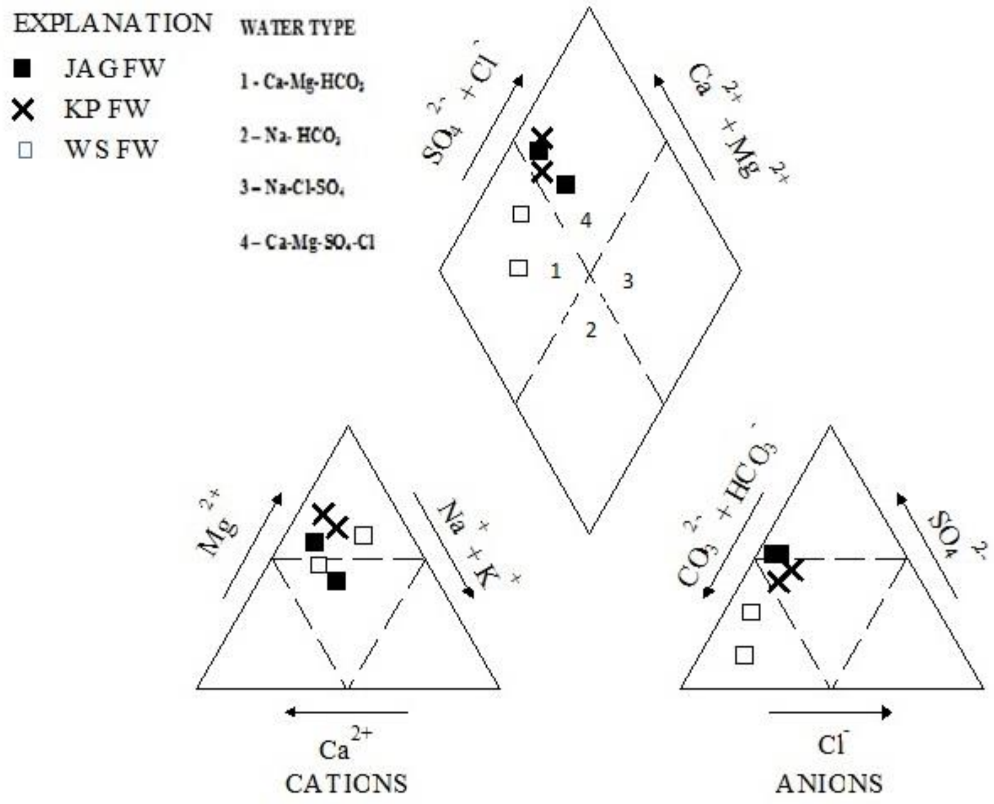


Figure 5-3. Piper plot for floodwater

5.1.3 Isotope characterization

Table 5-3 presents the statistical analysis of stable isotopes for community borehole water, Bhungroo water, floodwater and rainwater sources.

Table 5-3. Statistical summary of stable isotope data for the study area

Water source	$\delta^{18}O$				$\delta^{2}H$			
	Min	Max	Mean	SD	Min	Max	Mean	SD
CBW, n = 24	-5.37	-3.34	-4.29	0.51	-32.35	-17.4	-22.79	3.78
BW, n = 9	-4.36	-3.49	-3.82	0.28	-19.62	-16.2	-18.06	1.09
FW, n = 3	-3.91	0.73	-1.57	2.0	-10.53	-5.52	-8.06	2.51
RW, n = 6	-4.94	1.40	-1.16	2.82	-26.40	18.81	0.49	19.86

δ ^{18}O composition for rainwater ranged from -4.94 to 1.40 ‰ with a mean of -1.16 ± 2.82 ‰, while **δ**^{2}H ranged from -26.40 to 18.81 ‰ with a mean of 0.49 ± 19.86 ‰. Conversely, **δ** ^{18}O in floodwater varied from -3.91 to 0.73 ‰ with a mean of -1.57 ± 2.0 ‰, while **δ**^{2}H varied from -10.53 to -5.52 ‰ with a mean of -8.06 ± 2.51 ‰. Though mean **δ** ^{18}O and **δ**^{2}H isotope values for floodwater were lower (depleted) compared to rainwater, the contrary was expected due to the exposure of floodwaters to prolonged high temperatures (evaporation). This notwithstanding, the sampling period (April to June) for rainwater which involved sampling enriched early rains, increased the mean isotope values (**δ** ^{18}O = 1.40 ‰ and **δ**^{2}H =18.81 ‰) compared to floodwater (**δ** ^{18}O = 0.73 ‰ and **δ**^{2}H = -5.52 ‰) sampled in June. Thus, this phenomenon also acknowledged in similar studies in Ghana as the amount effect is attributable to drier and warmer conditions experienced by light early rains (Dansgaard, 1964; Gibrilla et al. 2017; Loh, 2014). Such evaporative enrichment is minimized once the dry air column above the ground becomes water-saturated and subsequent rainfall events become isotopically depleted (Clark and Fritz, 2013).

Again, from Table 5-3, **δ** ^{18}O composition of community borehole water (CBW) varied from -5.37 to -3.34 ‰ with a mean of -4.29 ± 0.51 ‰, and **δ**^{2}H varied from -32.35 to -17.4 ‰ with a mean of -22.79 ± 3.78 ‰. Similarly, **δ** ^{18}O composition of Bhungroo groundwater (BW) varied from -4.36 to -3.49 ‰ with a mean of -3.82 ± 0.28 ‰, and **δ**^{2}H varied from -19.62 to -16.62 ‰ with a mean of -18.06 ± 1.09 ‰. In spite of the observation that community boreholes are recharged differently from Bhungroos, these two groundwater systems had very similar isotopic signatures. For instance, **δ** ^{18}O and **δ**^{2}H composition for Bhungroos varied within the range (-5.37 to -3.34 ‰) determined for community boreholes. Additionally, similar mean values of **δ** ^{18}O and **δ**^{2}H were observed for Bhungroos (-3.82 ± 0.28 ‰ and -18.06 ± 1.09 ‰) and community boreholes (-4.29 ± 0.51 ‰ and -22.79 ± 3.78 ‰). It is therefore plausible to suggest that since the Bhungroo is a mixture of floodwater and ambient groundwater sources, defined by the extent of mixing, it had lost significant portions of its recharged component through the continuous abstractions undertaken from January to April leading to the Bhungroo having a signature similar to ambient groundwater but different from floodwater (-1.57 ± 2.0 ‰, and -8.06 ± 2.51 ‰).

The local meteoric water line (LMWL), Global meteoric water line (GMWL), Pelig-Ba's line and Akiti's line are shown in a **δ** ^{18}O ‰VSMOW and **δ**^{2}H ‰VSMOW plot (Figure 5-4) with regression lines for the various plots presented in equations 5-1 – 5-4. The establishment of the LMWL supported earlier observations made in Table 5-3 with respect to rainwater character and provided the basis for defining the origin and movement of groundwater and surface water in the hydrological environment (Loh, 2014). For instance, a lower slope and y-intercept of the LMWL (7.03 and 8.6) compared to GMWL (8 and 10) was indicative of a local precipitation that had experienced evaporative losses (Ingraham, 1998; Gibrilla et al., 2010; Saka et al., 2013). Again, the closeness of the gradients for equation 5-1 (6.9) and 5-3 (7.03) as opposed to equation 5-4 (7.86) confirmed the similarities in rainfall characteristics between the Pelig-ba's line and the LMWL compared to Akiti's line. Thus, since the present study area is located in the Northern Ghana, the finding confirms the observation that rainfall characteristics between Northern and Southern Ghana are distinct; with the former being more evaporative.

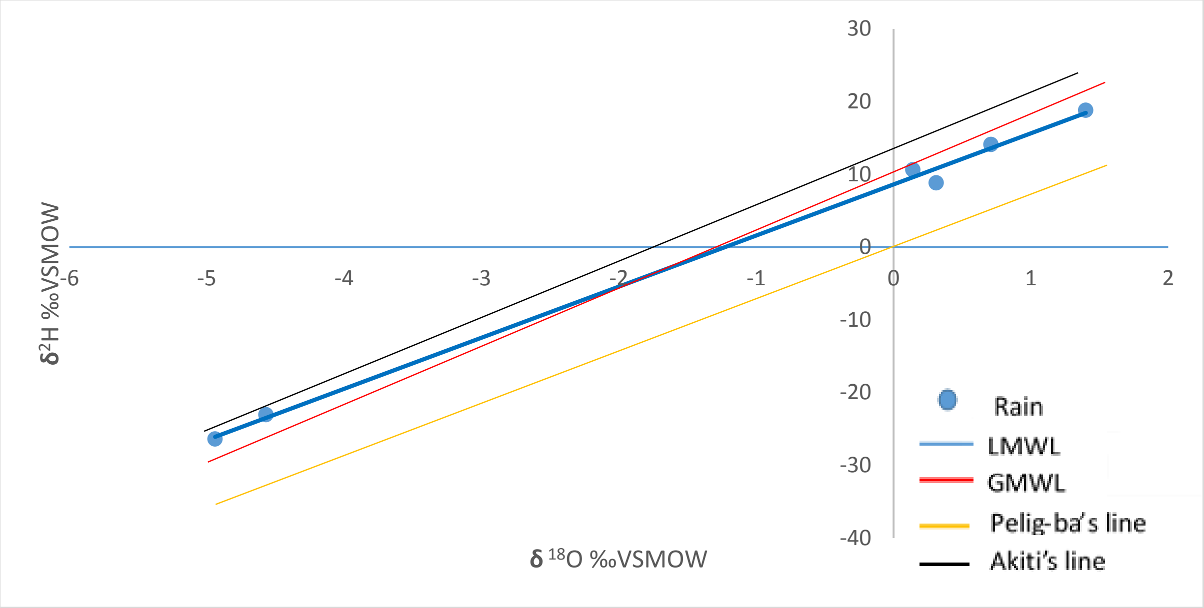


Figure 5-4. Global and Local Meteoric water lines

$\delta^2H = 7.03\delta^{18}O + 8.6, r^2 = 0.997$ (LMWL) 5-1

$\delta^2H = 8\delta^{18}O + 10$ (GMWL) 5-2

$\delta^2H = 6.9\delta^{18}O – 0.19$ (Pelig-ba, 2004) 5-3

$\delta^2H = 7.86\delta^{18}O + 13.61$ (Akiti, 1986) 5-4

Figure 5-5 compares the plots of **δ** ^{18}O ‰VSMOW against **δ**^{2}H ‰VSMOW for community borehole water (CBW), Bhungroo groundwater (BW), floodwater (FW) and rainwater (RW) in order to determine sources of groundwater recharge, evaluate floodwater and groundwater interactions and identify similarities or differences among the different water sources (Benjamin et al., 2004; Eddy-Miller & Wheeler, 2010). From Figure 5-5, CBW and BW samples plotted in a cluster with the CBWL and BWL intersecting at **δ** ^{18}O = -3.46 ‰ **δ**^{2}H = -17.07 ‰, confirming the similarities in isotopic signatures. The differences in floodwater isotopic signatures compared to the Bhungroo and the community borehole waters also confirmed there has not been any significant impact of recharged floodwater on the isotopic signature of Bhungroo groundwater since this study only covered the early flooding period where recharge had just began after about four months of recovery.

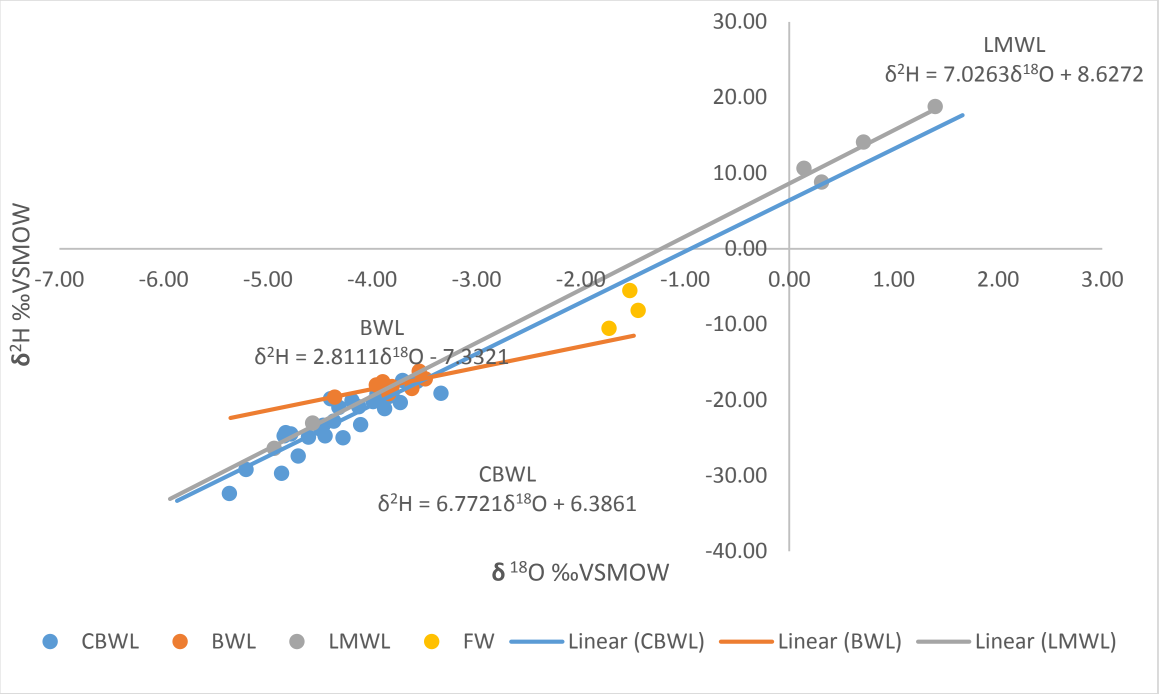


Figure 5-5. Overall Bhungroo and community borehole isotopic characteristics

$\delta^2H = 6.77\delta^{18}O + 6.39, r^2 = 0.8023$ (CBWL) 5-5

$\delta^2H = 2.81\delta^{18}O - 9.18, r^2 = 0.5173$ (BWL) 5-6

From Equations 5-1, 5-5 and 5-6, the gradient of the CBW and BW reduced from LMWL (7.03) in the order CBWL (6.77) > BWL (2.8). The closeness of the CBWL and LMWL or the BWL and LMWL suggested that the source of recharge is recent meteoric. Similarly, the closeness of CBWL slope (6.7) to LMWL (7.03) indicated meteoric recharge. The BWL slope however, deviated from this rule due to the continuous evaporation of floodwater and the greater relative enrichment of ^{18}O than ^{2}H (Barnes & Allison 1983; Payne, 1988; Clark and Fritz, 2013; Marfia et al., 2004; Dogramaci et al., 2012).

5.2 Temporal variations in water quality and water level

5.2.1 Bhungroo seasonal water character

Table 5-4 presents a summary statistics of the seasonal water character. It identifies significant differences between dry and wet season water quality using t-test and also compares the Bhungroo seasonal water quality to WHO and FAO standards for drinking and agricultural water use respectively.

Table 5-4. Mean seasonal Bhungroo groundwater quality

Parameter	**Unit**	**WHO**	**FAO**	**Mean Dry**	**Mean Wet**	**T-test**
				N = 9	N = 9	
Physical						
EC	µS/cm	-	-			0.964
Mean				169.9	154.27	
SD				60.8	122.4	
Range				69.3-238	32.08-349	
Turbidity	NTU	5	-			0.096
Mean				20.56	72.02	
SD				29.3	64.2	
Range				2-93	10-195	
pH	pH Units	6.50 –8.5	6 – 8.0			0.528
Mean				7.4	7.47	
SD				0.1	0.4	
Range				7.26-7.57	6.96-8.19	
TDS	mg/l	1000	2000			0.992
Mean				107.8	99.7	
SD				38.2	79.9	
Range				44.5-147	20.57-233	
Chemical						
Ammonia	mg/l	0.0 – 1.5	0-5			0.096
Mean				0.17	0.56	
SD				0.2	0.5	
Range				0.001-0.774	0.145-1.371	
Nitrate	mg/l	10	10			0.346
Mean				3.99	10.31	
SD				8	17	
Range				0.001-23.64	0.001-48.9	
Nitrite	mg/l	10	<5.0			**0.034**
Mean				**0.03**	**0.19**	
SD				**0.03**	0.2	
Range				**0.001-0.099**	0.001-0.468	
Phosphate	mg/l	-	0-2			0.301
Mean				0.06	0.14	
SD				0.1	0.1	
Range				0.001-0.181	0.04-0.377	
Sulphate	mg/l	250	960			0.123
Mean				8.4	30.97	
SD				7.9	33.3	
Range				1-26.2	6.56-112.7	
Fluoride	mg/l	1.5	1			0.150
Mean				0.31	0.1	

Parameter	**Unit**	**WHO**	**FAO**	**Mean Dry**	**Mean Wet**	**T-test**
SD Range				0.3 0.005-0.889	0.2 0.005-6.21	
Total Alkalinity Mean SD Range	mg/l	-	-	109.33 57.6 38-196	69.78 60.5 22-216	0.366
Calcium Mean SD Range	mg/l	200	400	27 7.8 12.8-34.5	21.72 16.6 8.82-58.52	0.600
Chloride Mean SD Range	mg/l	250	350	7.52 2.6 5-11.9	7.09 3.9 2.93-13.9	0.649
Total hardness Mean SD Range	mg/l	500	-	106.22 39.5 54-158	103.33 62.1 44-219	0.880
Magnesium Mean SD Range	mg/l	150	60	11.67 6.4 3.38-21.8	11.26 12.7 2.9-44.2	0.957
Potassium Mean SD Range	mg/l	30	0-2	3.61 3.1 1.2-9	5.48 4.9 0.8-13.2	0.319
Sodium Mean SD Range	mg/l	200	920	9.59 5.2 1.9-16.1	5.5 2.2 2.4-8.1	0.160
Bicarbonate Mean SD Range	mg/l	-	610	133.31 70.3 46.4-239	85.12 73.9 26.8-264	0.367
Calcium hardness Mean SD Range	mg/l	-	-	73.02 28.4 13.9-89.9	54.31 41.4 22-146.3	0.435
Magnesium hardness Mean SD Range	mg/l	-	-	48.09 26.6 13.9-89.9	49.02 51.5 11.9-182	0.893
Manganese Mean SD Range	mg/l	0.4	0.2	0.16 0.1 0.022-0.344	2.63 3.5 0.086-9.412	0.071
Total Iron Mean SD Range	mg/l	0.3	5	0.75 0.7 0.063-1.98	2.18 2.1 0.108-5.988	0.194
Microbiological						
E.coli Mean SD Range	cfu/100ml	0	100	7.89 14.7 0-46	53.56 148.8 0-450	0.375

From the results, there was no significant differences between the wet and dry season water quality, except for nitrite (p = 0.034) which indicated reduced dry season concentration (0.03 ±0.3 mg/l) compared to wet season (0.19 ±0.2 mg/l). Nitrite in groundwater is potentially due to the dissolution and washing of nitrate fertilizers and faecal matter from animal droppings and agricultural fields into the Bhungroo during wet season recharge. However, increased anaerobic conditions occasioned by high evapotranspiration rates, falling water table, and frequent abstractions in the dry season enhanced the conversion of nitrates to nitrites and subsequently to ammonia in a reduction process called denitrification (Sacchi et al., 2013; Anornu et al., 2017). The pungent odour (ammonia gas) in Bhungroos as observed in the field at the beginning of dry season abstraction, underscores the occurrence of denitrification process.

Comparing the water quality parameters to the WHO/FAO standards indicated that mean levels of nitrate (10.31 ±17mg/l), manganese (2.63 ±3.5mg/l) and iron (2.18 ±2.1 mg/l) exceeded the WHO/FAO MCL in the wet season, whereas mean levels of turbidity, potassium and E.coli also exceeded the WHO/FAO MCL in both seasons. Excess turbidity indicated the presence of high inorganic matter (such as precipitates of iron and manganese from natural sources which are not typically a health hazard in drinking water) and pathogens such as bacteria, viruses, and parasites in water. The precipitates of calcium, manganese and other solids could also increase the turbidity of the Bhungroo groundwater with a consequential effect of well and aquifer clogging. Iron exceeding WHO MCL is a common observation in most aquifers in Ghana mainly due to high iron content of the major geological systems in Ghana (BSG, 2012). Similarly, excess manganese found in association with iron has been observed in a few aquifers especially in Upper East and Ashanti regions of Ghana (Smedley et al., 1995; Buamah, 2009). E.coli exceeding WHO MCL is mainly due to the presence of faecal matter in the Bhungroo. While excess turbidity, manganese and iron do not pose any health problems apart from odour and aesthetics, excess potassium, nitrate and E.coli could result in increased susceptibility to kidney diseases, methamoglobinemia and diarrhoea respectively (Buckley et al., 1995). For an irrigation water with excess nitrates, production of several commonly grown crops are impaired because of over stimulation of growth, delayed maturity or poor quality (Ayers & Westcot, 1985). Similarly, excess potassium in irrigation water could significantly increase potassium concentrations in forage grasses, thus potentially creating concerns with lactating livestock (Ayers & Westcot, 1985).

Table 5-5 gives a more detailed analysis on the suitability of Bhungroo for dry season irrigation.

Table 5-5. Dry season Bhungroo irrigation water quality

Indicator	**Units**	**Mean**	**Min**	**Max**	**Degree on restriction of use**		
					None	Slight to moderate	Severe
Salinity							
Electrical Conductivity	dSm^{-1}	0.169	0.069	0.238	<7.0	7.3-30.0	>30.0
TDS	mg l^{-1}	107.8	44.5	147	<450	450-2,000	>2,000
Infiltration							
SAR = 0-3		**0.387**	**0.121**	**0.526**	>0.7	0.7-0.2	<0.2
= 3-6					>1.2	1.2-0.3	<0.3
= 6-12					>1.9	1.9-0.5	<0.5
= 12-20					>2.9	2.9-1.3	<1.3
= 20-40					>5.0	5.0-2.9	>2.9
Electrical conductivity	dS m^{-1}	**0.169**	**0.069**	**0.238**	>0.7	0.7-0.2	<0.2
Specific Ion toxicity							
Sodium (Na)							
Surface irrigation	SAR	0.387	0.121	0.526	<3.0	3.0-9.0	>9.0
Sprinkler irrigation	meq l^{-1}	0.417	0.083	0.7	<3.0	>3.0	
Chloride (Cl)							
Surface irrigation	meq l^{-1}	0.212	0.141	0.335	<4.0	4.0-10.0	>10
Sprinkler irrigation	meq l^{-1}	0.212	0.141	0.335	<3.0	>3.0	
Miscellaneous effects							
Bicarbonate	meq l^{-1}	**2.185**	0.761	**3.918**	<1.5	1.5-8.5	>8.5
pH		7.4	7.26	7.57	(Normal = 6.4 - 8.4)		
RSC	meq l^{-1}	-0.137	-0.161	0.376	<1.25	1.25-2.5	>2.5
SSP		14.72	7.981	13.793	<40	40-80	>80

Figure in bold indicate water has restriction on use (Modified Source: Ayers and Wescot, 1985)

From the results, the salinity hazard of the Bhungroo irrigation water was determined by the water's EC (electrical conductivity) and total dissolved solids (TDS). High EC and TDS due to high concentration of dissolved solutes (electrolytes) excessively increases salinity and stunts the crops by reducing the availability of soil-water, slowing crop growth and restricting root development (Allen et al., 1988). Additionally, high sodium and chloride toxicities increase the electrical conductivity of water and subsequently the salinity. From the results, however, mean EC (0.169 dSm^{-1}) and mean TDS (108 mg l^{-1}) were < 7.0 dSm^{-1} and 450 mg l^{-1} respectively indicating that the Bhungroo groundwater had no salinity problems and no restriction on use.

Soil water infiltration was assessed using the Sodium Adsorption Ratio (SAR) and Salinity (EC) of water since these parameters pose threats to water flow into the soil with the consequential effect of impeding nutrient uptake. SAR is an index that expresses the relative activity of sodium ions in the exchange reactions with the soil. High sodium ions in water affects the permeability of soil and causes infiltration problems. This is because sodium when present in the soil in exchangeable form replaces calcium and magnesium adsorbed on the soil clays and causes dispersion of soil particles. Dispersion results in breakdown of soil aggregates; soil becomes hard and compact when dry and reduces infiltration rates of water and air into the soil affecting its structure (Sanden et al, 2012). High salinity as a result of high concentration of mainly sodium and chloride has similar effects leading to loss of soil permeability of soil. From the results, EC ranged from 0.069 - 0.238 dSm^{-1} with the mean (0.169 dSm^{-1}) < 0.2 dS/m whereas SAR range from 0.121 - 0.526 with the mean (0.387) between 0 – 3. The low dry season TDS content observed could be due to the short residence time of the Bhungroo groundwater during recovery. Thus, at very low SAR (0.387) and EC (0.169 dSm^{-1}), water infiltration is poor and therefore a slight to severe restriction is indicated for Bhungroo groundwater use.

Bicarbonates tend to “tie up” calcium and magnesium during soil drying. This makes the sodium present potentially more damaging. High carbonates and bicarbonates in water essentially increases the sodium hazard of the water greater than indicated by the SAR. From the results, bicarbonate concentration varied from 0.761 - 3.918 meq l^{-1} with a mean value of 2.185 meq l^{-1}. The mean concentration between 1.5 - 8.5 meq l^{-1} indicated a slight to moderate restriction on irrigation water use due to associated sodium hazard and poor infiltration. Bicarbonate levels greater than 100 mg/l are sufficient to cause concern and concentrations of bicarbonates greater than 200 mg/l may pose a severe potential hazard. These levels in water may result in an unattractive white calcium carbonate deposit on plants and fruits under rapid evaporation (Ayers and Westcot, 1985).

SSP is not a satisfactory measure of sodium hazard compared to SAR, since the latter additionally expresses reactions with the soil (Tomar et al., 2012). However, water with SSP greater than 60 percent may result in sodium accumulations that will cause a breakdown in the soil’s physical properties (Wilcox, 1985). It is also used in characterizing the hardness of water i.e. high value indicates soft water and low value indicates hard water. With mean SSP of 14.72 < 40 and range 7.981 - 13.793 < 40, SSP indicated a no restriction on irrigation water use.

The specific ion toxicity indicated the toxic effect of sodium and chloride during surface and sprinkler irrigation. Thus, low concentrations of sodium and chloride implied water application would have no effect on surface and sprinkler irrigated crops and soils. However, irrigation water high in sodium and chloride ion concentrations could lead to the development of alkaline soils causing physical problems and reducing soil permeability (Kelley, 1951) or causing leaf injury (Begum & Rasul, 2009). For instance, during sprinkler irrigation at high temperatures and low humidity, chloride directly absorbed into the leaves damaging the foliar (Morris and Devitt, 1991). From the results, mean sodium (0.417 meq l^{-1}) < 3 meq l^{-1} and mean chloride

(0.212 meq l^{-1}) < 4 meq l^{-1} indicated Bhungroo groundwaterhad no restricted use since concentration in chloride and sodium would not affect foliage or soil permeability.

RSC gave indication on the amount of calcium and magnesium in irrigation water compared to carbonates and bicarbonates. Thus, the residual sodium carbonate (RSC) is an index reflecting alkalinity (carbonate or bicarbonate) hazard on plant and soil health (McLean et al. 2000). High bicarbonate concentrations in groundwater can retard plant growth and cause calcite precipitation. This can further lower soil permeability and infiltration capacity while increasing the potential for soil to erode (McLean et al., 2000). Again, reduced soil permeability affects the depth and the spread of plant roots in the soil due to lack of moisture. Thus, clay soils irrigated with high RSC index water leads to fallow alkali soils with the potential for soil erosion (Abrol et al., 1988; McLean et al., 2000). From the results, mean RSC value (-0.137) < 1.25, hence, indicating good alkaline water with no restriction on irrigation water use. The negative RSC value indicates that the risk of sodium accumulation is unlikely due to offsetting levels of calcium and magnesium. The potential for sodium to accumulate increases with increasing positive RSC value (Allen et al., 1988).

Mean pH (7.4) within the FAO range of 6.4 – 8.4, indicated good alkaline water with no restriction on irrigation water use. pH influenced by dissolved substances in water suggest a higher proportions of bicarbonate (mildly) contributed to pH > 7 i.e. alkaline water. This could also minimize the availability of micronutrients such as iron, manganese and zinc to plants.

Generally, all indicators showed no potential effect of irrigation water on crop or soil except sodium adsorption ratio, electrical conductivity and bicarbonate which showed slight to severe signs of sodium hazard and low infiltration. This could, however, be improved by minimizing runoff, increasing organic matter content and aggregation, and also minimizing soil compaction and disturbance (Ayers and Wescot, 1985). Additionally, the use of drip other than surface or sprinkler for dry season irrigation could also minimize runoff impact on soil disturbance and scale deposition on plant leaves (Ayers and Wescot, 1985).

To sum up, irrigation water quality can affect fertility needs, irrigation system performance and longevity, and how the water can be applied (Bauder et al., 2011). It is worth emphasizing that the use of suitable Bhungroo groundwater quality for crop production would result in reduction in pest, disease or the use of pesticides (Estrada-Acosta et al., 2014), improved crop yield (Bortolini et al., 2018), increased soil fertility (Bauder et al., 2011) and competitive pricing for harvested crops (Antia, 2018). Smallholder farmers are assured of all the benefits of having a suitable irrigation water, including no health risk to users and customers of harvested crops. For long term productivity, the knowledge of irrigation water suitability would help the Bhungroo smallholder farmer to understand and manage changes in crop production.

5.2.2 Groundwater level variations

Figure 5-6 gives an indication of Weisi and Kpasenkpe Bhungroo behaviour through the seasons from recharge to recovery. Thus, August to October 2016 and May to June 2017 depicts the wet season Bhungroo behavior where there is recharge with no pumping. November to December 2016 (storage with no pumping) and January to April 2017 depicts the dry season pumping. From the figure, the Weisi Bhungroo peaked around August at 0.6 m below ground level (bgl), whereas the Kpasenkpe Bhungroo peaked around September at 6 m bgl. Water levels, however, generally dropped from October to April at 9.6 and 7.3 m bgl for Weisi and Kpasenkpe respectively; after which the water levels began to rise again. The Bhungroo groundwaterabstraction in 2017, reflects the variations in groundwater levels from January till April contributing to a slight level drop in groundwater levels by about 1.5 m, since volumes abstracted were small.

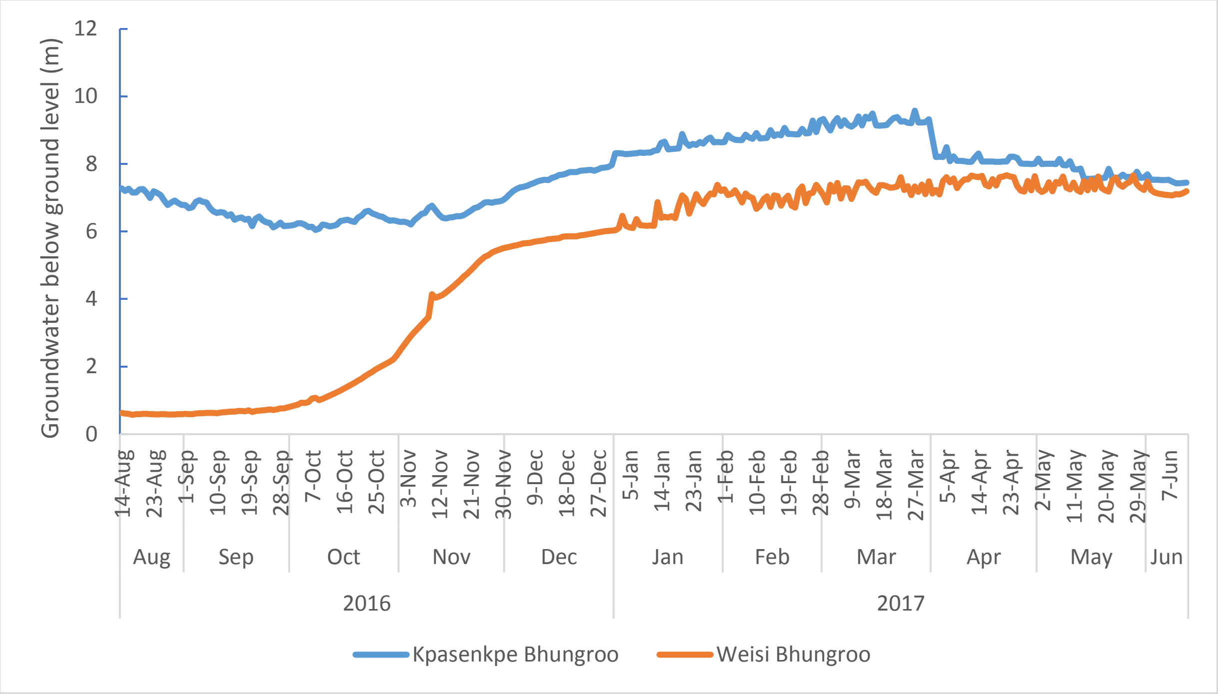


Figure 5-6. Bhungroo groundwater variations

A comparison between Bhungroos and monitoring wells in Figure 5-7 indicated a steady decline in groundwater levels for monitoring wells and Bhungroos from January to April 2017. During this period the water levels for Kpasenkpe Bhungroo and its monitoring well dropped from 9 to about 9.2 m bgl. On the contrary, at different water levels of 6.8 and 5.7 m bgl, the Weisi Bhungroo and its monitoring well maintained a constant water level drop during the same period, with some fluctuations in the latter, to 7.1 and 6.5 m bgl respectively. After April 2017, when abstractions had ceased, the Kpasenkpe Bhungroo began to rise while it's monitoring well continued to decline. Meanwhile, the Weisi Bhungroo maintained a steady water level while it's monitoring well rose sharply to a steady water level at 6.2 m bgl.

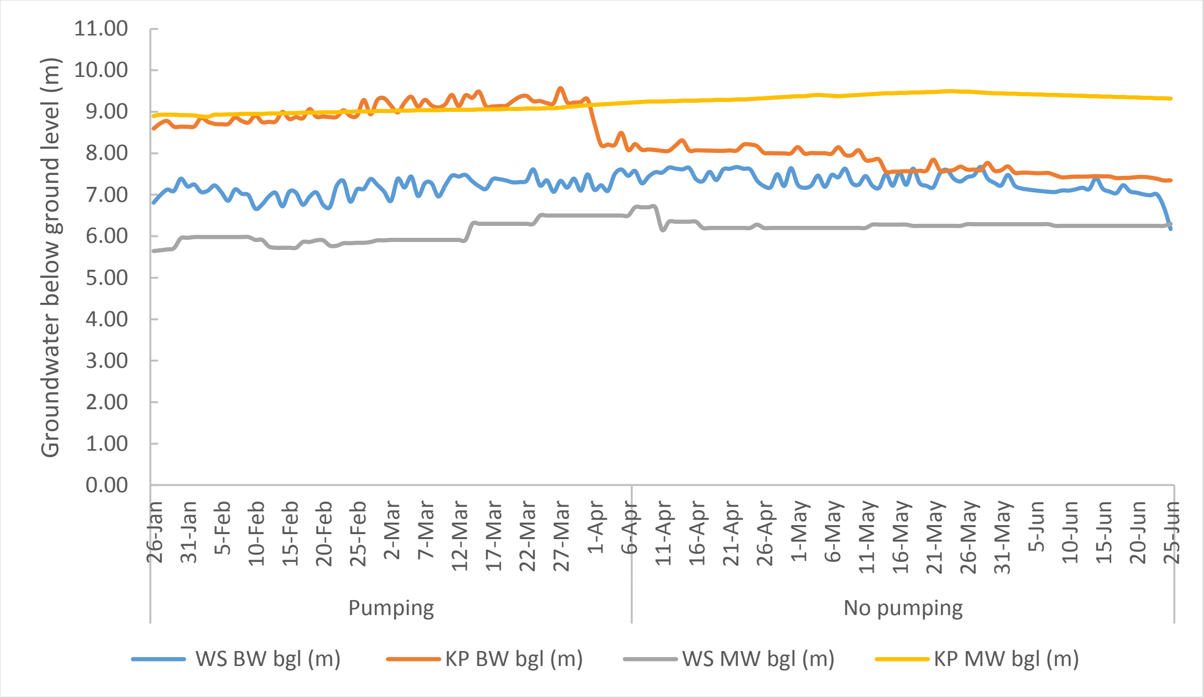


Figure 5-7. Water levels variation in *Bhungroos* and monitoring wells

The Kpasenkpe Bhungroo, unlike the Weisi Bhungroo, recovers quickly after pumping (especially after pumping ceases in April). Again, there is a relatively quicker response in water level drop during Bhungroo abstractions on the Weisi monitoring well, unlike the Kpasenkpe Bhungroo and its monitoring well. This suggests a hydraulic connection between the former.

At peak flooding, between August and September, the Weisi Bhungroo gets saturated (0.60 m bgl), whereas the Kpasenkpe Bhungroo keeps recharging or rising in water level (< 6 m bgl), This observation confirms the differences in storage behaviour between the two Bhungroos and suggests that the Kpasenkpe Bhungroo has greater available storage (excess storage) to accommodate additional recharge compared to the Weisi Bhungroo. Thus, available recharge compared to available storage is a limiting indicator to the former but to the latter it is the opposite (available recharge).

In the siting and construction of a Bhungroo, storage capacity remains a critical consideration in enhancing recharge performance especially in flood prone areas where both confined and unconfined aquifer are likely to be saturated during the flooding period.

5.3 Evaluation of Bhungroo contribution to groundwater recharge

5.3.1 Water Table Fluctuation (WTF) Method

The WTF method was used to estimate the artificial (Bhungroo) and natural (monitoring well) recharge rates for the study (Table 5-6).

Table 5-6. Estimated artificial and natural recharge values for year 2017

Community	Bhungroo			Monitoring well			ΔR_N	ΔR_N
	S_y	$\Delta\ h$ (m)	R_A (mm/yr)	S_y	$\Delta\ h$ (m)	R_N (mm/yr)	(mm/yr)	(%)
Weisi	0.03	7.4	222 (22.2)	0.03	5.8	174 (17.4)	48 (4.8)	27.6
	0.05	7.4	370 (37)	0.05	5.8	290 (29)	80 (8)	27.6
Kpasenkpe	0.02	7.0	140 (14)	0.02	1.3	26 (2.6)	114 (11.4)	438.5
	0.05	7.0	350 (35)	0.05	1.3	65 (6.5)	285 (28.5)	438.5

Values in bracket are expressed as a percentage of annual precipitation of 1000 mm/year, S_y is specific yield, Δh is the change in groundwater level. R_A is the artificial recharge, R_N is natural recharge, ΔR_N is the Bhungroo recharge performance

From the results, estimated natural recharge rates varied from 2.6 - 29 % of annual precipitation. Specifically, natural recharge rate at Kpasenkpe and Weisi varied from 2.6 - 6.5 % and 17 – 29 % of annual precipitation. Estimated artificial recharge rate from the Kpasenkpe and Weisi Bhungroos also varied from 14 – 35 % and 22 – 37 % of annual precipitation. Thus, considering the two Bhungroos, artificial recharge rate was 14 - 37 % of annual precipitation. For both natural and artificial recharge, the Kpasenkpe Bhungroo or monitoring well recorded lower recharge rate compared to the Weisi Bhungroo. However, the Kpasenkpe Bhungroo increased natural recharge about four folds (439 %) from 65 to 350 mm/yr compared to the Weisi Bhungroo which increase recharge by 28 % (290 to 370 mm/yr).

Generally, natural recharge rate (2.6 - 29 % of annual precipitation) for the study was within the range (1.8 - 29.4 % of annual precipitation) estimated for similar studies in West Africa (Sandwidi, 2007; Martin, 2006; van der Sommen & Geirnaert, 1988). However, the differences in natural recharge rates for the study locations can be attributed to the geological characteristics of the two study locations (HAP, 2006; Obuobie, 2008; Yidana et al., 2011). For instance, Obuobie (2008) estimated recharge for boreholes located in the Birimian from 10 – 24 % of annual rainfall whereas in the Voltaian estimated value was 2 - 7 % of annual rainfall. Thus, the crystalline basement rocks at Weisi consisting of granite with enhanced porosity and permeability is more suitable for natural recharge compared to the Voltaian sedimentary rocks at Kpasenkpe which consists of shales with very low permeability (Yidana et al., 2011).

The relative increases in natural recharge for Kpasenkpe (439 %) and Weisi (28 %) due to Bhungroo artificial recharge rate could have been influenced by the hydraulic character of the Bhungroo aquifer and the nature of the Bhungroo well (Pyne, 2005). In a confined aquifer, the specific capacity of a well varies with the percentage of open hole and it is maximum when the entire thickness of the aquifer is penetrated by a screen or open hole (Pyne, 1995). Thus, for a well situated in a confined or semi-confined aquifer, recharge potential is enhanced with increasing screens or access to the aquifer since these screens or holes remain recharge conduits to enhance bubble formation and storage of recharged water (Pyne, 1995). The increase in natural recharge was therefore attributed to the higher number of screens (6) which intercepted the aquifer for the Kpasenkpe Bhungroo compared to none (0) for the Weisi Bhungroo (refer to Table 3-4).

5.3.2 Chloride mass balance Method

The statistical summary of the variations in chloride concentrations are shown in Table 5-7 for 18 Bhungroo groundwatersamples (6 per location), 40 community borehole samples and 13 rainwater samples.

Table 5-7. Chloride concentrations for Bhungroos, community boreholes and rainwater

Sampling Location	Year	Chloride concentration (mg/l)	
		Bhungroo water	*Community borehole water*
Jagsi	**2016**		
	Mean	5.31	12.16
	SD	2.12	3.86
	Range	2.93-7.0	7.9-15.9
	2017		
	Mean	5.98	13.32
	SD	0.98	4.69
	Range	5-6.95	7.1-19.9
Kpasenkpe	**2016**		
	Mean	5.32	10.76
	SD	2.06	5.6
	Range	3.0-6.95	4.1-18.9
	2017		
	Mean	5.98	6.67
	SD	0.98	2.2
	Range	5-6.95	3.97-9.9
Weisi	**2016**		
	Mean	11.9	12.9
	SD	1.15	1.39
	Range	10.9-12.9	11.9-13.9
	2017		
	Mean	10.95	11.45
	SD	3.58	2.49
	Range	6.95-13.9	11.0-14.9
Study area *n = 13*	**2016/2017**		
	Mean	1.4	
	SD	6.03	
	Range	0.14-6.03	

Rainwater chloride concentrations from the study varied from 0.14 - 6.03 mg/l with a mean of 1.40±1.77 mg/l. These values were lower compared to the Bhungroo and community borehole chloride concentrations, since for example, the 2016 Bhungroo chloride concentrations at Jagsi, Kpasenkpe and Weisi varied from 2.93 - 7.0, 3.0 - 6.95 and 10.9 - 12.9 mg/l, with means of 5.31, 5.32 and 11.9 mg/l respectively. The results also suggested that the mean chloride concentrations for Jagsi (5.31±2.12 mg/l) and Kpasenkpe (5.32±2.02 mg/l) Bhungroos were lower with marginal variations compared to the Weisi Bhungroo (11.9±1.15 mg/l).

Also, chloride concentrations were generally lower for the Bhungroos compared to Community boreholes, since for instance, the 2016 and 2017 mean chloride concentrations for the Jagsi

Bhungroo at 5.31±2.12 and 5.98±0.98 mg/l were lower compared to 12.16±3.86 and 13.32±4.69 mg/l for community boreholes.

From this study, rainwater chloride values were comparable to studies conducted by Martin (2005) in the Atankwidi catchment and Obuobie (2008) in Upper East region of Ghana; where concentrations varied from 0.1 - 3.7 mg/l with a mean of 0.8 mg/l for the former and 0.2 - 6.08 mg/l with a mean of 0.8±0.43 for the latter. Again, chloride concentrations generally increased in the order, rainwater < Bhungroo groundwater< Community borehole water, due to increased evapotranspiration effect on rainwater as it moved into groundwater where chloride variations are principally influenced by rock-water interaction, mixing and dilution effect (Clark and Fritz, 2013; Appelo and Postma, 2005). Evapotranspiration rates in hotter climates influence the loss of water or humidity in the atmosphere thereby increasing the concentration of chlorides in rainwater. Subsequently, as water moves downwards through the soil, roots selectively remove water molecules thereby increasing chloride concentration. From a depth of about 3 m into the soil the effect of evaporation ceases and factors such as rock-water interaction, mixing and dilution effect become more pronounced. However, due to the mechanism of natural recharge, rock-water interactions result in the leaching and potential increase in chloride concentration in community borehole water. On the other hand, the artificial recharge of the Bhungroo minimizes rock-water interactions by enhancing direct infiltration, floodwater dilution effect and mixing. These processes eventually results in a comparatively lower Bhungroo chloride concentration than community boreholes (Granato et al., 1995). Further, between Bhungroos and community boreholes, the results indicates differences in chloride concentrations suggesting potential areas for groundwater recharge. Thus, low mean Bhungroo chloride concentrations with marginal variations, especially for Jagsi and Kpasenkpe Bhungroos compared to the community boreholes, serve as recharge zones with higher recharge rates (Obuobie, 2008).

Table 5-8 shows the results for 2016 and 2017 natural (community borehole) and artificial (Bhungroo) recharge estimates using the chloride mass balance method.

Table 5-8. Recharge estimation using the chloride mass balance

Year	Cl_p	Cl_{CB}	Cl_{BW}	**P**	R_N	R_A	ΔR_N
	mgl^{-1}			$mmyr^{-1}$			
Jagsi							
2016	1.4	12.16	5.31	1000	115 *(11.5)*	264 *(26.4)*	149 (**129**)
2017	1.4	13.32	5.98	1000	105 *(10.5)*	234 *(23.4)*	129 (**123**)
Kpasenkpe							
2016	1.4	10.76	5.32	1000	130 *(13.0)*	263 *(26.3)*	133 (**102**)
2017	1.4	6.67	5.98	1000	210 *(21.0)*	234 *(23.4)*	24 (**12**)
Weisi							
2016	1.4	12.9	11.9	1000	109 *(10.9)*	118 *(11.8)*	9 (**8**)
2017	1.4	11.45	10.92	1000	122 *(12.2)*	128 *(12.8)*	6 (**5**)

P is precipitation, Cl_p chloride in precipitation, Cl_{CB} is chloride in groundwater, Cl_{BW} is chloride in Bhungroo, R_N is natural recharge, R_A is artificial recharge, ΔR is the Bhungroo recharge performance, italiced values in bracket are expressed as a percentage of annual precipitation of 1000 mm/year, bold figures in bracket express percentage change

From the study, natural recharge (R_N) varied from 10.5 – 21.0 % of annual rainfall. Thus, the 2016 and 2017 natural recharge estimates varied marginally at Jagsi (10.5 – 11.5 %) and Weisi (10.9 - 12.2 %), but significantly at Kpasenkpe (13 - 21 %). However, considering the 21 % recharge rate at Kpasenkpe as an outlier, the study suggests a natural recharge rate of 10.5 – 13 % of annual precipitation for the entire area.

Similarly, Bhungroo artificial recharge (R_A) for 2016 and 2017 also indicated marginal variations in recharge rates for Jagsi (23.4 - 26.4 %), Kpasenkpe (23.4 - 26.3 %) and Weisi (11.8 – 12.8 %). However, these rates were high for Jagsi and Kpasenkpe Bhungroos compared to Weisi. Consequently, Bhungroo increased natural recharge (ΔR) for Jagsi, Kpasenkpe and Weisi from 123 – 129 %, 12 – 102 % and 5 – 8 % respectively.

From the study, natural recharge estimates (10.5 – 13.0 % of annual rainfall) were comparable to similar studies conducted in Northern Ghana. For instance, Obuobie (2008), Pelig-ba (2004) and Martin (2005) estimated natural recharge as 3.4 – 18.5 %, 4.5 % and 2.0 - 13 % of annual rainfall respectively. While these studies attempted to generalize findings to the entire Volta basin using long-term average inputs, the current study is quite localized and therefore results applicable mainly within the operational areas of the Bhungroo.

Further, the marginal differences in natural recharge (10.5 – 13 % of annual precipitation) for the study area suggested similarities in aquifer hydraulic properties. Thus, aquifers located in the flood prone areas of the Voltaian sedimentary and Birimian crystalline system with little or no primary porosities vary marginally in terms of natural groundwater recharge rate since the impervious character of the near-surface unweathered rocks allows only minimum opportunity for infiltration and recharge to groundwater. For instance, some studies in Northern Ghana estimates natural recharge for aquifers in the Voltaian and the Birimian as 11.9 and 11 % respectively of annual rainfall (Obuobie, 2008; Djan, 2016).

An increase in natural recharge using the Bhungroos indicated the potential of the aquifers to enhance recharge. However, the differences in the Bhungroo percentage increases could have been influenced by the nature of the well. Hence, the Kpasenkpe Bhungroo with the highest screens, followed by Jagsi and then Weisi increased recharge from 12 – 102 %, 123 – 129 % and 5 – 8 %

5.3.3 Infiltration approach

The infiltration method results are presented in Table 5-9. The results showed that the filter bed's infiltration capacity is between 9 and 15 times the infiltration capacity of the surrounding field. Assuming free flow below the wetting front, the Bhungroos can recharge up to 3,760 m^3/yr of water into the aquifer (a net benefit of 3,500 m^3/yr). The values obtained here are at the lower end of the spectrum of 4,000-40,000 m^3/y of potential recharge by Bhungroos as reported by Biplap (2013) in India. In India, the contribution of recharge enhancement to groundwater system is about 3 km^3/yr, making the country the world's lead (Dillon and Arshad, 2016). Additionally, recharge is achieved almost exclusively to unconfined aquifers through infiltration structures to help sustain groundwater supplies predominantly for agriculture and increasingly in urban areas (Dillon and Arshad, 2016). The recharge differences between India and Ghana could be attributed to the aquifer types used in recharge enhancement. For instance, while aquifers used in Northern Ghana are granite and shale aquifers, those used in India (Gujarat) where Bhungroos are common, are sandstone aquifers (Banoeng-Yakubo et al., 2010; CGWB, 2012).

Table 5-9. Recharge estimation from infiltration method

Site	Jagsi		Kpasenkpe		Weisi	
	Filter bed	Field	Filter bed	Field	Filter bed	Field
Soil texture	Silt	Sandy clay	Silt	Sandy loam	Silt	Sandy loam
Average K_s (m day^{-1})	3.06	0.22	7.46	0.531	4.49	0.518
H_w (m)	0.3	0.3	0.3	0.3	0.3	0.3
Porosity, η	0.501	0.43	0.501	0.453	0.501	0.453
h_{cs} (m)	0.15	0.35	0.15	0.25	0.15	0.25
L_f (m)	3.0	7.77	3.0	9.88	3.0	9.72
V_i (m day^{-1})	3.213	0.219	7.833	0.534	4.715	0.521
T (days season^{-1})	120	120	120	120	90	90
V_i (m yr $^{-1}$)	385.56	26.23	939.96	64.04	424.31	46.86
Area (m^2)	4	4	4	4	4	4
R_T (m^3 yr $^{-1}$)	1,542.24	104.92	3,759.84	256.17	1,697.22	187.44
R_N (m^3 yr $^{-1}$)	104.92		256.17		187.44	
R_A (m^3 yr $^{-1}$)	1,437.32		3,503.67		1,509.78	
R_N (%)	1,269.92		1267.71		705.47	

K_s is the hydraulic conductivity of wetted zone, H_w the water depth above soil, , η is the porosity, T is the time, h_{cs} the capillary suction or negative pressure head at setting front, L_f the depth of wetting front and V_i is the infiltration rate per unit of surface area.

5.3.4 Comparison between the different recharge methods

Overall, Table 5-10 presents summary results of the three methods used in estimating natural and artificial recharge. Recharge estimates for natural and artificial systems using WTF and

CMB were quite similar. Mean natural recharge using WTF and CMB were estimated at 139 mm/yr (14 % of annual rainfall) and 132 mm/yr (13 % of annual rainfall) respectively. Similarly, WTF and CMB for mean Bhungroo recharge were estimated at 271 mm/yr (27 % of annual rainfall) and CMB at 207 mm/yr (21 % of annual rainfall) respectively. Thus, Bhungroo could increase mean natural recharge between 57 - 95 % representing about 8 – 13 % of annual rainfall. The infiltration rate method estimated a total mean volume of about 2,150 m^3 as Bhungroo contribution to groundwater per year. The observation that the Bhungroos in Ghana could recharge 21 – 27 % of annual rainfall and increase natural recharge rate by an average of 76 % underscores the importance of the artificial recharge systems in increasing aquifer recharge potential, boosting aquifer yields, and also sustaining groundwater supplies for agriculture.

The increase in recharge buttresses the observation that Bhungroo is a climate change adaptation technology which helps in mitigating the impact of climate change by reducing waterlogging duration on farms, thereby making lands available for preparation and cultivation earlier than anticipated. Thus, the Bhungroo strategically plays a dual role of land and water management within the climate change and agricultural landscape.

Table 5-10. Summary of recharge estimates for the study

Recharge method		Recharge (mm/yr)			Recharge (% of annual rainfall)		
		R_N	R_A	ΔR_N (%)	R_N	R_A	ΔR_N
WTF	Range Mean	26-290 139	140-370 271	- 132 (95)	2.6-29 14	14-37 27	- 13
CMB	Range Mean	105-210 132	118-264 207	- 75 (57)	10.5-21 13	11.8-26.4 21	- 8
Infiltration rate (m^3 yr^{-1})	Range Mean	105-256 (183)	1,437-3,503 (2,150)	- 1,967 (1,075)			

5.4 Evaluation of Bhungroo Storage Potential

From the pumping test analyses, shown in Table 5-11. Pumping test analysis results the depth of the Bhungroos at Jagsi, Kpasenkpe and Weisi were 32.5, 38.9 and 18 m respectively. Also, at the same rate of abstraction (108 m^3/d), the Kpasenkpe Bhungroo recorded a higher drawdown of 3.59 m compared to the Jagsi Bhungroo drawdown of 2.89 m. Thus, Bhungroo specific capacities, which defines the yield rate per unit drawdown, varied in a decreasing order from Jagsi > Kpasenkpe > Weisi at 37.4 m^2/d, 30.1 m^2/d and 14.7 m^2/d respectively.

Table 5-11. Pumping test analysis results

Community	BD (m)	SWL (m)	Q (m^3/d)	s (m)	SC (m^2/d)	T (m^2/d)	S
Jagsi	32.5	7.2	108	2.89	37.4	13.1	0.0011
Kpasenkpe	38.9	9.97	108	3.59	30.1	9.7	0.0011
Weisi	18	6.67	86.4	5.88	14.7	8.4	0.0011
Mean	*29.8*	*7.94*	*100.8*	*4.12*	*27.4*	*10.4*	*0.0011*

BD is the Bhungroo depth, SWL is the static water level, Q is discharge rate, s is final drawdown, T is transmissivity, S is the Storativity, SC is the specific capacity * literature value for granite aquifers

Storativity values for Jagsi, Kpasenkpe and Weisi aquifers were the same at 0.0011 but with different transmissivities at 13.1, 9.7 and 8.4 m^2/day respectively. Mean transmissivity was estimated at 10.4 $m^2\ d^{-1}$. The Weisi Bhungroo aquifer transmissivity was within the range of 7.5 - 30 m^2/day determined for Precambrian crystalline aquifers (HAP, 2006). Similarly, the Jagsi and Kpasenkpe Bhungroo aquifer transmissivities were also within the range of 2.5 - 39.6 m^2/day observed for Voltaian aquifers (Gills, 1969; Yidana et al. 2012).

The storativity for the crystalline rock Bhungroo aquifers were lower than the range (0.003-0.008) reported (Bannerman and Ayibotele, 1984). However, the value suggested that the aquifers being understudied were confined or semi-confined since they are within the range of 0.00005 - 0.005 (Deb, 2014). Having the same aquifer storage capacity in different geological formations, could have been influenced by the degree of weathering or similarities in the depth of weathered zone (4 to 25m), since it significantly represents the productive zone of the aquifer (Larsson, 1984; Graham, 2008).

Since the differences in transmissivity values indicated differences in the quantity of water that the aquifer could deliver to a pumping well (Bhungroo), the lower transmissivity (8.4 $m^2 d^{-1}$) of the Weisi Bhungroo aquifer compared to the Jagsi (13.1 m^2/d) and Kpasenkpe (9.7 m^2/d) was indicative of a borehole (well) poorly connected to its aquifer with a relatively low potential to transmit water from the aquifer into the Bhungroo well or vice versa during recovery or recharge (storage) respectively.

The specific capacity of the Bhungroo well as obtained for Jagsi and Kpasenkpe also suggested that, at the same rate of abstraction, Bhungroos with higher specific capacities were more productive and performed better with minimal drawdowns. Thus, the storativities, transmissivities and specific capacities of the Bhungroo wells/aquifers in the order Weisi, < Kpasenkpe < Jagsi, establishes an increasing order of aquifer storage potential.

5.5 Evaluation of Bhungroo recovery potential

Table 5-12 shows the proportion of floodwater (X) in the Bhungroo groundwaterfor the 2016 and 2017 recharge-recovery periods using isotope and chloride tracers. From the results, floodwater proportions for 2017 recovery were lower than 2016 recharge period. For example, the tracers, ^{18}O, ^{2}H and Cl^-, indicated lower mean floodwater recovery of 0.17, 0.29 and 0.41 respectively compared to mean floodwater recharge proportion of 0.63 as determined by the Cl^- tracer. A recovery range of 0.17 – 0.41 suggested that the Bhungroo lost between 0.22 – 0.46 of its floodwater proportion by the end of the dry season, and therefore, going beyond four months of recovery could result in the unsustainable recovery of ambient groundwater.

Table 5-12. Proportion of floodwater in the Bhungroo

Bhungroo	**Year**	**Tracer**	***[BW]***	***[CBW]***	***[FW]***	***[BW]-[CBW]***	***[FW]- [CBW]***	***X***
Jagsi	2017	^{18}O (‰)	-3.94	-4.20	-1.57	0.26	2.63	0.10
	2017	^{2}H (‰)	-18.27	-21.33	-8.06	3.06	13.27	0.23
	2016	Cl^{-} (mgl^{-1})	5.31	12.16	4.49	-6.85	-7.67	0.89
	2017	Cl^{-} (mgl^{-1})	5.98	13.32	4.49	-7.34	-8.84	0.83
Kpasenkpe	2017	^{18}O (‰)	-3.85	-4.65	-1.57	0.80	3.08	0.26
	2017	^{2}H (‰)	-18.32	-26.06	-8.06	7.74	18.00	0.43
	2016	Cl^{-} (mgl^{-1})	5.32	10.76	4.49	-5.44	-6.28	0.87
	2017	Cl^{-} (mgl^{-1})	5.98	6.67	4.49	-0.69	-2.19	0.32
Weisi	2017	^{18}O (‰)	-3.59	-3.94	-1.57	0.35	2.37	0.15
	2017	^{2}H (‰)	-17.35	-19.73	-8.06	2.38	11.67	0.20
	2016	Cl^{-} (mgl^{-1})	11.90	12.90	4.49	-3.42	-8.41	0.12
	2017	Cl^{-} (mgl^{-1})	10.92	11.45	4.49	-0.53	-6.96	0.08
Mean	2017	^{18}O (‰)	-3.79	-4.26	-1.57	0.47	2.69	0.17
	2017	^{2}H (‰)	-17.98	-22.37	-8.06	4.39	14.31	0.29
	2016	Cl^{-} (mgl^{-1})	7.51	11.94	4.49	-5.24	-7.45	0.63
	2017	Cl^{-} (mgl^{-1})	7.63	10.48	4.49	-2.85	-6.00	0.41

[BW] tracer concentration in Bhungroo well, ***[CBW]*** tracer concentration in community borehole**,** ***FW*** is tracer concentration in surface water and ***X*** is the fraction of floodwater in the Bhungroo well

The general drop in the floodwater proportion of the Bhungroos could have been due to the effects of mixing and storage duration (Bouwer, 2002). Thus, after recharge, the long storage periods which lasted for approximately 90 days i.e. October to December, allowed more time for recharge water to mix with the ambient water and move down gradient, thereby decreasing recovery efficiency (Anderson & Lowry, 2004; Goyal et al., 2008). In a similar study, a farmer in Gujarat (India) reported that infiltrated water "disappeared underground" and could not be recovered (Bunsen, and Rathod, 2016).

Bhungroo recovery potentials of 0.17 – 0.41 were considered relatively lower compared to similar ASR systems which recovered between 0.38 – 1.0 (O'Hare et al., 1986, Bouwer et al. 2009). Like many ASR systems, the unrecovered Bhungroo groundwater during the 2015/2016 cycle should have formed a buffer zone well enough to ensure approximately 100 % recovery efficiency during the 2016/2017 cycle (Bouwer et al., 2009). However, this could not be fulfilled due to the effect of Bhungroo well collapse and clogging of some portions of the well intercepting the aquifer (refer Table 3-4). This occurrence led to the incomplete buffer zone formation and subsequent reduction in recovery performance. Thus, the report that Bhungroo could operate for the next 20 years at near zero maintenance cost could not be achieved for these Bhungroos since there is the need for well rehabilitation to open up the aquifer and also remove sediments in the well. In the study of seventeen (17) ASR sites with low recovery of injected water, Boomgaard (2013) recommended abandoning ASRs not economically prudent to keep operating. This notwithstanding, Bhungroo recovery potential is expected to increase over time as the Bhungroo continues to improve the buffer zone formation with more recharge-recovery cycles as observed in other systems (Pyne, 2005; Bouwer et al., 2009; Bloetscher & Muniz, 2010).

Community borehole water and floodwater did not show significant differences in chloride and isotope concentrations (refer to Table 5-7 and Table 5-3), and therefore could not accurately estimate the error margins in the equation used to determine the proportion of floodwater in the Bhungroo. Notwithstanding these limitation, the results gave glimpses of the recovery potential of the Bhungroos, which could serve as basis to improve the efficiency of recovery.

Overall, clogging affects the structural integrity of the Bhungroo technology by reducing recovery potential of the Bhungroo. It is noteworthy that unless the Bhungroo is necessarily abstracted, the chances of clogging occurring would be quite high and unless the minimum percentage recovery is capped Bhungroo overexploitation may be unavoidable, thus making

Bhungroo operations unsustainable. It's will be important therefore to update or promulgate policies and regulations to capture the use of Aquifer Storage and recovery since unlike the normal water supply boreholes, the failure of the Bhungroo will be quite synonymous to pollution. To the smallholder farmer this would mean an assurance for dry season farming, employment, food security and good health.

5.6 Determination of the Bhungroo sustainable yield

The sustainable yields for Jagsi, Kpasenkpe and Weisi Bhungroos are presented in Table 5-13.

Table 5-13. Estimated Bhungroo sustainable yields (l/s) for different methods

Bhungroo	*FC Boundary conditions*				*FC Programme*	*Lee (1915)*	*USEPA (1994)*	
	No flow boundary	*1 No flow boundary*	*2 No flow boundary*	*Closed boundary*	Q_{sus}	Q_{sus}	Q_{sus}	*Mean* Q_{sus}
Jagsi	0.52	0.37	0.28	0.17	0.31	1.18	3.04	1.51 (±0.39)
Kpasenkpe	0.44	0.32	0.25	0.15	0.27	0.87	2.45	1.20 (±0.12)
Weisi	0.20	0.12	0.09	0.05	0.10	0.78	1.22	0.7 (±0.07)
Mean	0.39	0.27	0.21	0.12	0.23	0.94	2.24	

Mean sustainable yields for the four FC boundary conditions comprising, no boundary, 1 boundary, 2 boundaries and closed boundary were 0.39, 0.27, 0.21 and 0.12 l/s respectively. From the four scenarios, sustainable yields decreased according to increasing boundary conditions, with the closed boundary recording the least yield. However, for the different Bhungroos, sustainable yields varied with the same boundary condition. For example, the Jagsi, Kpasenkpe and Weisi Bhungroo aquifers yielded 0.37, 0.32 and 0.12 l/s respectively for a 1 boundary condition.

From the three approaches used, the overall mean sustainable yields for the Jagsi Bhungroo was the highest at 1.51 (±0.39) l/s followed by Kpasenkpe and Weisi Bhungroos at 1.20 (±0.12) and 0.7 (±0.07) l/s respectively. Further, the mean sustainable yields for the FC programme was the most conservative (0.23 l/s), compared to Lee (1915) (0.94 l/s) and USEPA (1994) (2.24 l/s). The Bhungroo yield compared to the sustainable yields indicated some differences. For example, Kpasenkpe and Weisi Bhungroos discharged at 1.25 l/s and 1.0 l/s instead of 1.20 l/s and 0.7 l/s respectively.

Generally, for the FC programme, sustainable Bhungroo yields decreased from no boundary to closed boundary conditions due to the imposition of barriers on the aquifer areal extent. No-flow (finite) boundaries prevented flow lines from crossing impervious boundaries (Heath, 1983), thereby reducing aquifer yield. Meanwhile, for the same boundary conditions, aquifer sustainable yield differed due to differences in aquifer behaviour. For instance, during abstraction, the yield is influenced by the specific capacity and transmissivity. As discussed in earlier sections (5.4) these parameters increased in the order Weisi < Kpasenkpe < Jagsi.

The differences in sustainable yields for the three approaches hinged on the differences in solutions, assumptions and limitations underpinning each approach (Van Tonder et al., 2001). The low yields observed using the FC programme compared to Lee (1915) and USEPA (1994) approaches for instance, was potentially due to the capture of very sensitive and more detailed aquifer characters compared to the other approaches. For instance, in minimizing the uncertainties in the extrapolated drawdown data to determine the maximum operation time (years) at which the drawdown (s in meters) shall not exceed a maximum specified drawdown, the FC approach employed risk analysis to capture additional parameters such as transmissivity and storativity in order to fine tune the estimated sustainable yield (Murray, 1996; Kunstmann & Kinzelbach, 1998). Meanwhile, the effect of these sensitive parameters i.e. transmissivity, storativity and drawdown, on sustainable yields are more pronounced for fractured compared to weathered zone aquifers (Van Tonder et al., 2002). Hence, the suitability of USEPA (1994) and Lee (1915) compared to FC programme in the estimation of borehole sustainable yield in Northern Ghana (White Volta basin) especially where there is dominance of weathered compared to fractured aquifers (Kortatsi, 1994; Acheampong & Hess, 2000).

Further, Bhungroo yields for the study were far below yields observed in similar environments in Ghana. For instance, yields (0.7 – 1.51 l/s) observed in the study compared to studies conducted in the Kasena-Nankana District in the Upper East Region of Northern Ghana, indicated that Bhungroo yields formed part of the lower quartile of productive domestic borehole (0.18 – 6.62 l/s) (Anim-Gyampo et al., 2012). Meanwhile, the current Bhungroo operations indicate overexploitation for Kpasenkpe (1.25 l/s) and Weisi Bhungroos (1.0 l/s) where abstraction rates are above their respective mean sustainable yields of 1.20 l/s and 0.7 l/s respectively.

Operating a Bhungroo at mean sustainable yield ensures that in the event adequate artificial recharge does not occur within the extrapolated duration of two years, Bhungroo abstractions will still be sustainable (Murray 2008; Department of Water Affairs [DWA], 2010). Hence, in spite of the low yields, the key contributions of Bhungroos, in terms of augmenting existing agricultural irrigation options and improving dry season irrigation especially at a time when groundwater levels and yields have dropped significantly in most aquifers in the region, remains significant (Harvey, 2004; Anim-Gyampo et al., 2012). Additionally, it must be noted that sustainable yields vary with time and location and can only be estimated (Ponce, 2007), hence may carry a degree of uncertainty. Thus, there is the need for continuous monitoring of other parameters such as water quality to ensure the sustainability of the aquifer.

In practice, boreholes are often constructed to maximize yield from an aquifer, which helps to explain why several studies have found borehole yields to be directly related to transmissivity at a regional or national scale (Acheampong & Hess, 1998; Graham et al 2009). The determination of sustainable yields for borehole drilling is not the industry practice in Ghana. Rather, pumping test yields are recommended as discharge rates for many domestic or communal boreholes leading to overexploitation especially in the dry season. The provision of Bhungroo as an irrigation borehole therefore risk attracting higher demands even above the pumping test discharge rate during dry season farming.

5.7 Bhungroo potential irrigable area

5.7.1 Crop water and Irrigation water requirement

Table 5-14 shows the crop and irrigation water requirement for Corchorus/Amanranthus and Onions/Tomatoes for two cropping periods.

Table 5-14. Crop and irrigation water requirements for leafy vegetables and cash crops

Month	***Cropping Period***		***Growth Stage***	**ET_o (mm d^{-1})**	**K_c**	**ET_c (mm d^{-1})**	**I_{eff}**	***IR* (mm d^{-1})**
Nov	*C/A*	*O/T*	Initial/Devt.	3.95	0.7	2.77	0.9	3.08
Dec	*C/A*	*O/T*	Devt./Mid	3.72	1.00	3.72	0.9	4.13
Jan	*C/A*	*O/T*	Mid/Late	4.07	1.00	4.07	0.9	4.52
Feb	***C/A***	***O/T***	Late/Initial	4.10	1.00	4.1	0.9	4.56
Mar	**C/A**	**O/T**	Devt./Mid	4.66	1.00	4.66	0.9	5.18
Apr	**C/A**	**O/T**	Mid/Late	4.94	1.00	4.94	0.9	5.49
May	**C/A**	**O/T**	Late	4.79	1.00	4.79	0.9	5.32

C/A is Corchorus/Amanranthus, O/T is Onions/Tomatoes, italized and bold letters are for the first and second cropping period respectively

From Table 5-14, IR for Corchorus/Amanranthus and Onions/Tomatoes ranged between 3.08 – 5.49 mm/d. IR for the first cropping period peaked in February (4.56 mm/d) whereas the second period peaked in April (5.49 mm/d). The second cropping period result is similar to studies done at the Bontanga Irrigation Scheme by Agodzo (2003) who also estimated IR at peak value of 5.65. Thus, for the first and second cropping season the quantity of water necessary for crop growth was highest in February and April. Generally, these vegetables are cultivated under rainfed conditions where intensity is unregulated, however, under irrigation the required amount of water coupled with good farm management practices would ensure that for instance, tomatoes do not shed it flowers resulting in poor fruit setting or rotting of fruits (FAO, 2010).

5.7.2 Irrigable area

Table 5-15 presents the estimated irrigable area based on the sustainable Bhungroo yields. From the analyses, the irrigable area for the first and second cropping seasons range from 4,400 - 14,000 m^2 and 3,600 – 9,500 m^2 respectively. At the peak of the dry season in April where irrigation water requirement (5.49 mm/day) has peaked, the Bhungroo can irrigate between 3,600 - 7,900 m^2. Thus, for each Bhungroo i.e. the Jagsi, Kpasenkpe and Weisi Bhungroos, a minimum of 7,900 m^2 (0.79 ha), 6,300 m^2 (0.63 ha) and 3,600 m^2 (0.36 ha) respectively can be irrigated per year. Overall, pumping at a minimum of 0.7 l/s and a maximum of 1.51 l/s could irrigate an area between 3,600 m^2 (0.36 ha) - 14,000 m^2 (1.4 ha) per year.

Table 5-15. Irrigable area estimation using sustainable yield

Month	***IR (mmd^{-1})***	**Available water (m$^{3/}$d)***			**Irrigable area (m^2)**		
		Jag	***Kpa***	***Wei***	***Jag***	***Kpa***	***Wei***
Sustainable yield (l/s)		1.51	1.20	0.7			
Nov	3.08	43.5	34.6	20.2	14,123	11,234	6,558

Month	***IR* (*mmd*$^{-1}$)**	**Available water (m^{3}/d)***			**Irrigable area (m^{2})**		
		Jag	***Kpa***	***Wei***	***Jag***	***Kpa***	***Wei***
Sustainable yield (l/s)		1.51	1.20	0.7			
Dec	4.13	43.5	34.6	20.2	10,533	8,378	4,891
Jan	4.52	43.5	34.6	20.2	9,624	7,655	4,469
Feb	4.56	43.5	34.6	20.2	9,539	7,588	4,430
Mar	5.18	43.5	34.6	20.2	8,398	6,680	3,900
Apr	5.49	43.5	34.6	20.2	7,924	6,302	3,679
May	5.32	43.5	34.6	20.2	8,177	6,504	3,797

* assuming 8 hours pumping

The operations of the Bhungroo in Ghana, would be able to support a few subsistence farmers (a maximum of 4) assuming each farmer cultivates about 0.28 ha (Slaymaker & Blench, 2002) of Corchorus/Amanranthus or Onions/Tomatoes. Hence, the sustainability of the Bhungroo technology needs to be re-evaluated since it appears revenues generated from these farms may not be enough to pay for the cost of construction (US $24,000) as reported (CA, 2015). Cultivating for example tomato at a profit of GH¢ 284.83 (US $88.59) per hectare (Abubakari & Abubakari, 2015) could take a farmer several years i.e. 271 years to pay for cost of Bhungroo.

The determination of Bhungroo irrigable area (potential irrigable area) set the basis for farmers to plan for the season in terms of securing and repaying loans, purchasing farm inputs, hiring labour among others. Again, based on expected revenues a self-financing model can be instituted to support the upscaling of Bhungroo concept. Thus, knowing the potential irrigable area of the Bhungroo reduces the vulnerability of smallholder farmers to issues of food security, reduced incomes (poverty), malnutrition and migrating in search of employment among others.

CHAPTER SIX

6. Summary, Conclusions and Recommendations

The Chapter summarizes the entire study by giving a brief background and a summary on all the major findings according to the set objectives. It draws conclusions from the summary and recommends to stakeholders some areas for further studies as well as possible improvements which could be made to the study. The Chapter concludes on the relevance or contribution of the study based on the conclusions drawn.

6.1 Summary

For several decades flooding and waterlogging has been an issue in Northern Ghana, particularly for farmers in the White Volta basin owing to the generally flat topography of the area. The effect of water logging on many farmers coupled with scarcity of water for dry season irrigation, presented perennial issues of food security, malnutrition and migration. This section presents a summary of the findings of the study to assess the environmental and technical performance of the Bhungroo technology in recharging floodwater on agricultural lands for dry season irrigation according to the set objectives.

Objective 1: Determine the effects of Bhungroo artificial recharge, storage and recovery on groundwater characteristics

From the study, the Bhungroo groundwater compared to floodwater largely showed similarities in physicochemical characteristics but significant differences with ambient groundwater. Additionally, the hydrochemical characteristics of the Bhungroo groundwater [$Ca\text{-}Mg\text{-}HCO_3$ (72 %) and $Ca\text{-}Mg\text{-}SO_4\text{-}Cl$ (28 %)] and floodwater [$Ca\text{-}Mg\text{-}SO_4\text{-}Cl$ and $Ca\text{-}Mg\text{-}HCO_3$] showed similarities compared to ambient groundwater [$Ca\text{-}Mg\text{-}HCO_3$ (67 %), $Na\text{-}HCO_3$ (31 %) and $Ca\text{-}Mg\text{-}SO_4\text{-}Cl$ (6 %)]. These findings established that there was very minimal mixing of floodwater and ambient groundwater leading to Bhungroo groundwater maintaining the dominant characteristics of floodwater. It was furthered observed that Bhungroo groundwater was generally good for agricultural use notwithstanding the effect of sodium hazard on irrigated soils which could be managed with increased organic matter content. In terms of Bhungroo groundwater potability, the presence of E.coli in the Bhungroo made it unfit for drinking due to the exposure of users to public health risks. Generally, Bhungroo groundwater characteristics showed no significant seasonal variation, but the dry season isotopic signatures of the Bhungroo groundwater and ambient groundwater showed similarities due to the continuous removal of significant portions of the recharged water from storage, thereby restoring Bhungroo groundwater close to ambient groundwater characteristics.

The findings on water level variations established that the two limiting factors affecting Bhungroo recharge performance were the availability of recharge and availability of aquifer storage. For flood prone environments with excess water, however, availability of aquifer storage was the most pronounced limiting factor. Further, the study also established that Bhungroo wells hydraulically connected to other groundwater systems were not suitability for aquifer recharge and storage since they could serve as potential conduits for contaminant transfer and loss of water from storage.

Objective 2: Assess the contribution of Bhungroo to groundwater recharge

The study found that, the estimated increase in natural recharge was between 57 - 95 % (8 – 13 % of annual rainfall) with an estimated infiltration rate of about 3,500 m^3 per year. Thus, current water management practices in the study area where waterlogged farms are allowed to naturally drain into adjoining water bodies or recharge the aquifer can be improved with the use of the Bhungroo technology to the benefit of subsistence dry season irrigation farmers.

Objective 3: Assess the performance of Bhungroo in aquifer storage and recovery

The study established that Bhungroos sited in the Voltaian had higher potential to transmit water into the Bhungroo well (aquifers transmissivities, 9.7 - 13.1 m^2/day) than the Birimian aquifers (transmissivity, 8.4 m^2/day), due to higher degree of aquifer weathering (depth of weathered zone) coupled with higher potential for well-aquifer interception. Thus, for the same storativity of 0.001, Bhungroo wells in the Voltaian reflected higher specific capacities (30.1-37.4 m^2/d) compared to wells sited in the Birimian (14.7 m^2/d).

The findings on recovery potential of the Bhungroo showed that issues of well clogging, incomplete buffer zone formation, long duration of storage and well collapse potentially reduced the proportion of recharge water recovered leading to an estimated recovery potential of 0.17 – 0.41. However, a recovery of 0.17 is unsustainable and could defeat the purpose of artificial recharge.

Objective 4: Determine the sustainability of the Bhungroo in addressing dry season irrigation farming.

The study established Bhungroo sustainable yield as ranging from 0.7 - 1.51 l/s. But observed that current Bhungroo operations indicated overexploitation for Kpasenkpe (1.25 l/s) and Weisi Bhungroos (1.0 l/s) with abstraction rates above their respective mean sustainable yields of 1.20 l/s and 0.7 l/s. It was further established that, for a 100 day vegetable crop, a Bhungroo could irrigate between 3,600 m^2 (0.36 ha) - 14,000 m^2 (1.4 ha) per year i.e. 4,400 m^2 (0.44 ha) – 9,600 m^2 (0.96 ha) for first season; and 3,600 m^2 (0.36 ha) – 7,900 m^2 (0.79 ha) for the second season at sustainable yields. However, the high costs of the Bhungroo technology vis-a-vis the low potential irrigable area, tied to the low farm revenues suggest that the technology is economically unsustainable.

6.2 Conclusions

Objective 1: Determine the effects of Bhungroo artificial recharge, storage and recovery on groundwater characteristics

- The physicochemical, microbiological, hydrochemical and isotopic characteristics of Bhungroo groundwater compared to ambient groundwater established that:
    - Bhungroo is generally good for agricultural use but not for domestic use
    - Overall, there is minimal mixing of floodwater and ambient groundwater in the Bhungroo resulting in significant differences in the characteristics of the two water sources
    - Continuous dry season Bhungroo recovery restores Bhungroo groundwater close to ambient groundwater characteristics
- Bhungroos hydraulically connected to other groundwater systems are not suitable for aquifer storage and recovery since they could contribute to the loss of recharge in storage and serve as conduits for contaminant transfer
- In the siting and construction of a Bhungroo in flood prone environments, aquifer storage potential and characteristics remain the most critical consideration for enhancing recharge performance
- Weathered zone aquifers found in sedimentary rocks compared to crystalline rocks are more productive. Thus, aquifer suitability for storage increases with degree (depth) of weathered zone

Objective 2: Assess the contribution of Bhungroo to groundwater recharge

- In Northern Ghana, Bhungroo can increase recharge proportion of annual rainfall from 8 – 13 %, with a recovery proportion of 0.17 – 0.41 after approximately 90 days of aquifer storage

Objective 3: Assess the performance of Bhungroo in aquifer storage and recovery

- Two Bhungroos are exploited at rates above their sustainable yields making their current operations unsustainable.

Objective 4: Determine the sustainability of the Bhungroo in addressing dry season irrigation farming.

- At the discharge rates of 0.7 - 1.51 l/s, the Bhungroo can sustainably irrigate 3,600 m^2 (0.36 ha) - 14,000 m^2 (1.4 ha) per year for a 100 day crop.

6.3 Recommendation

Objective 1: Determine the effects of Bhungroo artificial recharge, storage and recovery on groundwater characteristics

- Farmers should manage sodium hazard by increasing organic matter content and aggregation, and also minimizing soil compaction and disturbance to improve soil water infiltration
- Aquifers hydraulically connected to other groundwater systems should be avoided in order to minimize or avoid loss of recharge and contaminant transfer
- For further research, an enhance long term monitoring of the technology should be undertaken to better understand the Bhungroo impact of the groundwater dynamics in the study area

Objective 2: Assess the contribution of Bhungroo to groundwater recharge

- The Water Resources Commission should lead other stakeholder like IWMI and GIDA in providing guidelines for the management of ASRs to ensure issues of overexploitation and pollution are handled professionally. This should include capping the proportion of floodwater on recovery to say 0.15, to avoid overexploitation.

Objective 3: Assess the performance of Bhungroo in aquifer storage and recovery

- In siting a Bhungroos, well qualified persons like the hydrogeologist should supervise the identification of suitable aquifers so as to avoid Bhungroo well collapse.
- Discharge rates of Kpasenkpe and Weisi Bhungroo should be adjusted to about 1.2 l/s or 0.7 l/s respectively to make their operations sustainable. Hence, there is the need to reset or change the pumps so as to deliver the expected yields.
- Attempt should be made at optimizing Bhungroo system performance through rehabilitation of the wells.
- Experimentation on the optimum storage duration needs to be explored further in order to increase recovery efficiency while reducing effect on water quality
- Study should be extended to other areas with different hydrogeological characteristics to give better understanding of the performance of the technology in Ghana

Objective 4: Determine the sustainability of the Bhungroo in addressing dry season irrigation farming.

- The economic sustainability of the Bhungroo Irrigation Technology in Ghana should be considered to augment the environmental and technical sustainability so better decisions could be made on the viability and scalability of the Bhungroo.

6.4 Relevance of Study

- This research contributed to knowledge on the environmental and technical performances of Bhungroo Irrigation Technology in the Ghanaian context. Specifically, the use of different approaches including isotopic, hydrochemical and physicochemical characterization to monitor trends and changes in groundwater quality impacted by the technology.

- This study offered a guide to the sustainable use of the Bhungroo technology in order to avoid aquifer depletion during dry season irrigation. I.e. in terms of the different Bhungroo structural designs, the study provided empirical evidence on the recharge, storage and recovery potential of the Ghanaian Bhungroo design which would potentially guide decision making in terms of the choice of design when scaling up.
- The study demonstrated that the identification of suitable aquifers capable of providing storage for wet season floodwater recharge could ensure security of supply to balance dry season demand and improve livelihoods
- The study assured the subsistence farmer of a sustainable dry season farming due to availability of Bhungroo water

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ANNEX 1A. Sample point information

No.	Community	Sample Label	Elevation (m)	Coordinates		Comment
				Eastings	Northings	
1	Jagsi	JG BW	146	718732	1161392	Bhungroo
2		JG FW	146	718732	1161392	Flood water
3		JG CB 3	165	717992	1160074	Community borehole
4		JG CB 2	149	718779	1161390	Community borehole
5	Kpasenkpe	KP BW	141	715752	1157685	Bhungroo
6		KP CB 1	119	713186	1155015	Community borehole
7		KP CB 2	123	713669	1154881	Community borehole
8		KP CB 3	130	713873	1155418	Community borehole
9		KP MW	138	715755	1157688	Monitoring well
10		KP FW	141	715752	1157685	Flood water
11	Weisi	WS CB 1	143	681937	1145140	Community borehole
12		WS CB 2	145	682141	1145328	Community borehole
13		WS CB 3	148	682604	1145073	Community borehole
14		WS BW	143	682096	1144998	Bhungroo Well
15		WS FW	140	682096	1144998	Flood water
16		WS MW	142	682097	1144996	Monitoring well

ANNEX 2. Number of samples

Water sources	**Number of sampling points**	**Number of sampling events (Water quality)**	**Number of sampling events (Isotope)**	**Total number of samples (Water quality)**	**Total number of samples (Isotope)**
Bhungroo wells	3	6	3	18	9
Monitoring wells	2	3	3	6	6
Community wells	8	5	3	40	24
Floodwater	3	2	1	6	3
Rainwater	3	3	3	9	9