

# **UNIVERSITY OF GHANA**

## **HYDROGEOLOGICAL CHARACTERIZATION OF THE WHITE VOLTA RIVER BASIN OF GHANA**

**BY**

**ELIZABETH DARKO**

**(10243702)**

**THIS THESIS IS SUBMITTED TO THE UNIVERSITY OF GHANA,  
LEGON IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR  
THE AWARD OF MPhil GEOLOGY DEGREE**

**July, 2015**

## DECLARATION

This thesis is the result of research undertaken by Elizabeth Darko towards the award of Master of Philosophy Degree in Geology in the Department of Earth Science, University of Ghana.

.....  
Elizabeth Darko  
(Student)

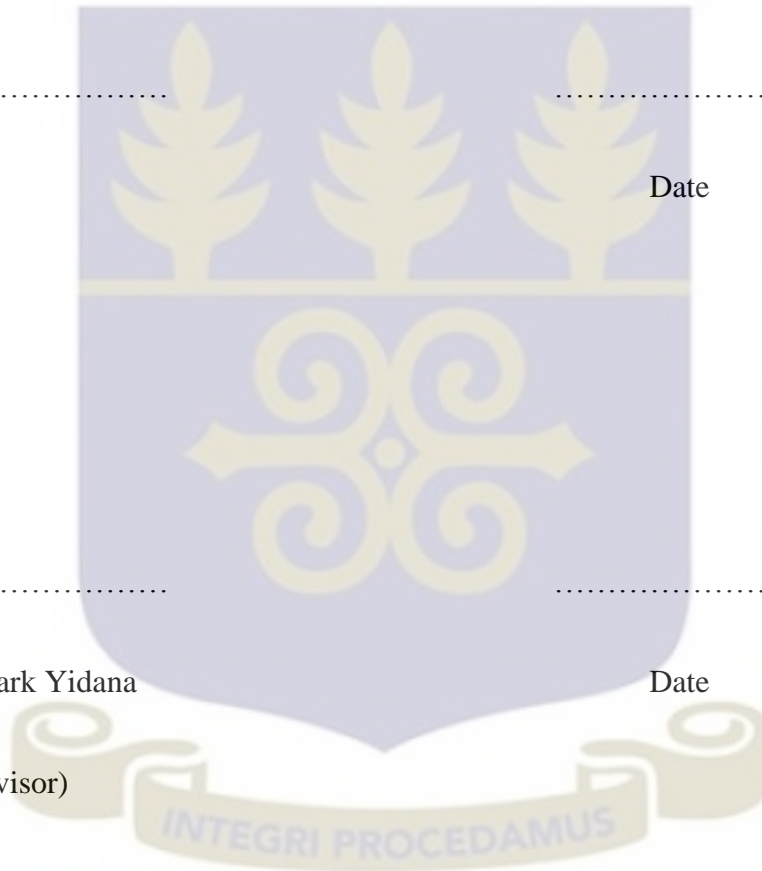
.....  
Date

.....  
Prof. Sandow Mark Yidana  
(Principal Supervisor)

.....  
Date

.....  
Prof. Prosper M. Nude  
(Co-Supervisor)

.....  
Date



## ABSTRACT

Fresh groundwater resource located in the shallow semi-confined aquifer system of the White Volta River Basin of Ghana contributes significantly to the livelihood of the communities in the basin. The objectives of this study were to evaluate the spatial variations in the hydraulic parameters of the shallow aquifer system of the White Volta River Basin of Ghana, develop a 3 - dimensional groundwater flow model for the basin and assess various scenarios of groundwater development and climatic variability on the shallow aquifers. Lithological data, groundwater hydraulic heads and relevant hydrogeological information were used to characterize and conceptualize the hydrogeological system of the shallow semi-confined aquifers. A groundwater flow simulation model was generated for steady state conditions using MODFLOW and MODPATH in the Groundwater Modelling System, GMS. Based on the borehole data and limited hydrogeological data, the domain was conceptualized as a single layer model. The top of the domain was conceptualized as semi-confining to mimic the prevailing conditions of limited direct vertical recharge from precipitation as recorded in previous studies. Confining conditions were ascribed to the bottom of the terrain to reflect the low hydraulic conductivities of the impervious rock and the confining clay layers that appear in places below the simulated aquifer. The vertical sides were conceptualized and simulated with the Robin's boundary condition so that subsurface lateral flows would be adequately characterized. The resulting numerical model was calibrated using observed hydraulic head data from 20 monitoring wells in the area. The results of the calibrated groundwater flow model show an apparent dominance of local flow systems. This is probably attributed to the variations in the hydraulic conductivity field, topography, structural entities and drainage patterns. The study found that hydraulic conductivity ranged from a low of 5.51 m/day in the central and southeastern portions of the domain, specifically the Voltaian aquifers to 80 m/day in the northern and north-eastern part of the study, representing the Birimian Basement

aquifers. A stochastic calibration approach was applied in MODFLOW to assess model non-uniqueness often associated with the uncertainties in aquifer hydraulic properties and recharge. Twenty solutions were simulated simultaneously and calibrated through the Stochastic Parameter Estimation (PEST). This approach enabled MODFLOW to produce a number of combinations of aquifer parameters and recharge. At calibration, statistical procedures were used to determine the extent to which the several solutions were different from each other. On the basis of this, the uniqueness of the simulation was assessed and the resulting scenario analyses were placed in the proper contextual framework. The results suggest that recharge rates range from 0.02 to 4% of the annual rainfall in the terrain appears to hold promise for large-scale groundwater development to support irrigation schemes. The stochastic model was used to simulate responses of the system to various scenarios of abstraction increment and recharge rates reduction. The simulation suggest that under the current recharge rates, the system can sustain increasing groundwater abstraction rates by up to 200% with minimal drawdown in the hydraulic head for the entire terrain. This suggests that groundwater can sustain future increased groundwater demands from population growth and industrialization. However, significant drawdowns will be expected in the wake of 80% reduction in recharge, due to intense climatic variability and change. This study strongly recommends the protection of some of the local groundwater recharge areas identified in the study and the promotion of artificial groundwater recharge through the development of dugouts to encourage recharge.

## DEDICATION

I dedicate this work to my parents, Mr. Daniel Yitu Darko and Mrs. Paulina Darko.

To my siblings Philip and Dorothy, I am most grateful for your love and support and may God richly bless you.



## ACKNOWLEDGEMENT

I am grateful to God, for His mercies and grace with which I have gone through this programme successfully. He deserves all the glory.

My profound gratitude goes to my supervisors Prof. Sandow Mark Yidana and Prof. Prosper M. Nude for their immense supervisions, constructive criticisms, and support in making this thesis work a success. God richly bless you.

Mrs. Yvonne S. Loh, I say thank you for helping me with some technical advice and input concerning this work. Your enormous effort is really appreciated and cannot be overlooked.

The financial support from my parents for this study is highly appreciated.

To my fellow Earth Scientists, Patience Bosompemaa, Patrick Banahene, Patrick Suuehullo Bayowobie, Emmanuel Bani and Jeremiah Anno-Onum, I say thank you for your support.

My sincere thanks go to Mr. Enoch Asare, Groundwater Specialist, of the Water Resource Commission, Ghana, under the Hydrogeological Assessment Project, (HAP), for the well data used in the simulation.

I also want to thank Mr. Samuel Nunoo and my siblings whose emphatic encouragement and prayers have made this work possible. Finally, I thank the Almighty God once again for all his manifold blessings now and forever.

<b>TABLE OF CONTENT</b>	<b>Pages</b>
DECLARATION .....	i
ABSTRACT.....	ii
DEDICATION .....	iv
ACKNOWLEDGEMENT .....	v
CHAPTER ONE .....	1
INTRODUCTION .....	1
1.1. BACKGROUND.....	1
1.2. PROBLEM STATEMENT .....	5
1.3. JUSTIFICATION.....	6
1.4. STUDY OBJECTIVES .....	7
1.5. STUDY AREA.....	8
1.5.1. Location and Physical Setting .....	8
1.5.2. Drainage.....	11
1.5.3. Climate.....	11
1.5.4. Vegetation and Soil .....	13
1.5.5. Geology .....	15
1.5.6. Hydrogeology .....	20
CHAPTER TWO .....	23
LITERATURE REVIEW .....	23
2.1. GENERAL OVERVIEW .....	23
2.2. GENERAL GROUNDWATER RESOURCES MANAGEMENT AND ASSESSMENT IN GHANA.....	24
2.2.1. Groundwater Resources Management.....	24
2.2.2. Groundwater Resource abstraction.....	26
2.3. CHARACTERIZATION OF GROUNDWATER FLOW SYSTEMS.....	30
2.3.1. Groundwater recharge .....	30
2.4. NUMERICAL SIMULATIONS AND SITE CHARACTERIZATION .....	38
2.4.1. Hydrostratigraphy units modelling and Site Characterization .....	38
2.4.2. Groundwater management Models.....	40
CHAPTER THREE .....	51
MATERIALS AND METHODS.....	51
3.1 DESK STUDY .....	51

3.2 DATA COLLECTION.....	51
3.3 POST FIELD WORK.....	52
3.3.1 Hydrogeological characterization and Numerical simulation models.....	52
CHAPTER FOUR.....	65
RESULTS AND DISCUSSION .....	65
4.1 GENERAL GROUNDWATER LEVEL AND FLOW IN THE WHITE VOLTA RIVER BASIN OF GHANA .....	65
4.1.1. Steady State simulations.....	65
4.1.2 General Hydraulic conductivity estimated in the numerical simulation.....	70
4.1.2.1. Steady State .....	70
4.1.3 Recharge rate estimation through the numerical simulation.....	74
4.1.3.1 Steady State .....	74
4.1.4. Sensitivity analysis of calibrated steady state model .....	79
4.1.5 Groundwater Modelled Mass Water balance summary .....	80
4.1.5. 1 Steady State .....	80
4.1.6 Stochastic Simulations of Groundwater Flow.....	81
4.1.6.1. Parameter Randomization Approach.....	81
CHAPTER FIVE .....	97
CONCLUSIONS AND RECOMMENDATION .....	97
5.1. Conclusion.....	97
5.2. Recommendation.....	98
References.....	100



## LIST OF FIGURES

Figure 1.1: Location map of the Study area, showing some towns and drainage network. ....	9
Figure 1.2: Digital Elevation Model (DEM) of the White Volta River Basin of Ghana showing the variations in topography. ....	10
Figure 1.3: Map showing the vegetation types with the White Volta River Basin of Ghana. ....	14
Figure 1.4: Map showing soil types within the study area. ....	14
Figure 1.5: Geological map of the study area. ....	19
Figure 1.6: Hydrogeological Map of Ghana (Banoeng-Yakubo et al., 2010). ....	22
Figure 3.1: Map showing the borehole locations in the White Volta River Basin of Ghana. ....	53
Figure 3.2: Digitized map of the coverage area explaining the process of conceptualization in GMS 7.1. ....	54
Figure 3.3: Map showing grid over entire coverage area. ....	58
Figure 3.4: Map showing grid over the active domain. ....	58
Figure 3.5: A summary of boundary conditions and the discretization used for the model in 2D/ plan view. ....	60
Figure 3.6: Summary of boundary conditions and the discretization used for the model in 3D / oblique view. ....	60
Figure 4.1: Potential field map resulting from the steady state calibrated model in a plan view. ....	66
Figure 4.2: The potential field map resulting from the steady-state calibration of the model in an oblique view. ....	66
Figure 4.3: A comparison between observed and model computed hydraulic heads. ....	67
Figure 4.4: Potential field map calibrated at steady state showing the groundwater flow directions plan view. ....	69
Figure 4.5: Potential field map calibrated at steady state showing the groundwater flow directions in oblique view. ....	69
Figure 4.6: Distribution of the calibrated hydraulic conductivity (m/day) of the area in plan view. ....	73
Figure 4.7: Distribution of the calibrated hydraulic conductivity (m/day) of the area in oblique view. ....	73
Figure 4.8: Distribution of recharge rate (m <sup>3</sup> /day) of the area under steady state in plan view. ....	78
Figure 4.9: Distribution of recharge rate (m <sup>3</sup> /day) of the area under steady state in oblique view. ....	78
Figure 4.10: Sensitivity plot of calibrated steady state model. ....	79
Figure 4.11: Map showing the standard deviations of hydraulic head from stochastic simulation. ....	82
Figure 4.12: Map showing the hydraulic head and hydraulic conductivity fields from stochastic simulation for first realization. ....	82
Figure 4.13: Map showing the hydraulic head and hydraulic conductivity fields from stochastic simulation for second realization. ....	83
Figure 4.14: Map showing the hydraulic head and hydraulic conductivity fields from stochastic simulation for third realization. ....	83
Figure 4.15: Map showing the hydraulic head and hydraulic conductivity fields from stochastic simulation for fourth realization. ....	83
Figure 4.16: Map showing the hydraulic head and hydraulic conductivity fields from stochastic simulation for the fifth realization. ....	84
Figure 4.17: Map showing the hydraulic head and hydraulic conductivity fields from stochastic simulation for the sixth realization. ....	84
Figure 4.18: Map showing the hydraulic head and hydraulic conductivity fields from stochastic simulation for the seventh realization. ....	84

Figure 4.19: Map showing the hydraulic head and hydraulic conductivity fields from stochastic simulation for the eighth realization. ....	85
Figure 4.20: Map showing the hydraulic head and hydraulic conductivity fields from stochastic simulation for the ninth realization. ....	85
Figure 4.21: Map showing the hydraulic head and hydraulic conductivity fields from stochastic simulation for the tenth realization. ....	85
Figure 4.22: Map showing Hydraulic head distribution after 10% increment in groundwater abstraction. ....	87
Figure 4.23: Map showing Hydraulic head distribution after 20% increment in groundwater abstraction. ....	87
Figure 4.24: Map showing Hydraulic head distribution after 30% increment in groundwater abstraction. ....	88
Figure 4. 25: Map showing Hydraulic head distribution after 40% increment in groundwater abstraction. ....	88
Figure 4.26: Map showing Hydraulic head distribution after 50% increment in groundwater abstraction. ....	89
Figure 4.27: Map showing Hydraulic head distribution after 100% increment in groundwater abstraction. ....	89
Figure 4.28: A map showing Hydraulic head distribution after 200% increment in groundwater abstraction. ....	90
Figure 4.29: Map showing hydraulic head distribution after 10% reduction in groundwater recharge. ....	91
Figure 4.30: A map showing hydraulic head distribution after 20% reduction in groundwater recharge. ....	91
Figure 4.31: A map showing hydraulic head distribution after 30% reduction in groundwater recharge. ....	92
Figure 4.32: A map showing hydraulic head distribution after 40% reduction in groundwater recharge. ....	92
Figure 4.33: A map showing hydraulic head distribution after 50% reduction in groundwater recharge. ....	93
Figure 4.34: Map showing hydraulic head distribution after 85% reduction in groundwater recharge. ....	95
Figure 4.35: Map showing hydraulic head distribution after 85% reduction in groundwater recharge and 100% increment in abstraction. ....	95

## LIST OF TABLES

Table 1.1: A summary of range values of some characteristics of aquifer systems in the White Volta River Basin of Ghana (Barry et al., 2005).....	22
Table 2.1.: Irrigable potential of some irrigation projects (FAO, 1985; Agodzo et al., 1994).....	29
Table 3.1: Wells used for model calibration.....	56
Table 3.2: Initial abstraction rates from boreholes used in this study.....	64
Table 4.1: Groundwater budget of the modelled domain under steady state condition.....	80



## **CHAPTER ONE**

### **INTRODUCTION**

#### **1.1. BACKGROUND**

The White Volta River Basin of Ghana is one of the four main sub-basins of the Volta River system which spans Togo, Burkina Faso and Ghana. It contributes to annually, an average of 20% of the inflow to the Volta Lake, hence making it an important element of hydropower generation at the Akosombo Dam and Kpong power stations in the lower Volta system (IWRMP, 2008). As such, any alteration of the river flow regime upstream, due to larger scale irrigation developments, would therefore have an impact on the potential output. Its attractiveness to investors and its function to economic growth of the country make the basin an interesting and motivating place for hydrogeological research. The fresh groundwater resource located within the shallow semi-confined aquifer system of the White Volta River Basin of Ghana contributes significantly to the socio-economic livelihood of the communities in the basin, (IWRMP, 2008; Obuobie et al., 2012).

Socio-economic activities such as water supply and sanitation, agriculture, industry, urban development, hydropower generation, inland fisheries, transportation and research, among others, are some of the economic value of the fresh groundwater resource located within aquifers in the basin (IWRMP, 2008).

In the wake of poverty reduction, hydrogeological investigations in the White Volta River Basin of Ghana have been conducted in various ways. Investigations include; groundwater level monitoring and recharge rate estimation by Obuobie et al., (2012), integrated water resources management (IWRMP, 2008) and numerical groundwater flow simulations under transient conditions (Ofosu-Addo et al., 2008). Nevertheless, few studies have been

conducted on the assessment and characterization of the hydrogeological conditions of the basin. This study is very imperative as it investigates the requisite for proper management and sustainability of the groundwater resource.

Knowledge of aquifer parameters is very important in every groundwater investigation studies for the management of the resource. Hydraulic conductivity, recharge rates, specific capacity, yield and aquifer depths are some of the fundamental properties used in describing groundwater aquifers. As such, several techniques are normally employed with the aim of investigating aquifer hydraulic properties (Soupios et al., 2007).

One of the conventional ways in estimating aquifer hydraulic parameters, such as hydraulic conductivity is the pumping test method (Fetter, 2001). Though, it provides safe yields of aquifer hydraulic parameters, sparse spatial distribution of available boreholes makes it problematic in obtaining hydrogeological conditions of the aquifer systems (Soupios et al., 2007). This is due the fact that, in most cases, numerous boreholes (made up of extensive arrays of pumping wells and observation wells) need to be drilled during the investigation, and this approach has proven to be costly and time consuming (Slater, 2002; Kalbus et al., 2006; Illman et al., 2007; Soupios et al., 2007). Also, pumping tests do not provide detailed information about the variability of hydraulic conductivity as they are often related to narrow or limited site characterizations, thus, data obtained are only point estimates (Slater, 2002; Yidana et al., 2015). Moreover, in some cases, the installation of wells and piezometers may not be justified (Kalbus et al., 2006).

Tracer test have also been used in the determination of aquifer hydraulic parameters. Although the procedure is simple in practice, results obtained are only approximations due to field limitations (Todd and Mays, 2005). Thus, an alternative approach in detailed regional hydrogeological investigations as characterization of the spatial patterns of behaviour of

aquifer hydraulic parameters is concerned, is through the use of groundwater numerical simulation model approach (Yidana and Chegbeleh, 2013).

Another pre-requisite in the assessment and evaluation of groundwater resources to determine sustainable yields of groundwater aquifers is the determination of recharge rate estimates (e.g. Simmers, 1998; Healy and Cook, 2002; Obuobie et al., 2012; Yidana and Koffie, 2014). A variety of methods exists in estimating for groundwater recharge rates and have been documented; water table fluctuation method (e.g. Obuobie et al., 2012), chloride mass balance method (e.g. Sami and Hughes, 1996; Mensah et al., 2014), tracer (isotope) methods (e.g. Scanlon et al., 2002; Pelig-Ba, 2009; Yidana and Koffie, 2014; Yidana et al., 2014), soil mass balance technique (e.g. Carrier et al., 2008a) and Darcian methods (numerical modelling) (e.g. Yang et al., 1999; Scanlon et al., 2002; Nimmo et al., 2008; Yidana et al., 2014).

Most cases, effective hydrogeological investigations require an integrated approach of hydrogeological characterization in the form of stratigraphy description and regional groundwater numerical flow simulation. Such dual approaches have been applied in the past decades to comprehensively assess and characterize groundwater flow systems. In Ghana, hydrogeological characterization studies are limited due to lack of access to well log information and insufficient data.

Notwithstanding, in recent years, the field of groundwater hydrology has focused on the use of numerical simulation models as a means to investigate aquifers parameters and determine hydrogeological conditions of aquifer systems. Studies conducted by (Lutz et al., 2007; Yidana et al., 2013; Yidana et al., 2014; Yidana et al., 2015;) are, but few examples in Ghana where groundwater models have been applied in determining aquifer properties and characterize groundwater flow systems. All these studies with the exception of (Yidana et al.,

2014) focused on steady state simulations and were quite limited in their search for effects of changes in groundwater storage on the aquifer systems.

Internationally, the use of groundwater flow models have been applied in various fields: They have been used to provide detailed analysis of seawater intrusion effects on coastal aquifers and as therefore act as useful supporting systems in the management of groundwater contamination (e.g. Karahanoglu and Doyuran, 2003; Zhang et al., 2004; Barazzuoli et al., 2008; Lin et al., 2009). They have also been applied in estimating groundwater budgets and managing groundwater flow dynamics (e.g. Van Der Hoven et al., 2002; Ahmed et al., 2005; Wang et al., 2008; Hu et al., 2011). Furthermore, groundwater models have been used to delineate capture zones for wells protection and groundwater management (e.g. Grubb, 1993; Barry et al., 2009), especially in areas where there are have been substantial decline in the potentiometric surface of aquifers due to over exploitation of the resource. Where the aquifer systems are faced with issues relating to water qualities and contamination from anthropogenic activities and waste disposal, groundwater models can serve as useful tools in solute and contaminant transport models ( Fleming and Haggerty, 2001; Brookfield et al., 2006; Harte et al., 2006).

Since mostly numerical flow models rely on set of assumptions on initial and boundary conditions, their accuracy are not highly reliable due to sparse and inconclusive field data, poor definition of stresses acting on the systems and errors in system conceptualization (Fetter, 2001; Yidana et al., 2015). Nevertheless, where there are sufficient and detailed hydrogeological data for models construction and calibration, groundwater models act as the best tools in predicting several scenarios and climatic variability. Comparatively, groundwater models with the availability of sufficient data are more economical and provide reliable information of continuum aquifer hydraulic properties as compared to the

conventional pumping test which provides point data on aquifer properties (Yidana and Chegbeleh, 2013). Where properly applied, numerical simulation models can provide reliable information about flow and transport processes, and assist in the design of remedial programs.

Though groundwater flow models play a significant role in defining aquifer hydraulic parameters, they are faced with major weaknesses of non-uniqueness in estimates of aquifer hydraulic parameters and its uncertainty in predictions, as it remains the difficulty in accurately describing the spatial variability in controlling parameters (Ophori, 1999). As such, there is the need for an additional investigation to take care of the non-uniqueness and uncertainty.

## **1.2. PROBLEM STATEMENT**

Under the pressures of economic development and surface pollution, arid and semi-arid regions face major challenges in the management of scarce freshwater resources. Groundwater is commonly the most important water resource in these areas. Mode of abstraction of the resource is through hand-dug wells with or without hand pumps, and boreholes with hand or electric pumps depending on the yield or protected springs which tap the aquifer at a relatively shallow depth (Dapaah-Siakwan and Gyau-Boakye, 2000). In recent times, rising water demands from the basin aquifers in the White Volta River Basin of Ghana has increased substantially, leading to the depletion of groundwater sources in some portions of the basin (Giesen et al., 2001; Gyau-Boakye, 2001; Gyau-Boakye and Tumbulto, 2006; Obuobie et al., 2012).

Also, rain-fed agriculture is the main occupation of the people in the basin (Yidana et al., 2015). This practice solely relies on rainfall patterns in the study area. However, the recent patterns of rainfall in the area have been observed to be quite uneven due to the variability in the global climatic conditions. Owing to this effect, crop losses have been rampant. This rapid decline in rainfall during the dry seasons has led to the migration of most residents, especially the youth to the southern portions of the country in search of greener pastures. Furthermore, the prevailing flood hazards during the wet season along the stream banks and in the vicinity of the main river and its tributaries is also a water resource issue characterizing the basin (IWRMP, 2008).

### **1.3. JUSTIFICATION**

Though groundwater offers the opportunity to improve supply coverage at a relatively lower cost, and with greater flexibility, it is of great importance to improve our knowledge of the resource for national and sustainable development and management (Obuobie et al., 2012). In addition, the strength of an economy relies upon its growing agricultural sector. Rapid increase in Ghana's population and the inhabitants of the Northern Ghana in particular, demands an increase in crop productivity and groundwater consumption for an irrigated agriculture (Yidana, 2011; Yidana et al., 2015), as these will enhance national food security and improve economic status. For this reason, detailed hydrogeological investigations of the aquifers in the basin are of great importance, not only to improve our knowledge of the resource, but to contribute to scientific data toward the development of a decision support system for a sustainable development and prudent management of the groundwater resources to meet the growing demand for irrigation and commercial needs.

In this particular study, the development of stochastic model has been incorporated into a steady state groundwater numerical flow model in some portions of crystalline basement and Voltaian aquifer systems in the White Volta River Basin of Ghana. The model is also being used to assess limited development scenarios under current groundwater recharge conditions and abstractions.

Thus, not only will the study form an initial stage in defining the aquifer hydraulic properties within the basin, but will confront the non-uniqueness and uncertainty associated with the groundwater steady state. Again the findings from this study will add up to existing scientific knowledge of the shallow groundwater aquifer systems and also advise policy makers and stakeholders in the management of the groundwater resource to meet growing needs of commercial, irrigated agricultural project, domestic and hydro-power generation purposes. Hence, detail hydrogeological conditions of aquifers in the study area will be defined for a proper groundwater management and sustainability.

#### **1.4. STUDY OBJECTIVES**

The main aim of the study is to investigate the groundwater flow geometry in the White Volta River Basin of Ghana.

The specific objectives include:

- To evaluate the spatial variations in the hydraulic parameters of the shallow aquifer system in the White Volta River Basin.
- Develop a 3-dimensional groundwater flow model for the White Volta Basin.
- Assess various scenarios of groundwater development and climatic variability on the shallow aquifers in the White Volta Basin.

## 1.5. STUDY AREA

### 1.5.1. Location and Physical Setting

The White Volta River Basin in Ghana lies within the boundaries of latitudes  $8^{\circ}50'N$  and  $11^{\circ}05'N$ , and longitudes  $0^{\circ}06'E$  and  $2^{\circ}50'W$ . It covers three (3) administrative regions, i.e. all of the Upper East Region, 70% of the Upper West Region and about 50% of the Northern Region (Fig. 1.1). The basin is bordered to the, east, west and south by Oti River Basin, Black Volta River Basin and the Mani/ Lower Volta sub – basins respectively (IWRMP, 2008). Burkina Faso forms its northern boundary (IWRMP, 2008). The total catchment area of the basin in Ghana is estimated to about  $45,804 \text{ km}^2$ . This represent 43.7% of the estimated  $104,752 \text{ km}^2$  of the entire White Volta River Basin system, which extends beyond the boundaries of Ghana to neighbouring Burkina-Faso and Togo (Obuobie et al., 2012 cited in MWH, 1998). The basin has a population of about 1.6 million inhabitants, with annual growth rate of 1.5% ( GSS, 2002; WRI, 2003; Codjoe, 2004) Settlement in the basin is mainly rural and dispersed.

The basin is characterized by fairly low relief with few areas of moderate elevation in the north and east. The lowest elevation is about 8 m and the highest portion reaches beyond 350 m (WRI, 2003), as shown in Fig. 1.2.

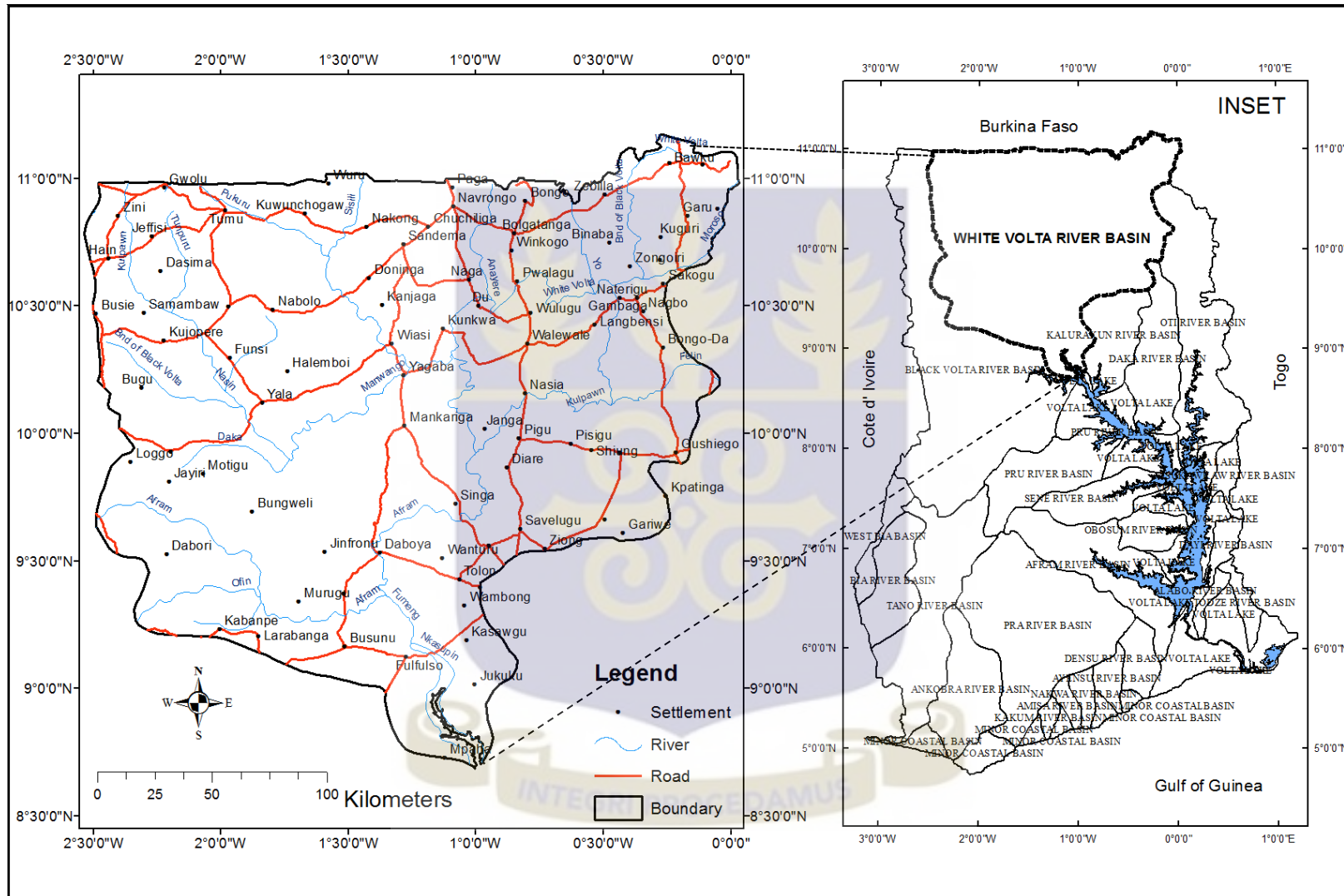


Figure 1.1: Location map of the Study area, showing some towns and drainage network.

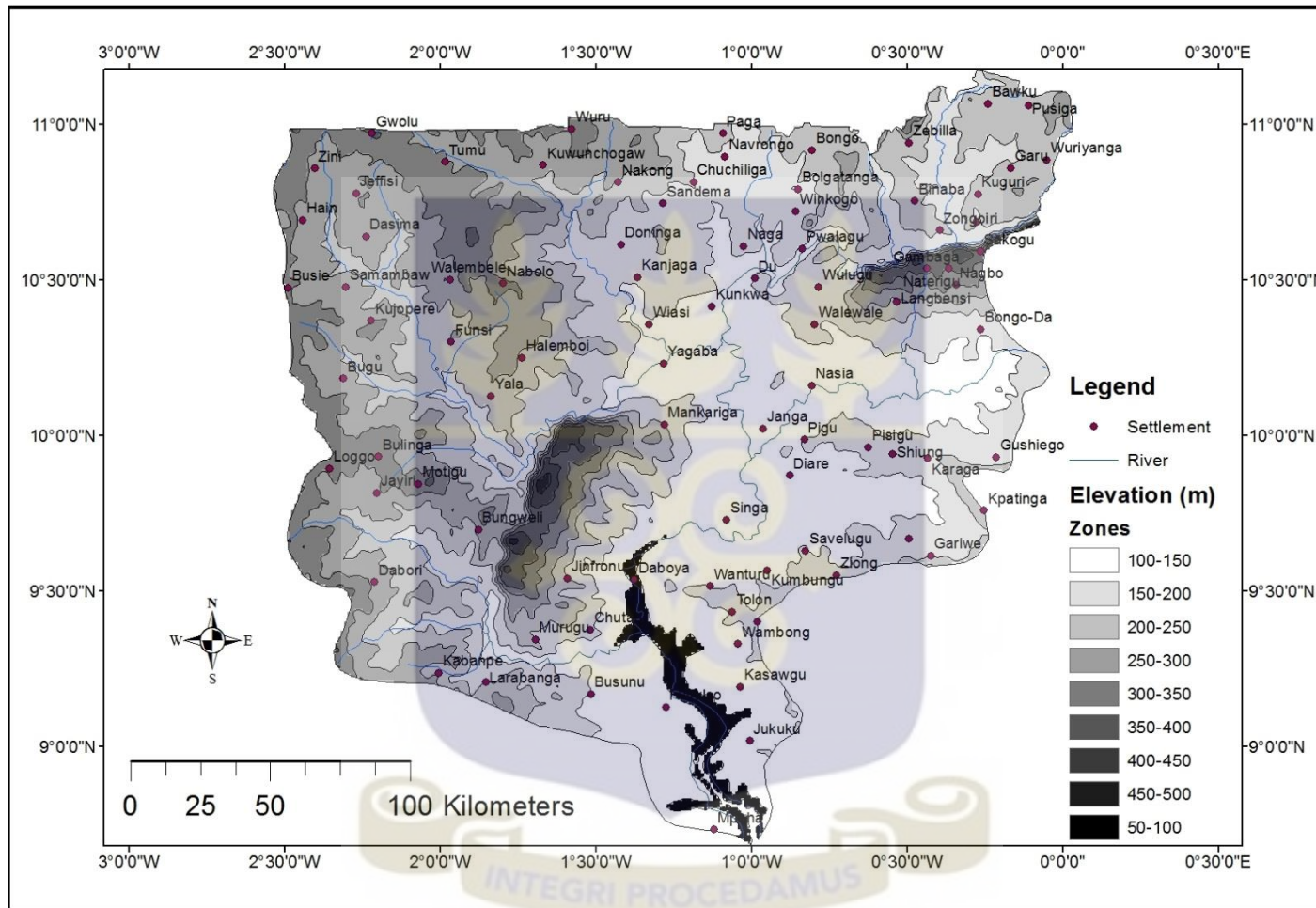


Figure 1.2: Digital Elevation Model (DEM) of the White Volta River Basin of Ghana showing the variations in topography.

### **1.5.2. Drainage**

The drainage area is about 45,804 km<sup>2</sup> (20% of Ghana's total land area), and constitutes about 44% of the total area of the White Volta River Basin (Barry et al., 2005). The White Volta River Basin, Ghana and its main tributaries in the northern part (Red Volta and the Kulpawn/ Sissili rivers) take their sources in the central and north-eastern portions of Burkina Faso (IWRMP, 2008). The entire catchment is drained by several rivers and streams, splitting into tributaries which form a dendritic drainage network. Notable among these rivers and streams are Tono, Morago, Kajia, Nasia, Zugo, Sissili, etc. Most of these streams and rivers are ephemeral and do not last the entire year as they dry out quickly during the dry seasons due to high evaporation rates coupled with high temperatures and low humidity (IWRMP, 2008).

The White Volta River first flows south on entering Ghana, turns west to be joined by the Red Volta, after which it continues westward through Upper East Region and then turns south. It is then joined by several tributaries, such as the Kulpawn/Sissili and Nasi rivers. It then continues southwards to Nawuni, flows westwards to Daboya and then southwards again where it is joined by the Mole river before entering the Volta Lake (IWRMP, 2008).

### **1.5.3. Climate**

The study area falls under the Inter-tropical Convergent Zone, the interface where two air masses, tropical continental and tropical maritime overlap (Dickson and Benneh, 1995). The frontal activity and relative movement of the two air masses control the amount and duration of rainfall. Rainfall, which is generally of short duration and high intensity and often preceded by thunderstorms and line squalls starts intermittently between March and April

through August to September when it turns stable and very heavy (Dickson and Benneh, 1995). The dry seasons are pronounced with temperature ranging between 18°C and 42°C with mean value of approximately 30°C, except during the harmattan seasons (November – February), when temperatures can go as low as 20°C or less. Relative humidity during wet/rainy season is in the range 40 and 70% and drops to about 15% during the rest of the year (Dickson and Benneh, 1995). The observed low humidities and high temperatures have led to high potential and actual evapotranspiration rates in the basin (Obuobie et al., 2012). Several researchers have reported various values of evapotranspiration rates. For instance, Kwei, (1997) reported potential evapotranspiration rates ranging between 650 mm/year to 1300 mm/year. However, Van der Sommen and Geirnaert, (1988) proposed quite high potential evapotranspiration rates in the range between 1776 mm/year to 2112 mm/year. The mean annual rainfall ranges from 800 mm/year to 1140 mm/year (Shahin, 2002; Gyau-Boakye and Tumbulto, 2006). The mean relative humidity varies from 80% at the peak of the rainy season in September to about 20% in January (peak of the harmattan period). Water table depth varies from ground level in the rainy season to about 15 m in the dry season. Previous monitoring of water levels in the study area revealed a sharp rise and decline in the water table during the wet and dry seasons, respectively (Martin, 2006). However, the recent observation in the climatic conditions of the area and the Northern Region of Ghana as a whole is that, the pattern is quite unpredictable and does not follow specific period or duration. As a result, much of the agricultural activities and irrigational projects carried out in these regions are under serious pressures in productivity.

#### 1.5.4. Vegetation and Soil

The White Volta River Basin of Ghana is located within the Interior wooded or tree Savanna (Fig. 1.3), and constitutes Guinea and Sudan Savannah. It forms the largest single vegetation zone in Ghana covering an area of about 170,000 square kilometres (Dickson and Benneh, 1995). The vegetation is dominantly of trees such as baobab, dawa-dawa, acacias and shea tress. Grasses in this vegetation zone grow in tussocks and may reach a height of 3 m or more. During the rainy season, trees blossom and grasses shoot rapidly looking green with life. However, the leaves begin to alter in colour and the trees begin to shed their leaves soon after the rains. Due to an extended period of grazing of livestock and anthropogenic activities such as regular burning and cultivation, relatively fewer trees have survived (Dickson and Benneh, 1995). Thus, vegetation in this zone is quite open and dominated by short grasses. There are a number of small and large scale irrigation systems practiced within the basin (IWRMP, 2008) and crops such as rice, sugarcane and vegetables are cultivated.

The dominant soils types in the basin are luvisols and lithosols, which together constitute more than 85% of the soil resources as shown in Fig. 1.4 (FAO-UNESCO, 1994).



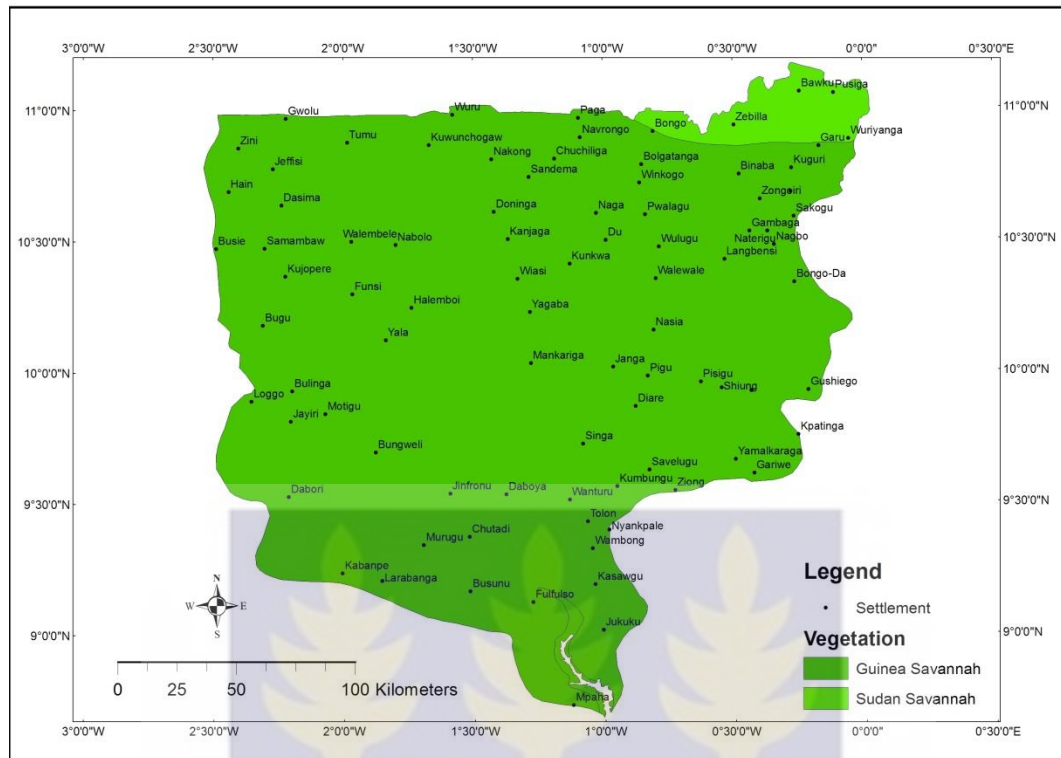


Figure 1.3: Map showing the vegetation types with the White Volta River Basin of Ghana.

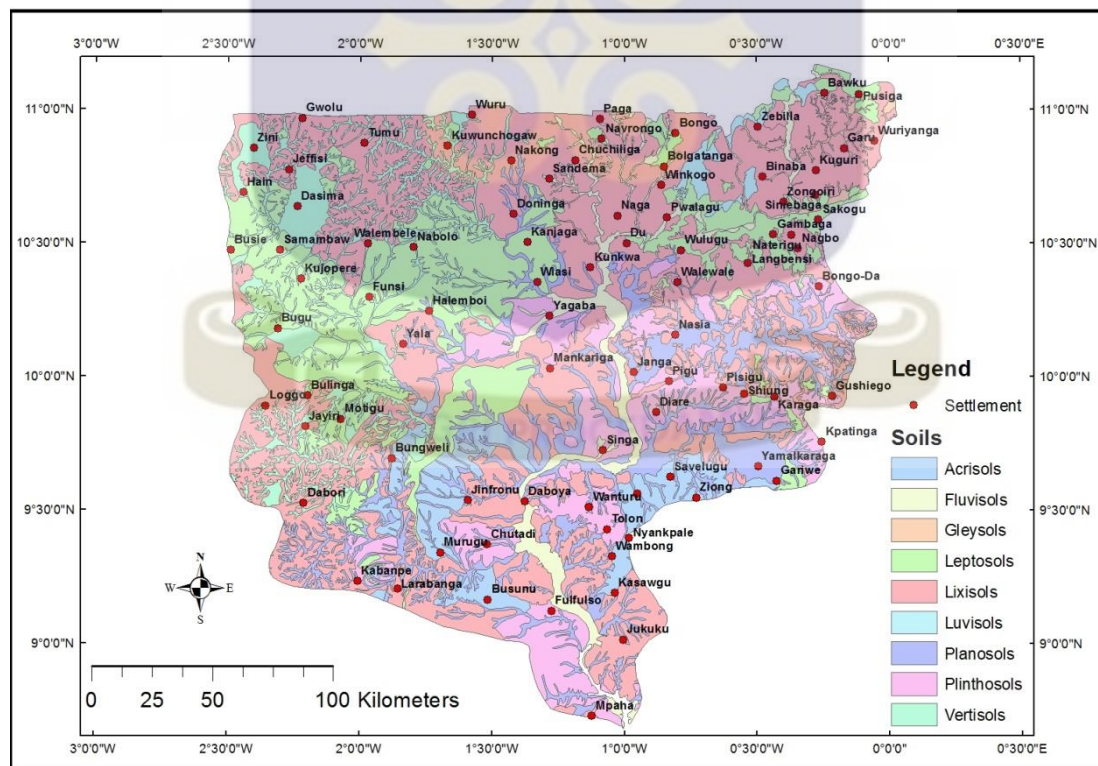


Figure 1.4: Map showing soil types within the study area.

### 1.5.5. Geology

The Volta Basin ( Junner and Hirst, 1946; Bozhko, 1969; Annan-Yorke, 1971; Affaton et al., 1980; Affaton, 1990) is an up to ~5 km thick succession of Neoproterozoic to lower Palaeozoic sandstones and mudstones with subordinate proportions of limestone, which occupies a surface area of ~115,000 km<sup>2</sup> in Ghana, as well as smaller areas in Togo, Burkina Faso, Benin and Niger. Along its western margins, Voltaian strata unconformably overlie the strongly deformed Palaeoproterozoic basement of the Man-Leo block, consisting of metabasaltic, metasedimentary and granitoid rocks of the Birimian complex and the slightly younger Tarkwaian sedimentary succession.

The geology of the White Volta Basin, Ghana is composed of the Birimian rocks and its associated Granitic intrusives, isolated patches of Tarkwaian formations, and Voltaian systems (Fig. 1.5). The Birimian unit or crystalline basement complex occurs mainly in the western and north-eastern parts (based on field observation) and are the oldest rock units in the basin. Junner (1940, 1935) subdivided the Birimian into two stratigraphic successions; the Upper and Lower Birimian. Rocks of the Birimian Structural Unit that occur in the White Volta River Basin of Ghana belong to both the Upper and Lower Birimian.

The Upper Birimian is the dominant rock formation and consists of metamorphosed lavas and pyroclastic rocks. Most of the rocks have metamorphosed into calcareous chlorite schists and amphibolites (greenstones). Pillow structures indicating subaqueous eruption of the original basaltic lavas are commonly observed. Rocks of the Upper Birimian formation are highly fractured, foliated and deeply weathered. Generally, rocks of this unit are intensely folded with dips often steeper than 60 and with a general north-south or north-west strikes (Junner, 1940). Furthermore, rocks of this formation have been highly sheared and usually

form high ranges which stand out above the lower relief associated with the Lower Birimian formation (Adu and Asiamah, 1992).

The Upper Birimian unconformably overlies the lower Birimian formation (Junner, 1935). However, recent reinterpretation of the stratigraphy by Leube et al., (1990) recognise the two units as contemporaneous with the two assemblages representing the distal facies, or basins, between sequences of evenly spaced volcanic belts. Typical Lithologies that make up the Birimian metasediment include tuffaceous shale, siltstone, phyllites, schists, tuffs, hyperbyssal intrusives and greywacke (Eisenlohr and Hirdes, 1992), and are dominant in the western part of the basin.

The Birimian Basement Complex is intruded by Granitoids of uncertain age, but which are believed to be of post-Birimian and pre- Tarkwaian age (Junner, 1935; Kesse, 1985). These Granitoids with their associated gneisses occupies mainly the northern and western parts of the study basin (field observation). The granites in the basin are classified as the Basin type granites or the Cape-Coast granite complex. Similar to the Upper Birimian formation, the Basin type granites are deeply weathered and foliated.

The Tarkwaian rocks make up a small percentage in the White Volta River Basin of Ghana and occur as intercalations between the Birimian metasediments and metavolcanics in the north-eastern section of the basin. They consist of coarse clastic sediments and usually considered to be the youngest unit in the Birimian (Bessoles, 1977 and Hastings, 1982). Both the Birimian formation and the Tarkwaian rocks have suffered greenschist facies metamorphism, thus they are intensely folded and highly deformed (Eisenlohr and Hirdes, 1992).

The Neoproterozoic sedimentary formations, locally referred to as the Voltaian Formation, underlie about 43% of the country (Acheampong and Hess, 2000) and consist mainly of

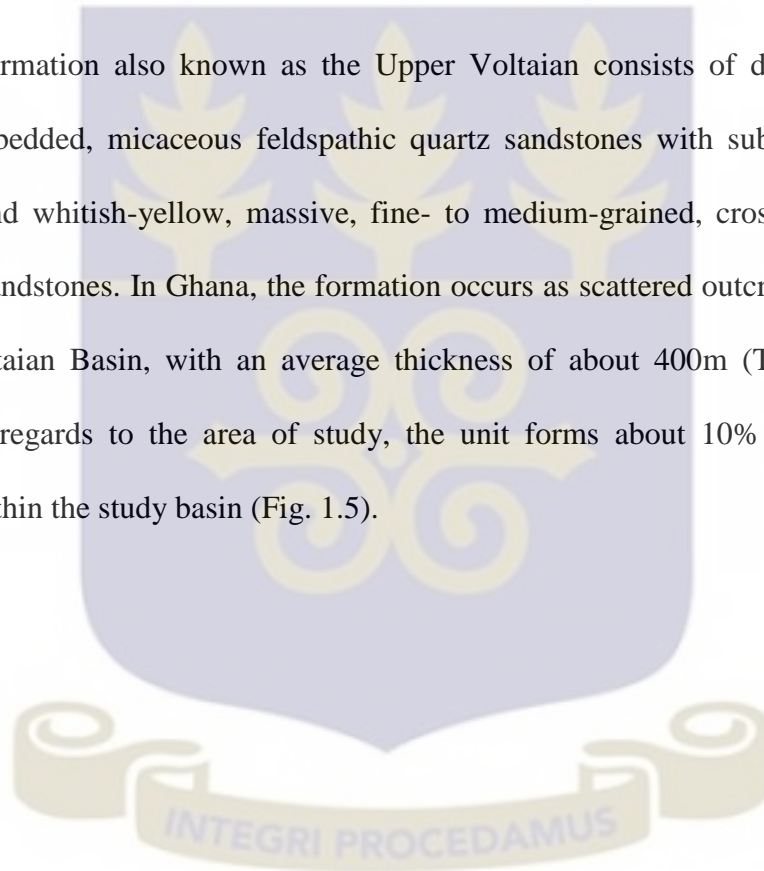
sandstone, shale, arkose, mudstone, sandy and pebbly beds, and limestone. The Voltaian formation consists of well-preserved sedimentary rocks that unconformably overlie the crystalline basement of the West – African Craton (Affaton, 1990). It extends over a large part of the central, eastern and southern portions of the study basin and is considered to be of late Precambrian to Palaeozoic age (Junner and Hirst, 1946). The Voltaian Formation is further subdivided on the basis of lithology and field relationships into three main lithostratigraphic units defined as supergroups (Deynoux et al., 2006). These are Bombouka/Kwahu/Kintampo/Damongo/Gambaga/Basal Sandstone/Lower Voltaian, Pendjari or Oti, and Tamale or Obosum supergroups and are the various units occurring in the White Volta River Basin.

The Basal sandstone is mainly a quartz sandstone formation about 75 m thick occurring at the northern and western peripheries of the Voltaian system. It overlies the Upper Birimian in the north and the Lower Birimian in the west. The Lower Voltaian is dominated by massive cross-bedded feldspathic sandstones. It is flat lying and intensely folded towards the Togo belt. A radiometric age of  $993 \pm 62$  Ma gives the approximate period for the beginning of sedimentation for the lower part of the Lower Voltaian Formation (Leprun and Trompette, 1969; Affaton, 2008). Depositional environment for the Lower Voltaian Formation is likely to have been shallow marine or fluvial.

The Oti-Pendjari Supergroup or Middle Voltaian formation in Ghana generally rest with angular unconformity on the Lower Voltaian, and in some places rest directly on the basement. It is 1500 – 4000 m thick (Affaton, 2008; Carney et al., 2008) and forms the most extensive sedimentary sequence in Ghana (Dapaah-Siakwan and Gyau-Boakye, 2000; Yidana, 2010). It comprise of argillaceous sandstones, arkose, siltstones, interbedded mudstone, sandy shale and conglomerates. The beds are generally gently dipping and very

well consolidated rendering them inherently impermeable, except at some few locations where weathering and fracturing induce secondary permeability (Dapaah-Siakwan and Gyau-Boakye, 2000). The Pendjari Supergroup is made up of mainly fine and immature materials deposited in a deep and very subsident marine environment (Saunders, 1970). K-Ar dating of glauconite from a borehole core at Tibagona yielded an age of  $600\pm 20$  Ma. With reference to the White Volta River Basin in Ghana, the Oti-Pendjari beds form about 45% of the Voltaian system occurring mainly to the south-eastern and central parts of the basin.

The Obosum formation also known as the Upper Voltaian consists of dirty-yellow, fine-grained, thinly bedded, micaceous feldspathic quartz sandstones with subordinate argillite intercalations and whitish-yellow, massive, fine- to medium-grained, cross-bedded arkosic and quartzose sandstones. In Ghana, the formation occurs as scattered outcrops in the central part of the Voltaian Basin, with an average thickness of about 400m (Trompette, 1969). However, with regards to the area of study, the unit forms about 10% occurring at the northern part within the study basin (Fig. 1.5).



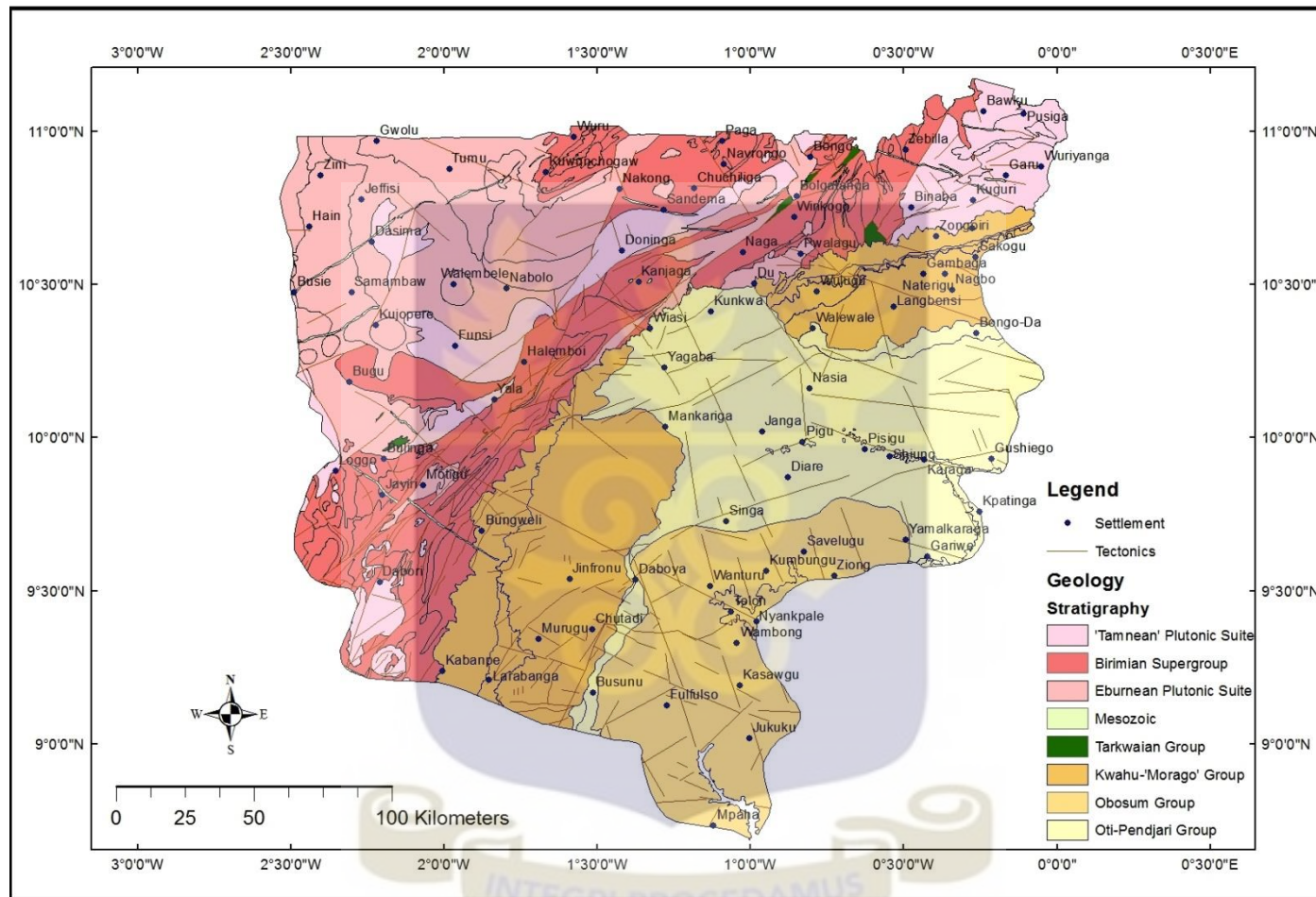


Figure 1.5: Geological map of the study area.

### 1.5.6. Hydrogeology

Five hydrogeological provinces (Fig. 1.6) have been identified in Ghana based on wells, geophysical investigations, and hydrochemical analysis by Banoeng-Yakubo et al., (2010). The provinces are the Birimian Province, the Crystalline Basement Granitoid Complex Province, the Voltaian Province, the Pan African Province, and Coastal Sedimentary Province. These provinces follow, to some extent, the lithologies of Ghana but do not necessarily connote the grouping of rocks that define the various geological formations (Banoeng-Yakubo et al. , 2010).

The Hydrogeology of the White Volta Basin of Ghana consists of Birimian Province, the Crystalline Basement Granitoid Complex and the Voltaian Province. Birimian formation and its associated granite intrusions/ crystalline basement rock as well as the Voltaian formation are characterised essentially by little or no primary porosity (MWH, 1998). Groundwater in the Crystalline Basement Provinces occurs mainly in the saprolite, saprock and in the fractured bedrock. They are more distinctive in their occurrence, and characteristically, are largely a consequence of the interaction of weathering processes related to recharge and groundwater through-flow (Wright, 1992). The most productive zones in terms of groundwater in the Birimian Province comprise the lower part of the saprolite and the upper part of the saprock which usually complement each other in terms of permeability and storage (Carrier et al., 2008). The upper less permeable part of the saprolite can act as a semi-confining layer for this productive zone, while the lower, usually saturated part of the saprolite is characterized by lower secondary clay content, thus creating a zone of enhanced hydraulic conductivity.

Furthermore, the granite and gneiss associated with the Birimian rocks are of considerable importance in the water economy of Ghana because they underlie extensive and usually well

populated areas (Dapaah-Siakwan and Gyau-Boakye, 2000). They are not inherently permeable, but secondary permeability and porosity have developed as a result of fracturing and weathering. Where precipitation is high and weathering processes penetrate deeply along fracture systems, the granite and gneiss commonly have been eroded down to low-lying areas. On the other hand, where the precipitation is relatively low, the granite occurs as massive, poorly jointed inselbergs that rise above the surrounding lowlands. In some areas, weathered granite or gneiss form permeable groundwater reservoirs. Major fault zones also are favourable locations for groundwater storage (Dapaah-Siakwan and Gyau-Boakye, 2000).

With regards to the Voltaian formation, sandstones within the White Volta River Basin have lost their primary porosity due to cementation and consolidation (Acheampong and Hess, 2000). As a result, groundwater occurrence is concomitant to fractures under confined and semi-confined conditions (Acheampong and Hess, 2000).

The development of secondary porosities within the Birimian and Voltaian formation have given rise to two distinct types of aquifers in the White Volta River Basin; the weathered zone aquifers and the fractured zone aquifers (Kortatsi, 1994; Acheampong and Hess, 2000). The weathered zone aquifers usually occur at the base of the thick weathered layer and are either phreatic or semi-confined to confined depending on the permeability of the upper weathered layer. The fractured zone aquifers tend to be more localized in nature, and groundwater occurrences are controlled by the degree of fracturing and the nature of groundwater recharge. Borehole yields within the fractured zone are determined by the extent and degree of fracturing. A formation which combines a thick weathered zone with a well fractured bedrock zone provides the most productive aquifer situation.

Groundwater is abstracted from all geological formations in the basin (Obuobie et al., 2012). Aquifer yields are generally low in Ghana as they vary from one geological formation to

another (Obuobie et al., 2012). In Ghana, the mean yield of boreholes rarely exceeds  $6 \text{ m}^3/\text{h}$  and ranges from  $2.1 \text{ m}^3/\text{h}$  in the White Volta Basin to  $5.7 \text{ m}^3/\text{h}$  in the Lower Volta Basin (MWH, 1998). A summary of average values of some characteristics of aquifer systems in the White Volta Basin of Ghana is presented in table 1.1.

Table 1.1: A summary of range values of some characteristics of aquifer systems in the White Volta River Basin of Ghana (Barry et al., 2005).

Volta Sub-basin	Borehole Yield ( $\text{m}^3/\text{h}$ )	Specific Capacity ( $\text{m}^3/\text{h}/\text{m}$ )	Depth to aquifer (m)	Depth to Borehole (m)
White Volta	0.03 - 24.0	0.01 - 21.1	3.7 - 51.5	7.40 - 123.4

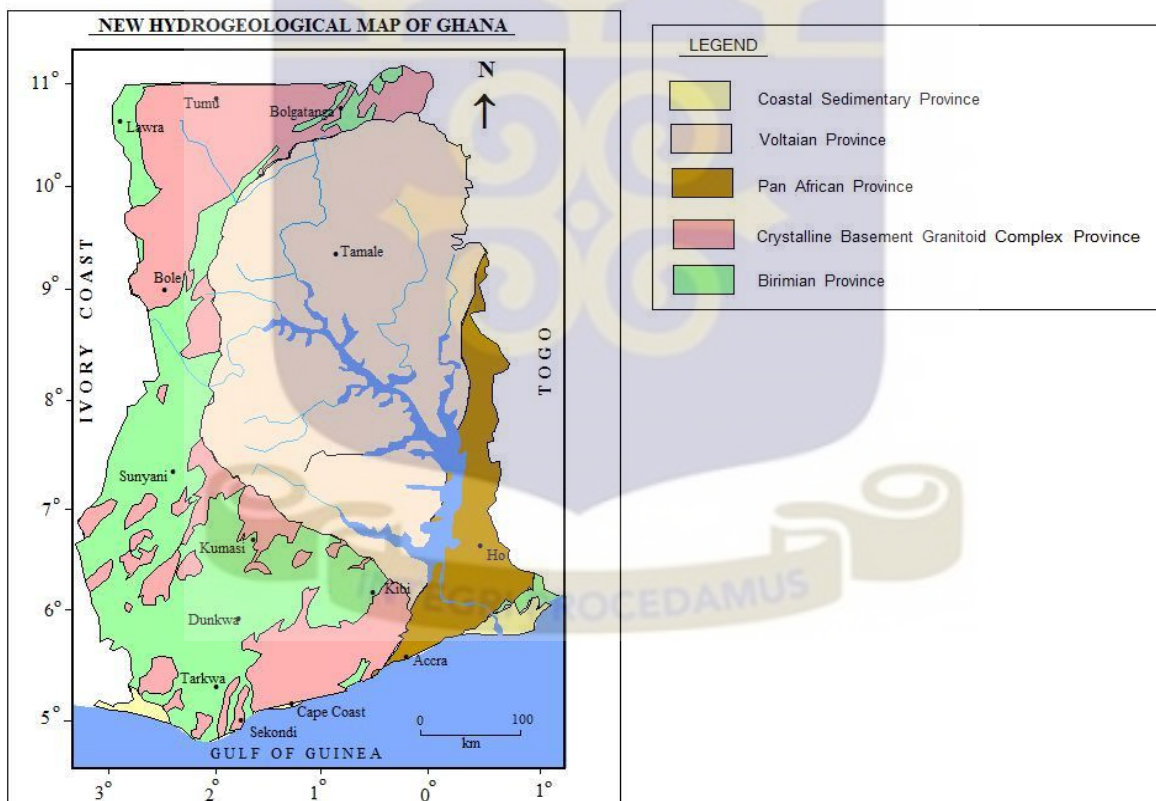


Figure 1.6: Hydrogeological Map of Ghana (Banoeng-Yakubo et al., 2010)

## CHAPTER TWO

### LITERATURE REVIEW

#### 2.1. GENERAL OVERVIEW

In Ghana, groundwater represents the most feasible source of potable water supply for most of the population in rural communities. This is because surface waters which are traditionally used in most of the rural communities dry out during the dry season or are heavily polluted and are the source of water-borne and water-related diseases, such as guinea worm infestation, bilharzias and typhoid fever (Adomako et al., 2010; Dapaah-Siakwan and Gyau-Boakye, 2000).

The White Volta River Basin, Ghana is a source of water for the three Northern Regions of Ghana; Upper West, Upper East and Northern, delivering about 173 million m<sup>3</sup> of water yearly (IWRMP, 2008). Water demand in the basin is expected to increase in response to rapid population growth, urbanization, industrialization and irrigational activities (IWRMP, 2008).

One of the Governments' goal in Northern Ghana, is to supply rural and urban populations with potable water. However, due to limited technical resources, this objective is sometimes not realized. Rural water supply programs, such as the Ghana Rural Water Project (GRWP), affiliated with Non-Governmental Organizations (e.g. World Vision International), assume roles in helping to provide rural communities with potable water (Lutz et al., 2007). Success in achieving these goals can be determined by increasing the provision of hand-pumps in the northern regions of Ghana.

## **2.2. GENERAL GROUNDWATER RESOURCES MANAGEMENT AND ASSESSMENT IN GHANA**

### **2.2.1. Groundwater Resources Management**

Over the past decades, the proper management of groundwater resources for optimum development and growth has been of global significance, and as such, national agencies tasked with the management and improvements of water resources have the responsibility to spearhead policies towards preserving the resource. This is especially critical in recent times due to climatic vulnerability and change and its impact on sustainable livelihoods. Thus, the efficient management of groundwater resources will certainly have to be moderated for optimal development and sustainability (Yidana et al., 2014).

Over the past years, several actions have been initiated to address the constraints associated with sustainable development and management of the country's fresh water resources. These include; Water sector reforms, coordination of national water resources management and strengthening of water resources information agencies. As such, changes were made in the legislation to redefine the status and mandates of some water-sector institutions (Dorm-Adzobu and Ampomah, 2013).

In Ghana, the Water Resource Commission (WRC) was established by an act of Parliament (Act 522 of 1996) with the mandate to regulate and manage the development and utilization of the country's water, and to coordinate any policies in relation to them (Agyenim and Gupta, 2011; Dorm-Adzobu and Ampomah, 2013). The commission is represented by other institutions as outlined by Dorm-Adzobu and Ampomah (2013) and their functions have been documented; hydrological and meteorological services (Hydrogeological and Services Department and Ghana Meteorological Agency respectively), water research (Water Research Institute), urban water supply (Ghana Water Company Limited), rural water supply

(Community Water and Sanitation Agency), respectively), irrigation development (Ghana Irrigation Development Authority), hydro-electric power generation (Volta River Authority), environmental protection (Environmental Protection Agency), forestry (Forestry Commission), minerals (Minerals Commission), and chieftaincy (traditional authority).

- The Ghana Water Company Limited (GWCL), is a semi-autonomous company that was transformed from the state-owned Ghana Water and Sewerage Corporation (Birner et al., 2010). It is responsible for urban water supply under the Conversion of Company Act (2003) as amended by Legislative Instrument (LI) 1648.
- The Community Water and Sanitation Agency (CWSA) is responsible for rural water supply under the Act (1998).
- On the other hand, the Environmental Protection Agency (EPA) under the Act (1994) is mandated to protect and safeguard the environment.
- Furthermore, the Volta River Authority (VRA) was set up for the development and generation of hydropower and as well regulates the use of the water of the Volta River or the Volta Lake.
- Ghana Irrigation Development Authority, (GIDA) was also established as a semi-autonomous public body by SMC (Supreme Military Council) Decree 85 and empowered to make regulations on the use of any reservoir created for any irrigation project, taking the national interest into consideration (Namara et al., 2011).

Moreover, the WRC had publicized two legislative Instruments (LI) for water resources.

These are:-

- a) Water Use Regulations Legislative Instrument (LI) 1692 of 2000. This LI demands that any person who wishes to have water for domestic, commercial, industrial,

municipal, agricultural, power generation and fisheries purposes shall apply for a water permit from the Commission.

- b) Drilling License and Groundwater Development Regulation Legislative Instrument (LI) 1872 of 2006 requires that any person who wishes to construct a well for the abstraction or monitoring of groundwater for research should obtain a water drilling license from the Commission.

The second set of regulation seeks to:

- Provide licences to companies that prospect for and drill water wells;
- Regulate in an environmentally sustainable manner the development of Ghana's groundwater resources; and
- Gather information on the groundwater resource availability in Ghana and its exploitation for effective planning and management of groundwater development activities.

Successful implementation of policies and development of decision supporting systems is required for an effective groundwater management, monitoring and resource comprehension. Hence, there is a need for a broad scientific knowledge and understanding of the origin of groundwater, its spatial location, distribution and utilization, hydraulic properties, lifespan and its elasticity to external stresses such as climate vulnerability and extraction limits.

### **2.2.2. Groundwater Resource abstraction**

Groundwater is abstracted from all hydrogeological provinces in the country (Obuobie and Barry, 2012). The modes of groundwater abstraction in Ghana are through boreholes fitted with hand-pumps or electric pumps depending on the yield, hand-dug wells with or without

hand-pumps, and dugouts (Gyau-Boakye et al., 2008). However, in the White Volta River basin, groundwater is extracted from boreholes equipped with hand pumps (Martin and Van de Giesen, 2005). It is estimated that groundwater production in the basin is around 88 million m<sup>3</sup>/yr, and is equivalent to less than 5% of the average annual groundwater recharge to the basin aquifers, which is promising for further groundwater development (Martin and Van de Giesen, 2005). Though drying of open wells and reduction in yields in deeper boreholes are common, the changes in climatic conditions coupled with ephemeral surface flows make groundwater a relative safe source of water preferably in quality (WRI/DANIDA, 1993)

As at 1984, about 7,800 boreholes and 9,500 wells had been drilled in the various geological formations in the country (Dapaah-Siakwan and Gyau-Boakye, 2000; Gyau-Boakye et al., 2008). By the year 1994, total of 56,000 groundwater abstraction systems have been drilled, comprising 10,000 boreholes and over 45,000 hand-dug wells in the country (Kortatsi, 1994). The values increased to 11,500 boreholes and 60,000 hand-dug wells as at March, 1998 (Dapaah-Siakwan and Gyau-Boakye, 2000; Gyau-boakye, 2009). At the end of 2004, 13,196 boreholes and 1,344 hand-dug wells had been constructed and were serving as sources of portable water to rural communities and some small towns.

Estimate shows that over 95% of groundwater use in Ghana is for domestic and other drinking purposes (Gyau-Boakye et al., 2008). Most often the use of groundwater as a resource for drinking purpose depends on the quality and the quantity of the groundwater available (WRI / DANIDA, 1993). As such, with the exception of Greater Accra (due to high levels of salinization of water in the gneisses underlying parts of the region), boreholes from all the nine regions are used for drinking and domestic water supply due to some factors of yield and good quality compared to surface waters (Kortatsi, 1994).

The use of groundwater for irrigation in Ghana is limited mainly to the Southern Volta regions, the Accra Plains and the Northern Regions (Kortatsi, 1994). Irrigation systems in Ghana may be classified into either conventional, which are mainly developed by the Ghanaian government or non-governmental organizations (NGOs), or the emerging systems, which are initiated and developed by private entrepreneurs and farmers (Namara et al., 2011). Regarding to size, irrigation can be categorized as small, medium or large. Size of up to 200 ha are regarded as small and solely owned and managed by a single farmer or group of farmers. Anything within the range of 200–1000 ha is medium and jointly owned and managed by the state through GIDA and farmers. In the same vein, irrigated projects of size greater than 1000 ha are termed as large and are state owned managed by the state or quasi-governmental agencies (Kyei-Baffour and Ofori, 2005).

In the White Volta River Basin of Ghana, groundwater serving irrigation purpose is used mainly for farming of rice and leafy vegetables (IWRMP, 2008). For instance, during the dry seasons, Upper East and Upper West regions abstract groundwater from alluvial channels along the course of ephemeral streams with the aid of hand-dug wells and dugouts for vegetable production (Obuobie and Barry, 2012). According to Kortatsi, (1994), water is lifted from wells and dugouts by means of buckets and watering cans to irrigate between 0.04 and 0.1 ha vegetable farm. Also, it is estimated that about 100 to 200 ha of land are used for emerging irrigation system in the dry season with groundwater in the Attankwidi – Anayare catchment area in the Upper East Region (Laube et al., 2008). A summary of the most prominent existing irrigations in the White Volta River Basin of Ghana is shown in Table 2.1.

Table 2.1.: Irrigable potential of some irrigation projects (FAO, 1985; Agodzo et al., 1994).

<b>Irrigation Project</b>	<b>Irrigation Potential (Ha)</b>
<b>Tono</b>	2632.00
<b>Vea</b>	1417.00
<b>Bontanga</b>	540.00
<b>Integrated Tamale Fruit Company (ITFC)</b>	1000.00

Livestock watering with groundwater is practiced mainly in the Upper East, Upper West, Northern and Greater Accra regions in Ghana (Obuobie and Barry, 2012). As at 1996, the three northern regions recorded about 2.2 million of livestock population (IWRMP, 2008). However, it is assumed that the current population is 2.5 million and the unit water consumption per livestock head is 10 - 15 litres/day. These imply that the present total livestock water requirement is about 31,000 m<sup>3</sup>/day, equivalent to 11.3 million m<sup>3</sup> (IWRMP, 2008).

In Ghana Industrial use of groundwater is very recent, but the interest in its usage is gradually rising. In the southern portion of the country, a number of boreholes are being drilled purposely for large scale commercial bottled water industries (Gyau-Boakye et al., 2008; Kortatsi, 1994). A previous survey of groundwater use in the Densu basin in southern Ghana came out with the finding that the entire major commercial bottled water industries in Ghana use groundwater sources for the water production (Darko et al., 2003).

Mining and gold washing are the major uses of water for industrial purposes in the White Volta River Basin of Ghana, though the practice is posing a negative effect on the water resource (Birner et al., 2010). Furthermore, the development of industrial and service sectors in the Upper East region, such as food processing industry and the tourism sector have increased the demand for industrial use (Birner et al., 2010).

## **2.3. CHARACTERIZATION OF GROUNDWATER FLOW SYSTEMS.**

### **2.3.1. Groundwater recharge**

Accurate estimation of groundwater recharge is extremely important for proper management of groundwater systems (Healy and Cook, 2002). The amount of recharge received by aquifers is far more critical to the sustainable use of water in arid and semi-arid regions, than it is in humid environments.

Recharge to groundwater can be categorized as: (i) direct or indirect on the basis of the origin of the recharging water, (ii) piston or preferential flow on the basis of the flow process through the unsaturated zone, (iii) point, line or areal recharge on the basis of the area on which it acts, and (iv) present-day, short-term or long-term recharge on the basis of the time scale during which it occurs ( Obuobie et al., 2012 cited in Lerner et al., 1990). Again, recharge can be classified as actual, which refers to water that has infiltrated and reached the water table, or potential, which refers to infiltrated water that may or may not reach the water table because of unsaturated zone processes (Scanlon et al., 2002 cited in Rushton, 1997). In many locations, a combination of the recharge categories occurs.

Groundwater recharge rate estimation in dry- and semi-dry-regions can be challenging, since in such areas the recharge is usually low compared to the average annual precipitation, thus difficult to determine accurately (Scanlon et al., 2002). Recharge processes vary from one place to another, and there is no guarantee that a method developed and used for one locality will give reliable results when used in another. Many methods are available to calculate recharge but not all are applicable to various terrains as most are unable to satisfy local conditions. Thus, a common recommendation is that recharge should be estimated by using multiple methods to increase reliability of recharge estimates (Healy and Cook, 2002; Scanlon et al., 2002).

Some of the recharge rate estimation methods and techniques used are chloride mass balance, soil moisture balance technique, water table fluctuation, environmental tracer technique and hydrological modelling.

### 2.3.1.1. Chloride Mass Balance Technique

The Chloride Mass Balance (CMB) is a very useful tool in estimating recharge in arid and semi-arid regions, due to the difficulty encountered in using conventional water balance methods (Allison et al., 1994). It is one of the widely used methods in water resources development and management (Fabryka-Martin et al., 1987; Wood and Sandford, 1994; Kattan, 2001). The chloride ion (Cl<sup>-</sup>) used in Chloride Mass Balance technique is a popular approach which is economical in its application, free from pollution and conserved in nature.

The Chloride Mass Balance method for estimating groundwater recharge is based on several assumptions; it offers a direct estimate of recharge and is least expensive with low time integrating properties. The application of CMB method is simple, with no need for any sophisticated instrument. It also assumes that there is a balance of meteoritically derived chloride within the hydrologic cycle (Krautstrunk, 2012). The Chloride Mass Balance method is based on the knowledge of three important components; annual precipitation, chloride (Cl<sup>-</sup>) concentrations in rainfall and groundwater storage (Subyani, 2004) as shown in equation 2.1.

$$q = R \frac{Cl_{war}}{Cl_{gw}} \dots\dots\dots 2.1$$

Where q is the recharge flux, R is the average precipitation, Cl<sub>war</sub> is the weighted average of chloride concentration in rainfall and Cl<sub>gw</sub> is the weighted average chloride concentration in groundwater. The CMB method appears to be useful in estimating paleo-climate recharge

rate dating back thousands of years (Murphy et al., 1996 and Tyler et al., 1996), but CMB has also been used for estimating modern recharge rates, including those that have increased in response to land-use change, specifically where vegetation had been altered and deep-rooted trees were replaced with shallow-rooted grasses (Walker et al., 1991).

The chloride Mass Balance technique has been used successfully to evaluate recharge in a range of environments, more especially in the White Volta River Basin of Ghana;

In some portions of the White Volta Basin of Ghana, Mensah et al. (2014) tested the representativeness of groundwater recharge using the Chloride Mass Balance technique, and estimated recharge rate to range between 0.9% and 21% of annual precipitation. These estimated ranges were also consistent with evaporation rates computed from stable isotope data of groundwater and surface water in the Voltaian Basin.

Chloride Mass Balance method together with the Soil Balance technique have been used by Carrier et al. (2008) to estimate groundwater recharge in parts of the Voltaian in Northern Ghana. The results of their estimates indicated that recharge ranges from 1.5% to 11.2% of mean annual rainfall. These variations in the estimated recharge rate indicated variability of geological characteristics within the unsaturated zone and the climatic heterogeneity in the study area.

Obuobie et al. (2010) used the chloride mass balance (CMB) method in the Upper East region of Ghana to estimate the recharge to groundwater aquifers. Their findings estimated groundwater recharge to represent 3 to 19% of the mean annual rainfall and was indicative of a huge groundwater potential as demand in the study area was estimated to be less than 14% of the recharge.

Estimates of groundwater recharge using the CMB method by Yidana and Koffie (2014) suggested recharge in the range of 1.8 to 32% of the annual precipitation and attributed the highest estimates of recharge to localities with open wells which act in encouraging rapid groundwater recharge.

The method of groundwater recharge estimation with CMB can be useful when the assumptions as stated by Zhu (2003) are considered; (1) atmospheric deposition is the only source for Cl<sup>-</sup> in groundwater, (2) Cl<sup>-</sup> behaves as a conservative tracer along its path, (3) Cl<sup>-</sup> uptake by roots and anion exclusions are negligible, (4) leaching of Cl<sup>-</sup> deposit at ground surface and in the soil zone is complete, (5) groundwater movement in both unsaturated zone and saturated zone can be approximated as one-dimensional piston flow, and (6) surface run-on and runoff can be neglected, then the Cl<sup>-</sup> concentration of groundwater recharge is a result of evapotranspiration (ET) loss of water.

However, the major limitation in the Chloride Mass Balance technique is that changes in land use can affect the results obtained from groundwater recharge estimates. A typical example is shown by Fayer et al. (1996) who used the chloride mass balance to estimate point-recharge estimates for various soil texture and vegetation cover and came out with the following findings; recharge rates for cheat grass in loamy sand range from 0.4 to 0.2 mm/year, less than 0.3 mm for shrubs in loamy sand while shrubs with silt loam estimated less than 0.1 mm/year.

#### 2.3.1.2. Water Table Fluctuation (WTF)

Another method used in estimating groundwater recharge over a wide variety of climatic conditions is the water table fluctuation method (Healy and Cook, 2002; Scanlon et al., 2002). It is considered to be one of the most favourable and attractive methods in recharge

rate estimation due to its ease of use, accuracy and low cost of application in semiarid regions (Beekman and Xu, 2003).

The WTFM is based on the assumption that rises in groundwater levels in unconfined aquifers are caused by rainfall recharging the aquifer (Crosbie et al., 2005). Thus, with the knowledge of the rise in water level and specific yield, recharge rate from precipitation can be defined in equation 2.2;

$$R = \Delta h \times S_Y \dots\dots\dots 2.2$$

Where (R) = Recharge from precipitation

$\Delta h$ = Change in water table height

$S_y$ =Specific yield.

The flexibility involved in applying the Water Table Fluctuation method for recharge rate estimations has been highly recommended by policy makers in assisting groundwater resource management processes. For example, Moon et al. (2004) evaluated the spatial variability of groundwater recharge using a modified WTF method in Korea. Their studies found that the estimated recharge can be considered as the maximum value, and could be used as a cut off guideline for groundwater development in the river basin.

The water table fluctuation method has been used in estimating groundwater recharge in and around the White Volta River Basin of Ghana. Examples include the study conducted by Obuobie (2008) to quantify groundwater recharge for the period between 2006 and 2007 and also analyse the fluctuations in the water table in the south of the White Volta Basin of Ghana. Results obtained for the two study years showed that the mean groundwater recharge

in the White Volta Basin is 8 % and 7 % of the mean annual rainfall for 2006 and 2007 respectively.

Furthermore, Bannerman and Ayibotele (1984) monitored water levels in the Upper East and Upper West Regions of Ghana, all in the White Volta Basin and observed fluctuations of 0.3 to 5.4 m between the dry and wet seasons for the period 1976 to 1979. Their results have shown that groundwater recharge can be as low as 2% in some parts of the basin.

The major constraint with the Water Table Fluctuation method is that it can only be best applied for short duration periods and in shallow water tables. Difficulty 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 not the result of changes in atmosphere pressure and the presence of entrapped air as a result of pumping (Scanlon et al., 2002).

Furthermore, Healy and Cook (2002) outline some few limitations regarding the use of this method;

1. The method is best applied to shallow water tables that display sharp water-level rises and declines. Deep aquifers may not display sharp rises because wetting fronts tend to disperse over long distances. Nonetheless, the method has been applied to systems with thick unsaturated zones that display only seasonal water level fluctuations.
2. Typically, recharge rates vary substantially within a basin, owing to differences in elevation, geology, land surface slope, vegetation, and other factors. Wells should be located such that the monitored water levels are representative of the catchment as a whole.
3. The method cannot account for a steady rate of recharge. For example, if the rate of recharge was constant and equal to the rate of drainage away from the water table, water levels would not change and the WTF method would predict no recharge.

4. Other difficulties relate to identifying the cause of water-level fluctuations and calculating a value for specific yield (Beekman and Xu, 2003).

#### 2.3.1.3. Environmental Tracer (Isotope) Technique

Estimation of recharge using tracers is based on the conservation of mass of the tracer, and the assumption that the tracer moves freely with water (Sharma, 1986). Environmental tracers applied mostly in waters and dissolved solids include stable isotopes  $^{13}\text{C}$ ,  $^{18}\text{O}$ ,  $^2\text{H}$ ,  $^{34}\text{S}$ ,  $^{15}\text{N}$ , and the radioactive isotopes  $^3\text{H}$ ,  $^{14}\text{C}$ ,  $^{87}\text{Sr}$ ,  $^{36}\text{Cl}$ , and U disequilibrium. Uranium disequilibrium includes the large progeny of decay schemes for the parents  $^{238}\text{U}$ ,  $^{235}\text{U}$ , and  $^{232}\text{Th}$  (Ivanovich and Harmon, 1992). However, of the above stated tracers,  $^3\text{H}$  (tritium),  $^2\text{H}$  (deuterium) and  $^{18}\text{O}$  (oxygen-18) most accurately simulate the flow of water because they form part of the water molecule (Sophocleous, 2004).

Environmental isotopes provide information on geochemical evolution, recharge processes, rock-water interaction and the origin of salinity (Clark and Fritz, 1997; Kendall and McDonnell, 1998; Cook and Herczeg, 2000). As such, they serve as a tool in the characterization of groundwater flow systems (Moore, 2002).

Environmental tracing techniques have been demonstrated to be especially useful in fractured rock and karst hydrogeological settings and for identifying and characterizing contaminant transport pathways and transport velocities. In addition, differences in concentrations of environmental tracers between groundwater and surface water can be used to detect and delineate zones of groundwater discharge or recharge, provided the differences are sufficient large (Kalbus et al., 2006). For instance, stable isotope data were used to relate meteoric water to groundwater in parts of the Nabogo sub-catchment of the Voltaian Basin by Yidana et al. (2014). Their study found that groundwater recharge within the weathered zone is of meteoric origin and shows evidence of significant evaporation of rainwater in the range of 34

to 70%, which were attributed to high temperatures and low relative humidities. Also in the Northern region of Ghana, Pelig-Ba (2009) studied the stable isotope ( $^{18}\text{O}$  and  $^2\text{H}$ ) contents of groundwater and surface waters and predicted that the groundwater is directly recharged from local precipitation, though suffers evaporation during transit from the atmosphere to the water table.

Furthermore, Yidana and Koffie (2014) explained the groundwater recharge regime in parts of the Voltaian Basin in Northern Ghana using isotope data of groundwater and precipitation. Stable isotope data of  $^{18}\text{O}$  and  $^2\text{H}$  for local precipitation suggested enrichment relative to the Global Meteoric Water Line (GMWL) and indicated that precipitation takes place at a relative humidity less than 100%. Though the application of environmental isotope technique has played an important role in solving hydrogeological problems, sampling for tracers such as  $^3\text{H}/^3\text{He}$  and  $^{36}\text{Cl}$  are complex, and the cost involved in their analysis are relatively expensive (Scanlon et al., 2002). Also, isotope tracer such as  $^3\text{H}$  are not valid in areas with deep root zones, and interpretation of data may become difficult if flow regimes are not found to be reasonably uniform (Allison et al., 1994).

In the current study, estimation of recharge rate is based on hydrogeological modelling using numerical simulation approach. Numerical model has been adopted over the above stated techniques as it helps to evaluate conceptual models, determine the sensitivity of recharge estimates to various parameters, and predict how future changes in climate and land use may affect estimated groundwater recharge rates (Scanlon et al., 2002), which may not be provided for the other techniques used in recharge rate estimations.

In addition, numerical modelling techniques are been considered because it takes into account spatial variability of physical properties, such as hydraulic conductivity which is not considered in the stated methods of recharge rate estimations (Sophocleous, 1991).

## 2.4. NUMERICAL SIMULATIONS AND SITE CHARACTERIZATION

### 2.4.1. Hydrostratigraphy units modelling and Site Characterization

Models are used to analyse hypothetical flow situations to gain generic understanding of flow systems (Fetter, 2001). They are used to help establish locations and characteristics of aquifer boundaries and assess the quantity of water within a system and determine the amount of recharge to aquifers (Anderson and Woessner, 1992).

The initial phase of a groundwater modelling project usually begins with site characterization (Owen et al., 1996). Defining the hydrogeology of a region forms the basis for determining model boundaries, the number of aquifer layers to be modelled, location and the extent of each aquifer layer (Herzog et al., 2005). Seaber (1988) defined hydrostratigraphic units (HSUs) as a body of rock distinguished and characterized by its porosity and permeability. These units are defined by the number, size, shape, arrangement, and interconnection of the interstices or fractures, and are recognized on the basis of their nature, extent and magnitude in any rock or soil (Seaber, 1988).

Furthermore, understanding the hydrostratigraphic units of a basin serves as a prerequisite to groundwater flow modelling (Kassenaar et al., 2001 and Majumdar et al., 2002). Numerous studies have been carried out in the last decades on computer simulated 3D hydrostratigraphic models (Ross et al., 2005) most especially with the use of MODFLOW software (Drellack et al., 2002; Lemon and Jones, 2003; Herzog et al., 2005; Mukherjee et al., 2007).

The work of Weiss and Williamson (1985) in Gulf Coastal Plain focused on subdivision of thick sedimentary Units into Layers for simulation of groundwater flow. In their studies, they indicated that subdividing thick sedimentary units into model layers solely on stratigraphy

can lead to erroneous results as it may lead to serious violation of ground-water flow modelling restraints. As such, borehole geophysical data can be used to suggest relative permeabilities and delineate model layers that are more likely to have uniform hydraulic properties than layers delineated by stratigraphic definition alone.

One of the approaches in constructing hydrostratigraphic units is the solid model approach. It completely and clearly defines the volume of a three-dimensional object.

The “solid modelling” approach has been investigated by several researchers as a tool for constructing three dimensional models of geologic structures ( Gjoystdal et al., 1985; Bak and Mill, 1989; Bayer and Dooley, 1990; Fisher and Wales, 1990; Jones and Wright, 1993; Lemon and Jones, 2003).

Previous studies carried out by Lemon and Jones (2003) focused on the use of solid models from boreholes and user defined cross sections used to build solids directly from borehole data with minimal user intervention. In their studies, they presented a new method for developing solid models of geologic units called the “horizons” approach using the Hydrogeological Unit Flow (HUF) package (Anderman and Hill, 2000) in MODFLOW 2000, and is found to be simpler and more robust as compared to other approach (set operations).

Zhu et al. (2012) developed solid models of sedimentary stratigraphic systems from borehole data in an application to a construction project in Shanghai, China. The method they adopted in generating the 3D solid model was the Borehole -Surface -Solid approach. Result of the model constructed showed discontinuous geological surfaces as induced by missing strata in the sedimentary strata.

Furthermore, hydrostratigraphic modelling of a complex glacial – drift aquifer system in Central Illinois was carried out by Herzog et al. (2003) to identify possible areas within the

aquifer from which regional water supply could be obtained with minimal adverse impacts on the aquifer system. The thickness, distribution and hydraulic properties of seven uneven and discontinuous layers served as prerequisite information in completely understanding the groundwater flow system in the model domain.

#### **2.4.2. Groundwater management Models**

Groundwater models are first and foremost an integration and synthesis of knowledge about a groundwater system allowing one to gain insights into how subsurface flow system function (Bredehoeft, 2005; Vandenbohede et al., 2011; Yihdego et al., 2015). Models may either be physical or mathematical. A physical model simulates groundwater flow directly while a mathematical model simulates groundwater flow indirectly. Simulation of groundwater flow using mathematical model approach can be solved analytically or numerically (Anderson and Woessner, 1992). This is by means of governing equations to represent the physical processes that occur in a system, together with equations that describe heads or flows along the boundaries of a model.

Globally, hydrogeological investigations involving numerical groundwater flow models have been carried out in various fields to assist in the development of appropriate decision support systems for effective groundwater management. Groundwater models have been used to define local and regional groundwater flow systems and constrain aquifer hydraulic parameters (e.g. Ophori, 1998; Ophori, 1999; Van Der Hoven et al., 2002; Boronina et al., 2003; Senthilkumar and Elango, 2004; Lutz et al., 2007; Yidana et al., 2011; Yidana et al., 2013; Yidana et al., 2014; Yihdego et al., 2015), contaminant transport studies (Hussein and Schwartz, 2003; Tiwary et al., 2005) and in the analysis of capture zones for groundwater abstraction wells (e.g. Cole and Silliman, 2000; Barry et al., 2009). Numerical modelling of

groundwater is an attempt to simplify the physical hydrogeological system using physical equations and governing boundary conditions. Thus, groundwater flow modelling procedure begins with a proper understanding of the hydrogeological setting or physical system and the problem to be investigated. Once the system is well understood, the next step is to translate the physical system into a set of solvable mathematical equations. This has resulted in the familiar groundwater flow and transport equations in common use today. The three dimensional movement of groundwater of constant density through a porous earth material may be described by the partial differential equation (Don et al., 2006) as presented in equation 2.4:

$$\frac{\partial}{\partial x} \left( K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{zz} \frac{\partial h}{\partial z} \right) - W = S_s \frac{\partial h}{\partial t} \dots\dots\dots 2.4$$

where  $K_{xx}$ ,  $K_{yy}$ , and  $K_{zz}$  are the hydraulic conductivities in the x, y and z directions respectively which are assumed to be parallel to the axes of hydraulic conductivity ( $LT^{-1}$ ),  $h$  is the potentiometric head (L),  $W$  is a volumetric flux per unit volume and represents sources and/or sinks of water ( $T^{-1}$ ),  $S_s$  is the specific storage of the porous material ( $L^{-1}$ ), and  $t$  is the time (T). Equation 2.4 describes groundwater flow under transient or non-equilibrium conditions in a heterogeneous and anisotropic medium when the principal axes of hydraulic conductivity are aligned parallel to the coordinate directions.

Under steady state conditions, the time variable nature of the hydraulic head on the right hand side of (Equation 2.4) becomes negligible when sinks are not considered significant enough to cause such changes. As such, (Equation 2.4) is reduced to (Equation 2.5)

$$\frac{\partial}{\partial x} \left( K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{zz} \frac{\partial h}{\partial z} \right) = 0 \dots\dots\dots 2.5$$

Equations 2.4 and 2.5 are both derived from the law of conservation of mass and the continuity equation for heterogeneous anisotropic media. Two main approaches are used to solve equations 2.4 and 2.5. These are the finite element approach and the finite difference approach. In either case, a system of nodal points is superimposed over the problem domain (Wang and Anderson, 1982) and the aquifer sub-divided into a grid to analyse the flows associated within a single zone of the aquifer (Igboekwe and Achi, 2011).

However, the choice of a numerical method depends on the convenience and expertise of the modeller and the nature of the data available.

#### 2.4.2.1. Finite Element Approach (FEM)

Finite element method is a general algorithm for groundwater flow analysis (Kazda, 1990; Konikow and Reilly, 1998) and has been applied to simulate the flow of groundwater globally. FEMWATER (Yeh et al., 1992) is a high quality computer code of 3D finite element program which has been applied worldwide to simulate flow and transport in both the saturated and the unsaturated zone (He et al., 2008). It is currently being maintained by the US Army Corps of Engineers, waterways experiment station (WES).

Finite element groundwater model (FEM) is the most efficient and powerful current method to analyse groundwater flow (Kinzelbach, 1986; Anderson and Woessner, 1992; El-Kadi et al., 1994).

The finite element approach has been adopted because it treats each element separately and assembles equations for all elements into a global matrix equation, thereby reducing computational storage requirements and time (Anderson and Woessner, 1992). Furthermore, finite element models help in defining vertical dimensions, geological geometry and the number of aquifers to be modelled (Bear and Verruijt, 1987).

For instance, Karahanoglu and Doyuran (2003) investigated the effects of seawater intrusion into a quarry-site coastal aquifer in Turkey by predicting sea water intrusion into the aquifer as well as water discharge rates to a maximum depth of 30 m using a finite element numerical simulation approach.

Also, a three dimensional finite element model was used as a representative to develop both steady and transient models for a coastal aquifer in Italy, and aid in establishing the efficacy of sea water intrusion into the aquifer as a result of groundwater extraction along the coast for irrigational purposes. Thus, the effects of hypothetical aquifer exploitation were assessed for water budgets and hydraulic head evolution.

Despite the flexibility involved in designing grids with the finite element approach, it has some major limitations as outlined by Anderson and Woessner (1992):

1. The input of data required to define the grids in finite element models are more laborious. This is because finite element models require that each node and element be numbered and the coordinate location of each node and the node numbers affiliated with each element be input to the model.
2. Finite element grids do not have inactive nodes because the elements are fitted exactly to the boundaries of the model. As such when it becomes necessary to simulate interaction between the groundwater system and the boundaries, it may be critical to approximate the boundaries as closely as possible. An example of such a simulation is one involving the calculation of flow into or out of a surface water body.

#### 2.4.2.2. Finite difference method (FDM)

Finite difference method, (FDM) is an approach to computational fluid dynamics (CFD) and very effective to groundwater flow modelling (Igboekwe and Achi, 2011). It is discretization

technique for solving a partial differential equation (PDE) by replacing the continuous domain of interest by a finite number of regular-spaced mesh of grid-points (i.e., nodes) representing volume-averaged subdomain properties, and by approximating the derivatives of the PDE for each of these points using finite differences, the resulting set of linear or nonlinear algebraic equations is solved using of iterative matrix solving technique (Anderson and Woessner, 1992).

In the finite difference method, there are two different types of grid systems; one is the Block-centred Grid system and the other is the Point-centred Grid system. The main difference between the two solely lies in the way in which flux boundaries are handled. The computer code MODFLOW, which is a full three-dimensional groundwater flow model developed by the United State Geological Survey (McDonald and Harbaugh, 1988), employs the Block-Centred Grid System and LPF system. In the Block-Centred Grid System, a point within each cell is called a “node” at which head is calculated. In the Block-Centred formulation, the blocks formed by the set of parallel lines are the cells and the nodes are at the centre of the cells.

Under the finite difference method, the differential equations are solved by replacing the continuous system represented by the differential equations into a set of discrete points in space and time, and the partial derivatives are replaced by differences in heads at these points. These solutions constitute approximations to the time varying head distributions that would be obtained by solving the differential equations. One of the familiar numerical codes for solving groundwater flow problems, MODFLOW (McDonald and Harbaugh, 1988), uses this approach. The major limitation associated with finite difference grid is the presence of inactive nodes mostly associated with models, though they (inactive nodes) are not associated

with the solution. As a result, the inactive nodes increase the computational storage space in the arrays needed by the code (Anderson and Woessner, 1992).

Globally, the finite difference approach has been applied in most numerical simulations of groundwater models due to the following advantages;

1. The finite difference approach is easier to handle and requires fewer data input compared to other numerical methods (Anderson and Woessner, 1992).
2. Irregular boundaries can be simulated with finite difference approximations though such formulas are not included in most finite difference codes (Rushton and Redshaw, 1979).
3. In a finite difference approach (block centred grid type), the grid is designed such that flux boundaries fall on the edge of the blocks as specified head boundaries fall on the node.

Nevertheless, it has been established that the accuracy of numerical solution by Finite Difference Method is largely dependent on the initial particle distribution and the number of particles assigned to a cell (Igboekwe and Achi, 2011).

#### 2.4.2.3. Model boundaries

In order to solve the groundwater flow equation (equation 2.5.), it is imperative to specify the initial and boundary conditions governing the model. For a steady state condition, boundary conditions are required; while for a transient problem, boundary and initial conditions are specified (Igboekwe and Achi, 2011). For the purpose of this study, boundary conditions are stated. Though there are various boundary conditions, three main types regarding groundwater flow equations as outlined by Wang and Anderson (1982) are discussed;

1. Dirichlet condition or specified head boundary is used when the head is known at the flow region.
2. Neumann condition or specified flow boundary is applied if the flux across a boundary to the flow region is known. They are used to describe fluxes to surface water bodies, spring flow, underflow, and sea-page to or from bedrock underlying the modelled system. No flow boundary is applied when the flux across a boundary is set to zero. A no-flow boundary may represent impermeable bedrock, an impermeable fault zone, a groundwater divide, or a streamline.
3. Head dependent flow boundaries (Cauchy or missed boundary conditions) are used in the calculation of flux across a boundary when a boundary head is given. This type of boundary condition is called a mixed boundary condition because it relates boundary heads to boundary flows. A type of boundary condition under the head dependent flow boundary condition is the Robin's or induced flux boundary condition which has been applied in the current study. The Robin's boundary condition is applicable when there is no observable physical and geographical boundary in the model domain. Thus the quantity of flow is a function of the change in hydraulic head and the model material or conductance.

In order to simulate boundary conditions, cells are grouped either as constant head cells or inactive (or no flow) cells. Constant head cells have a specified value through all time steps of the simulation. Inactive cells do not allow flow into or out of the cell (Todd and Mays, 2005).

Numerical simulation methods have been extensively used to study and predict effects of management decisions on watersheds for some time now.

Although it is naturally impossible to use a computer code to correctly represent a physical domain, groundwater flow models have been constructed to represent physical domains with a reasonable degree of accuracy, and have been accepted as management tools in decision making. The accuracy of a flow simulation model improves with an improved understanding of the domain and the hydrologic units to be simulated and increasing technical expertise to carry out the exercise. Also, the accuracy of a model depends on the quantity and quality of the data used to build it, and the numerical code used. MODFLOW-2000 (Harbaugh et al., 2000) is one of the most familiar simulation codes used widely in simulating local and regional groundwater flow phenomena. This is a finite difference numerical code which is based on the assumption that groundwater is of uniform density and viscosity throughout the basin (Harbaugh et al., 2000). This assumption is valid if the resource is relatively fresh. In most cases, the assumption is valid, and the use of MODFLOW results in reliable management decision support systems. MODFLOW-2000 is therefore not suitable for simulating variable density groundwater flow systems such as occurs with saline water intrusion into freshwater aquifers. Except in the Keta area of the Volta region where seawater effects have resulted in marked differences in groundwater densities at different locations, all other basins in Ghana can be reliably modelled using this code (Yidana et al., 2011).

Internationally, extensive research has been undertaken by a large number of researchers using groundwater modelling as a tool in solving various hydrogeological challenges. For instance, Senthilkumar and Elango (2004) used a two layered finite difference model to simulate groundwater flow in the Lower Palar River basin in Southern India under both steady and transient conditions for the period of eleven years (1991 to 2001) to model effect of pumping rate on their the aquifer system. Also, Boronina et al., (2003) used steady state numerical groundwater flow model in the study of groundwater balance and resources

management in the Kouris catchment in Cyprus, to estimate amount of groundwater recharge of the total annual rainfall.

In Zimbabwe, Houston (1988) estimated groundwater recharge of the of basement aquifers in the Victoria Province through simulation modelling, river baseflow analysis and hydrochemical analysis. He et al. (2008) as well used a three-dimensional numerical finite element model under steady state and transient condition for a groundwater flow assessment in the coastal Dogo Plain. They also under the same conditions, but different scenarios, established correlation between the ground surface elevation and the groundwater level in the shallow coastal aquifer.

In the Unkheltseg Basin, 3-D numerical groundwater flow simulation for geological discontinuities was carried out by Yihdego et al. (2014). Using the “DRAIN Package” and “Fracture-Well Package FW4” in MODFLOW-SURFACT, to effectively constrain recharge and discharge across the fault barrier.

In addition, Ebraheem et al. (2003) used a regional numerical model to investigate the hydrodynamic impacts of different groundwater management options on the potentiometry of aquifers of Southern Egypt for various scenarios unveiled a real danger of either dewatering the shallow aquifer in some areas, or increasing the water depth to an uneconomic lifting depth.

Furthermore, Khan et al. (2008) developed a surface-water, groundwater quantity and quality model to assess future groundwater trends in the Rechna Doab, a sub-catchment of the Indus River Basin, where scenario analysis showed that if dry conditions persist, there will be an overall decline in groundwater levels of around 10m for the whole of Rechna Doab during the next 25years.

Locally, few studies have been conducted using numerical flow simulations to advise management decisions on the allocation of groundwater resource. The use of this tool has been largely focussed on groundwater recharge estimates and aquifer hydraulic properties to accurately characterize various aquifers that exist in the country.

As such, Yidana et al. (2012) in a simulation of groundwater flow in a crystalline rock aquifer system in the Densu Basin of Southern Ghana, evaluated the effects of increased groundwater abstraction on the aquifers using a transient groundwater flow model; where they suggested a safe annual increment in groundwater abstraction by 5% under usual recharge conditions beyond which the basin will wide drawdown in the hydraulic head by 4m by the end of the prediction period 2009 – 2024.

Previous work by Yidana et al. (2013) in a crystalline aquifer in southwestern Ghana focused on using a steady state numerical model to provide an initial basis for characterizing the hydrogeology of the terrain. The study was carried out with a view to assisting in large scale development of groundwater resources for various uses (e.g. for large-scale groundwater development to support irrigation schemes). The findings of Yidana et al. (2013) indicated the system can only sustain increased groundwater abstraction by up to 150% of the current abstraction rates. Thus suggesting that, prudent management of the resource will require a much more detailed hydrogeological study that identifies all the aquifers in the basin for the assessment of sustainable basin yield.

Also, Attandoh et al. (2012) conceptualized the hydrology and hydrogeological conditions of some sedimentary aquifers in Savelugu-Nanton and surrounding areas, Northern Ghana. The model simulated under steady state condition using MODFLOW/MODPATH, indicated prominent flow direction (NE-SW), and calibrated ranges of recharge rate and hydraulic

conductivity estimated at 0.3% to 4.15% of the annual precipitation and 1.90 m/day and 10.81 m/day respectively.

Furthermore, Yidana et al. (2015) conducted a study in parts of a crystalline aquifer system in Northern Ghana to estimate the regional distribution of aquifer hydraulic parameters and recharge. Estimated hydraulic conductivity estimated values ranging from 1.70 m/day to 2.24 m/day and groundwater recharge ranges between 0.036 m/yr. and 0.164 m/yr., representing 3.6% and 16.4% of the local annual precipitation. Thus, suggesting under the current calibrated groundwater recharge conditions, the system can sustain increment in groundwater abstraction by up to half of the current abstraction rates (8.64 m<sup>3</sup>/day to 103.68 m<sup>3</sup>/day) with negligible effects on the system.

Lutz et al. (2007) used a steady state numerical groundwater flow model to determine water balances in the Nabogo Basin, a sub-catchment of the White Volta River Basin of Ghana, highlighting the effects of several scenarios on groundwater abstraction in the area. Their simulation indicated that the current rate of groundwater extraction may be too small to play a significant role in the regional water balance. In addition, Ofofu-Addo et al. (2008) used steady state model in simulating the groundwater system and regional effects of groundwater development alternatives in the White Volta Basin of Ghana, indicating that groundwater flows from the northern Savannah highlands (higher topography) to the lower northern savannah plains recharging the Lake Volta in the process.

Considering the scope of thorough literature review compiled, both on global and local research works and various approaches that were used in their hydrogeological characterization of various basins, this work captures some similar approach but now in the context of numerical and stochastic modelling of groundwater flow. Details of numerical and stochastic modelling are outlined under broad methodology in the next chapter of this work

## **CHAPTER THREE**

### **MATERIALS AND METHODS**

This research was carried out in three stages; desk study, data collection and post field work.

#### **3.1 DESK STUDY**

Literature was reviewed on related topics through electronic search, journals and relevant text books. Some previous works on the geology and hydrogeology concerning the White Volta River Basin of Ghana as well as similar works in neighbouring countries were also reviewed. In addition, information on maps covering the topography, climates, agricultural and anthropogenic activities in the study area were gathered and reviewed.

#### **3.2 DATA COLLECTION**

Data was collected on monitoring wells, pumping test and borehole lithological logs of wells drilled in the White Volta River Basin of Ghana. These data were obtained from the Water Resource Commission of Ghana as part of the Hydrogeological Assessment Project data (HAP). Furthermore, topographical and geological maps were also obtained from the Survey Department of Ghana and the Department of Earth-Science of the University of Ghana respectively.

### 3.3 POST FIELD WORK

#### 3.3.1 Hydrogeological characterization and Numerical simulation models

Lithological log data obtained during the field survey were carefully studied and compared with the known geology and hydrogeology of the study area to ensure coherency and accuracy. The data captured information on the borehole IDs, their spatial positions (longitudes and latitudes in degree decimals) and locations, well depths (in metres), top and bottom elevations (in metres), hydrogeological Unit descriptions and lithology types. A total of twenty-one wells were logged showing rock types such as clay, mudstone, and shale, intercalations of mudstone/siltstone, laterite, sandstone, granite and gneiss. A distribution of the wells locations with regards to their spatial positions is shown in Fig. 3.1. Drill depth of boreholes in the study area is recorded between 50 m to 155 m. The lowest drill depth recorded for boreholes situated in towns of Tinguli, Bugya-Pala, Dusie-Camp and Bonia whilst towns of Yanyounyiri, Janga, Noverinsa, Tamaligu, Tumu, Kanshegu and Nelerigu logged deeper drill depths.

The longitudes and the latitudes of the boreholes were converted to Universal Transverse Mercator in units of metres. Also, elevations and descriptions on the well logs were imported into MODFLOW for lithological and hydrostratigraphy modelling.

Static Water level values obtained from the monitoring well data were averaged for the period 2005 to 2012 and processed into appropriate formats for steady state simulation in MODFLOW. Hydraulic head data was obtained by subtracting the averaged static water levels from the reference elevations of the boreholes.

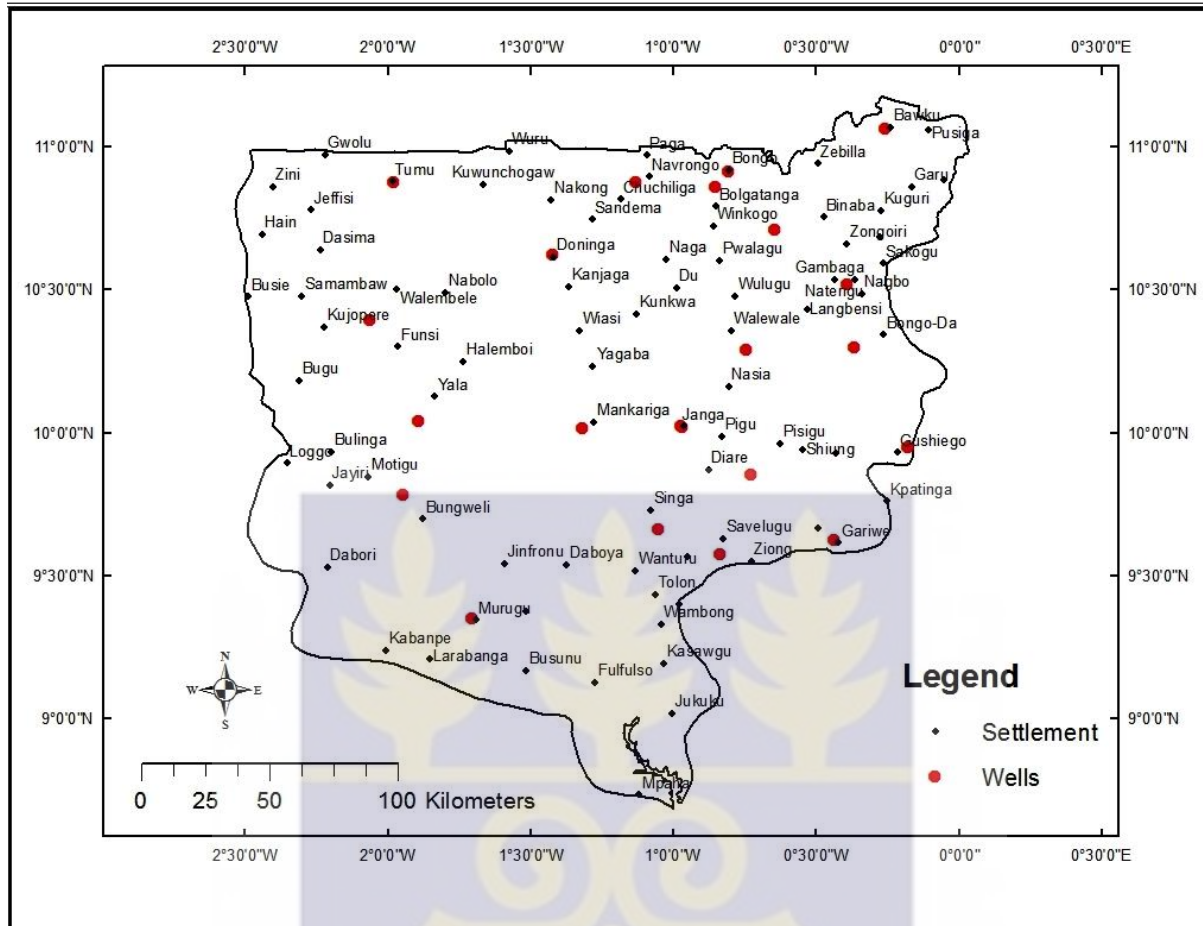


Figure 3.1: Map showing the borehole locations in the White Volta River Basin of Ghana.

### 3.3.1.1 Conceptualization of hydrogeological framework

Model conceptualization is the process in which data describing field conditions are assembled in a systematic way to describe groundwater flow and contaminant transport processes at a site (Kumar, 2002). Model conceptualization aids in determining the modelling approach and which software to use.

The development of a conceptual model forms one of the basic steps in groundwater flow modelling, as it simplifies the field problem and organizes the associated field data so that the system can be readily analysed (Anderson and Woessner, 1992).

The conceptual model was constructed within the Groundwater Modelling System (GMS 7.1). Geologic map of the area was imported and registered to serve as basemap coverage for the construction of the conceptual model using the Geographical Information System (GIS) map tools in GMS. The boundary of the map was delineated to form the boundary of the model. The study area is bounded in the west by Black Volta, the north by Burkina Faso and the east by the Oti River Basin. Fig. 3.2 shows the digitized map from which the aquifer parameters were assigned.

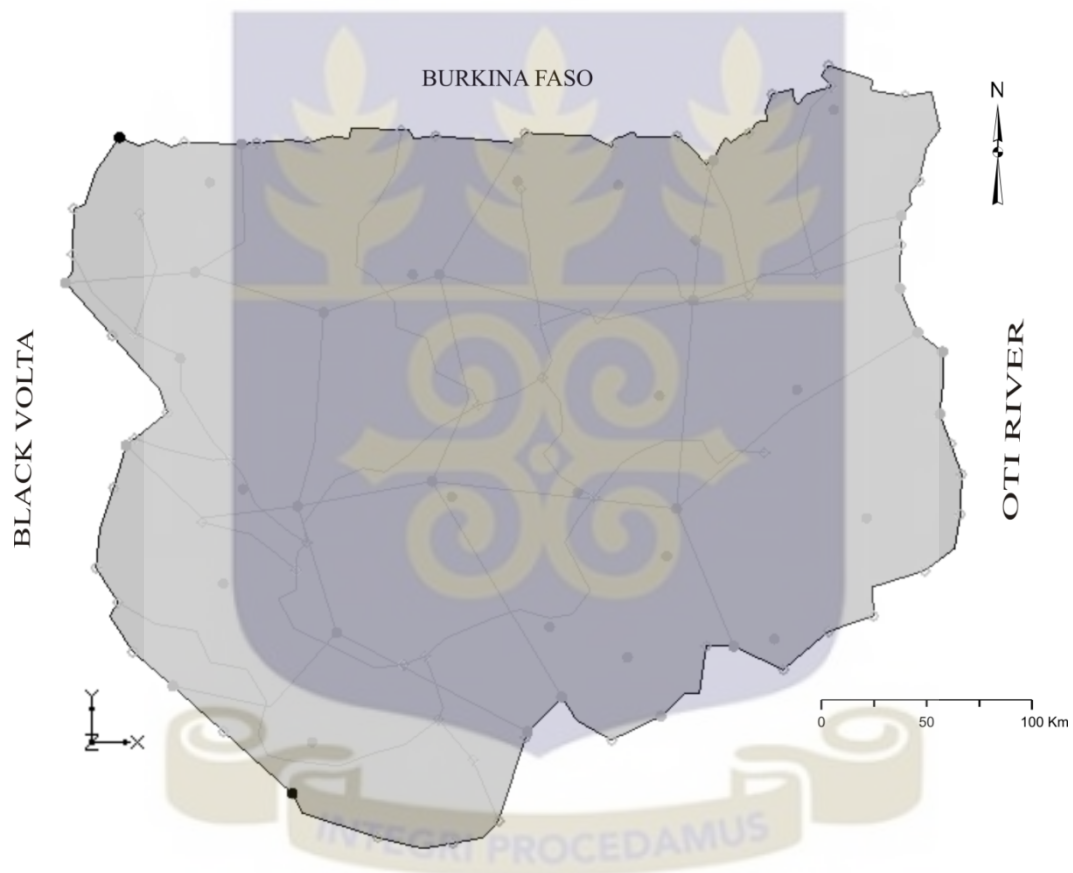


Figure 3.2: Digitized map of the coverage area explaining the process of conceptualization in GMS 7.1.

The model design and input of aquifer parameters were defined based on drainage network, hydraulic conductivity, recharge, observed hydraulic head, general boundary conditions and grid design. These mentioned parameters are respectively outlined below.

The study area is bounded by several rivers and tributaries. As such, the river networks of the area were also digitized and incorporated into the model as river coverage. Elevations and conductances were assigned to the river network.

The domain was zoned for hydraulic conductivity coverage and assigned hydraulic conductivity values based on the results of the hydrogeological investigation (pumping tests), data on the well logs and standard literature for the geology of the area. The vertical anisotropy was kept at default while the initial hydraulic conductivities in the range of 0.02 m/day and 15 m/day were assigned to the hydraulic conductivity zones created in the hydraulic conductivity coverage.

One of the main sources of recharge to the aquifer is precipitation. Nevertheless, data on groundwater recharge in the study area are sparse and expected to vary due to the vegetation cover, land use patterns and most importantly, the heterogeneity of the soil and rocks.

The study area was divided into thirteen recharge zones, which were subsequently converted into coverages using the map tools in GMS 7.1. Average precipitation was used to estimate recharge based on the 3 to 5% ratio of the mean annual rainfall that becomes groundwater recharge. Recharge values ranging between  $2.15 \times 10^{-6}$  m/day and  $3.5 \times 10^{-4}$  m/day were assigned based on previous studies reported by other authors within similar lithologies of the Voltaian and Basement Complex aquifers (Obuobie et al., 2012; Yidana et al., 2012 and Yidana et al., 2014).

The hydraulic head values for all the wells, together with their individual coordinates were imported into the conceptual model and assigned under the observation head coverage. The hydraulic heads were computed as the difference between the ground elevation and the measured water levels. For the sake of calibration, 20 wells were used for the model. Table 3.1 contains details of the wells used for the model calibration.

Table 3.1: Wells used for model calibration.

<b>Hole ID</b>	<b>X (m)</b>	<b>Y (m)</b>	<b>Ground Elevation (m)</b>
<b>WV001</b>	785478.334	1163544.37	341
<b>WV002</b>	611496.291	1202006.52	305
<b>WV003</b>	704383.862	1202408.42	183
<b>WV004</b>	734756.059	1201217.82	184
<b>WV005</b>	757962.819	1184679.68	195
<b>WV006</b>	799569.868	1223879.00	243
<b>WV007</b>	615667.436	1081403.57	280
<b>WV008</b>	684513.817	1107407.90	245
<b>WV009</b>	747024.415	1137902.27	151
<b>WV010</b>	809416.596	1100979.83	182
<b>WV011</b>	781568.063	1064673.76	201
<b>WV012</b>	642456.861	1033575.54	217
<b>WV013</b>	737425.517	1059073.47	162
<b>WV014</b>	722337.29	1108701.67	121
<b>WV015</b>	788553.19	1139642.22	150
<b>WV016</b>	749245.009	1089661.65	131
<b>WV017</b>	713966.597	1068356.31	108
<b>WV018</b>	672728.092	1174267.70	171
<b>WV019</b>	602723.452	1149049.55	211
<b>WV020</b>	621677.736	1109756.95	188

The head-dependent flow ( $Q_b$ ) through a boundary simulated by the General Head Boundary (GHB) package is calculated from (modified from McDonald and Harbaugh, 1988):

$$Q_b = C_b (h_o - h) \dots \dots \dots \text{Eq. 3.1}$$

Where  $C_b$  is the conductance of the boundary analogous to the stream-bed conductance  $h_o$  is the hydraulic head at the boundary cell, and  $h$  is the hydraulic head at the aquifer cell adjacent to the boundary.

The boundaries of the whole study area were conceptualized as follows; the top and bottom elevations of the aquifer being modelled were imported using the 2D scatter points. The top of the domain was conceptualized as semi-confining to mimic the prevailing conditions of limited direct vertical recharge from precipitation as recorded in previous studies. Confining conditions were ascribed to the bottom of the terrain to reflect the low hydraulic conductivities of the impervious rock and the confining clay layers that appear in places below the simulated aquifer. All the vertical boundaries were conceptualized and simulated with the Robin's boundary condition so that subsurface lateral flows would be adequately characterized.

The conceptual model of the entire domain was discretized into 10,000 cells, with 100 rows and 100 columns as shown in Fig. 3.3. The model grid is oriented north-south and covers a total of 5,973 active cells distributed over a single layer (Fig. 3.4). Vertically, the domain was conceptualized as a single layer with spatially variable hydraulic properties.

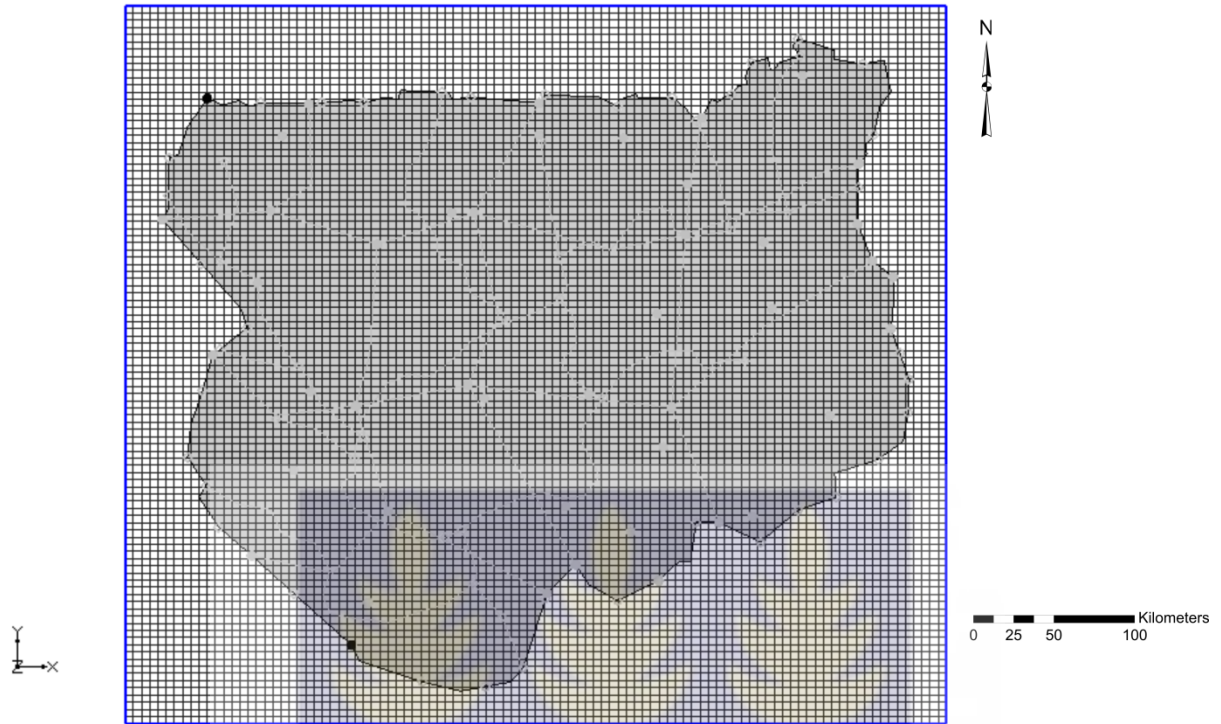


Figure 3.3: Map showing grid over entire coverage area.

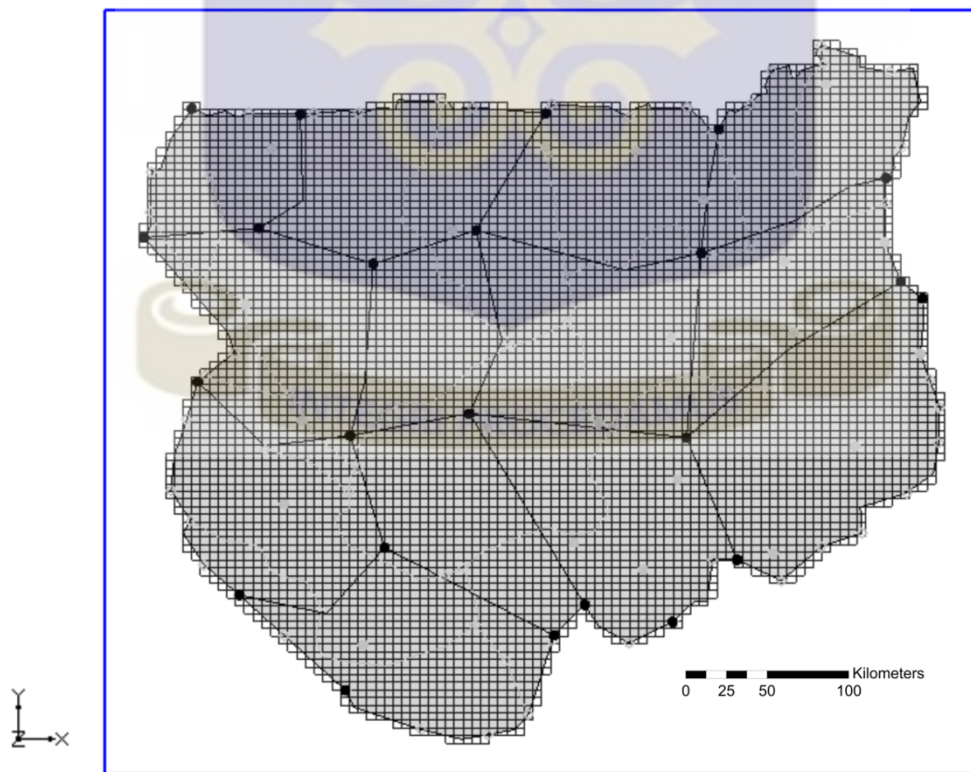


Figure 3.4: Map showing grid over the active domain.

### 3.3.1.2 Numerical Simulation of flow

A good numerical model proceeds from an adequate conceptualization of the essential components of the hydrogeology of the terrain being modelled (Yidana et al., 2012). MODFLOW (McDonald and Harbaugh, 1988) incorporated into the Groundwater Modelling Software, GMS, was used for the numerical simulation.

When all the initial values were assigned to the various coverages in the map model, MODFLOW was initialized and the conceptual model was converted to a numerical MODFLOW model to begin the simulation (Figs. 3.5 and 3.6). The thicknesses of layers were defined by mapping the top and bottom elevations obtained from the borehole logs into MODFLOW. The model was calibrated under steady state conditions. The layer property flow (LPF) package was used in the solution of the groundwater flow equation (equation 2.5). This package is similar to the true layer option under the block centred flow (BCF) package in the older versions of MODFLOW. In the LPF package, the user defines the layer elevations, horizontal hydraulic conductivities and vertical anisotropies and MODFLOW computes the cell-by-cell conductance using the hydraulic conductivity values and the layer geometry. In addition, the LPF package has only two options for layer types: convertible or confined. In this study, the convertible option was selected because the aquifer units in the study area are mostly semi-confined. This allows MODFLOW the flexibility to assign confined or unconfined conditions to locations based on the computed water level. Fig. 3.5 and Fig. 3.6 are a summary of the numerical simulation used in the model in plan view and oblique view respectively.

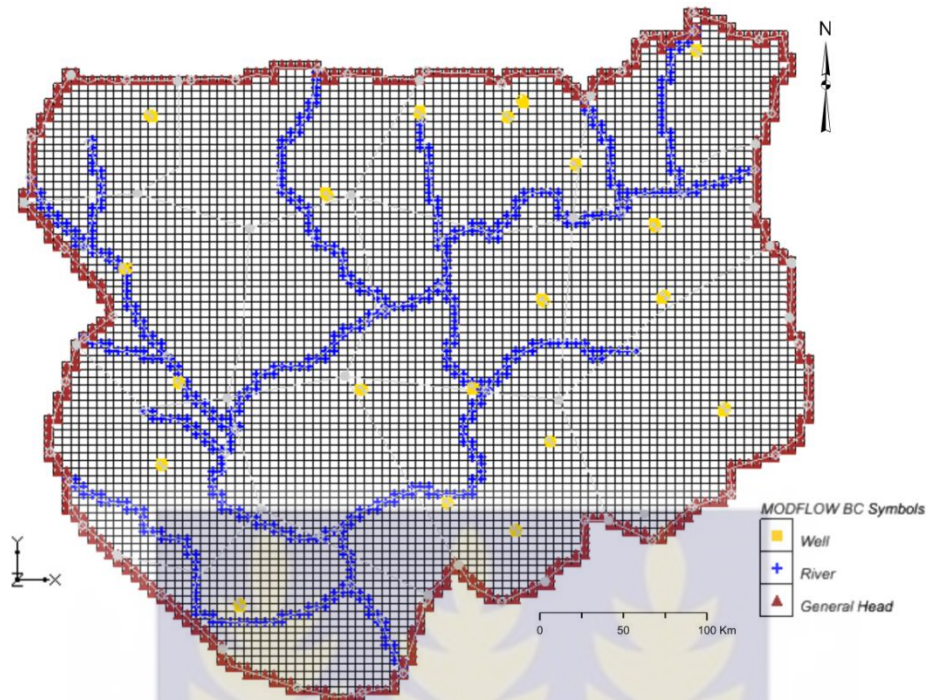


Figure 3.5: A summary of boundary conditions and the discretization used for the model in 2D/ plan view.

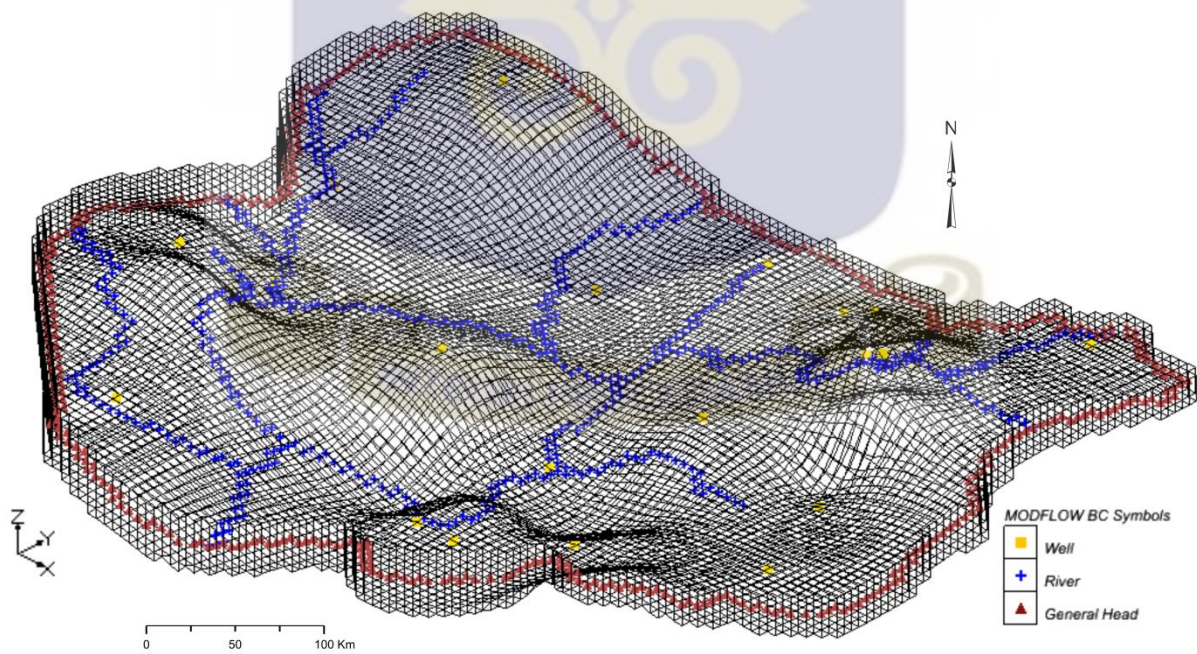


Figure 3.6: Summary of boundary conditions and the discretization used for the model in 3D / oblique view.

### 3.3.1.3 Model Calibration

Every model must be calibrated before it can be used as a tool for predicting the behaviour of a considered system. In model calibration, one tries to tune the model to the field situation so that it can be as representative of the field as possible. This is done through two approaches; the manual calibration and the automated parameter estimation simulation module. In this study, both procedures were employed. The model was first calibrated manually by trial and error using the following procedure. First, hydraulic conductivity values of all the zones were adjusted successively such that the variance of the difference between the measured and calibrated head was minimal. When this was achieved, the values of the recharge rates were adjusted within the different zones to again minimize the variance of the head differences; subject to the constraints that the total recharge remained constant and the zones at higher altitudes had higher recharge rates. Then, during the calibration phase, the initial estimates of model coefficients were modified. This was done by matching the observed groundwater heads against predicted heads in the twenty observed wells within the model domain. The next step was to adjust the values of the river bed conductances and altitudes so as to match the discharge rates in rivers with their measured values. Finally, the variance of the head differences was checked, and all the steps repeated in sequence until an acceptable variance was obtained.

After the first simulation using the manual method, subsequent calibration was adopted using the pilot points approach in PEST till the observed and computed heads were closely matched, and further changes in most of the sensitive parameters brought no change. The mean residual head and root mean square head were used to determine the most optimal balance between the observed and calculated heads. Twenty wells were used with a calibration target of  $\pm 1$  set for all the wells. Furthermore, efforts were made to ensure that the root mean square error (RMSE) was as low as possible at the end of the calibration.

#### 3.3.1.4 Sensitivity Analysis

The purpose of sensitivity analysis is to measure the stability of the model in the face of subtle changes in some of the model parameters (Anderson and Woessner, 1992). A highly sensitive model to any of the parameters is considered unstable and therefore not suitable for use in any predicting scenarios. In this study, sensitivity analysis was carried out to identify model parameters and boundary conditions that influence model results. This was automatically done through PEST and histograms were generated at the end of the calibration to indicate parameter sensitivities. The model was well calibrated against the recharge rates, hydraulic conductivity, head stages and river bed conductances. After suitable analysis was obtained, the hydraulic conductivity, recharge rates, hydraulic head fields and graph of the observed against the computed heads were exported as tiff files for discussion.

#### 3.3.1.5. Stochastic Modelling

There is always a significant amount of uncertainty associated with groundwater flow models (Anderson and Woessner, 1992). This may be due to the conceptual model or with the data and parameters associated with the various components of the model such as hydraulic conductivity and recharge which are particularly prone to uncertainty. In stochastic modelling, the mean, variance, and correlation length are used to generate a quantitative description of the hydraulic conductivity field. Furthermore, a set of model is constructed where each model in the set is thought to be equally probable. Each model is then used to simulate a given scenario and the results are used to eliminate a probability that a certain outcome will occur. Two basic approaches are used in generating stochastic simulations, parameter randomization and indicator simulation. In this study, stochastic simulations were generated using parameter randomization approach. In this approach, selected parameters (recharge and hydraulic conductivity) were randomized using a Latin Hypercube method

(Harbaugh et al., 2000) and the combination of the input parameters were used to define a model instance. The model was run to estimate a probability that a certain outcome will occur for 20 realizations.

### 3.3.1.6. Scenario Analysis

This stage is used to make the model predict the consequences of the changes in internal stresses or water management practices. Since the model was conceptualized and calibrated under steady state conditions, it cannot be used to determine the fluctuations of groundwater in storage. As such, the twenty solutions obtained from the stochastic analysis were used in various scenarios of groundwater abstraction and recharge. Twenty wells with available yields obtained during the pumping test were used for this study. Details of the abstraction rates associated with the various wells are contained in Table 3.2.

In the first scenario groundwater abstraction for each well was increased by 10%, 20%, 30%, 50%, 100% and 200% beyond the estimated and assigned well yields under the same conditions of groundwater recharge estimated during calibration.

In the second scenario, the abstraction rate obtained as yields from the pumping test remained the same, whilst the groundwater recharge was reduced by 10%, 20%, 30%, 50% and 85%.

In the third scenario, the recharge rates were reduced by 10%, 20%, 25%, 50%, 85%, whilst the abstraction rates were increased by 10%, 20%, 25%, 50%, 100% and 200% respectively. Although, the above stated scenarios are not transient models, the simulation of such scenarios will provide similar facts regarding the tolerable groundwater abstraction rate in the area. Simulation of such scenarios would not be significantly different if a transient model was used.

Table 3.2: Initial abstraction rates from boreholes used in this study.

<b>Well ID</b>	<b>X (m)</b>	<b>Y (m)</b>	<b>Discharge Rate (l/min)</b>	<b>Discharge Rate (m<sup>3</sup>/day)</b>
<b>9854</b>	611496.3	1202007	254.37	366.29
<b>9855</b>	704383.9	1202408	185.00	266.40
<b>9856</b>	734756.1	1201218	190.12	273.77
<b>9857</b>	739687.1	1207007	45.65	65.73
<b>9858</b>	757962.8	1184680	23.53	33.88
<b>9859</b>	799569.9	1223879	109.35	157.47
<b>9860</b>	615667.4	1081404	13.54	19.50
<b>9861</b>	684513.8	1107408	471.88	679.50
<b>9862</b>	747024.4	1137902	11.60	16.70
<b>9863</b>	809416.6	1100980	407.23	586.41
<b>9865</b>	642456.9	1033576	960.42	1383.00
<b>9868</b>	737425.5	1059073	189.30	272.59
<b>9870</b>	722842.1	1107987	6.45	9.29
<b>9877</b>	785478.3	1163544	36.25	52.20
<b>10097</b>	788553.2	1139642	21.07	30.34
<b>10100</b>	749245	1089662	334.10	481.10
<b>10102</b>	713966.6	1068356	21.85	31.47
<b>10105</b>	672728.1	1174268	253.60	365.19
<b>10106</b>	602723.5	1149050	112.17	161.52
<b>10107</b>	621677.7	1109757	41.65	59.98

## CHAPTER FOUR

### RESULTS AND DISCUSSION

#### 4.1 GENERAL GROUNDWATER LEVEL AND FLOW IN THE WHITE VOLTA RIVER BASIN OF GHANA

##### 4.1.1. Steady State simulations

The steady state fully calibrated model is represented in Fig. 4.1 and 4.2 in both plan and oblique view. It shows the general hydraulic head in the domain of the model as well as the groundwater flow patterns in the study area. The distribution of hydraulic heads in the basin was an overall average on the basis of observed water levels between January 2005 to January 2012, and they range from 41.20 m to 419.37 m. It is highest at the north-eastern, north-western and south-western portions of the domain, more specifically at the highest elevated areas. However, the hydraulic heads are lowest in the topographic lows. This indicates that recharge areas are from the topographic highs to the topographic lows (Fetter, 2001). The groundwater contours portray the nature of the geology and the fact that the groundwater flow is controlled by secondary permeabilities imposed on the rocks as a result of pressure release through fracturing, weathering and tectonic activities related to the Pan African collisional event (Affaton et al., 1980).

The model was calibrated by matching the observed groundwater heads against predicted heads in twenty (20) wells within the model domain. The model was deemed calibrated when the computed heads for all the wells were within 1.0m of the observed heads. The results of the calibrated head versus the observed head have a mean error of -0.002, a mean absolute error of 0.038 and a root mean square error of 0.08. These values indicate that; the model is deemed calibrated. The relationship between observed and model calculated hydraulic heads

in the basin is presented in Fig. 4.3. A good match between the computed and the observed hydraulic head suggest that the model is reasonably calibrated within the limits of the data used and is therefore representative of the hydrogeological conditions in the terrain. Thus, the model realistically simulates the groundwater elevation and flow direction across the model domain

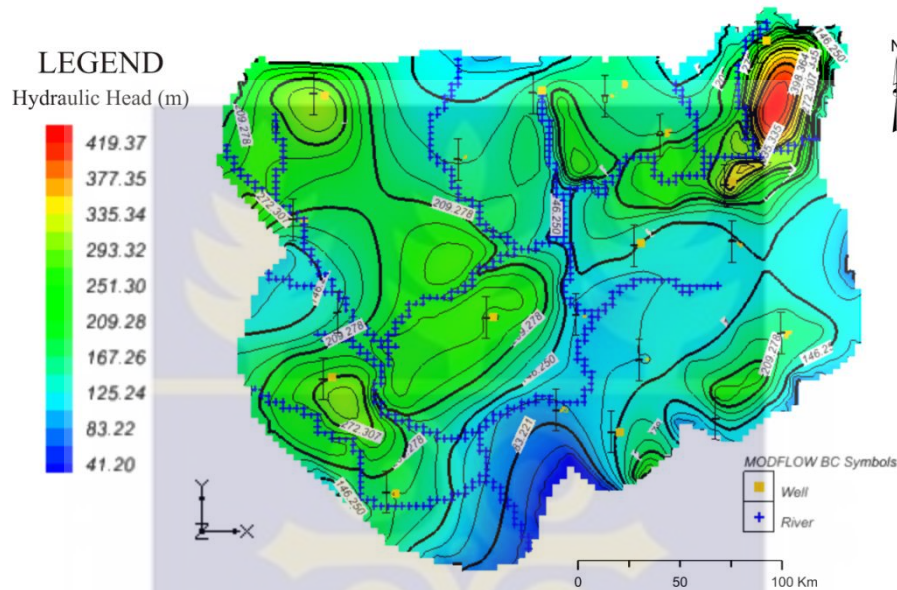


Figure 4.1: Potential field map resulting from the steady state calibrated model in a plan view.

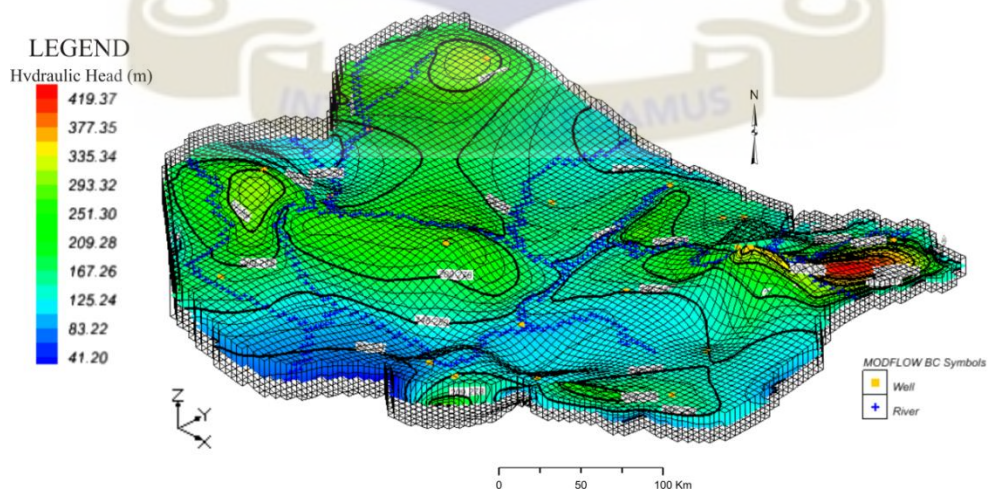


Figure 4.2: The potential field map resulting from the steady-state calibration of the model in an oblique view.

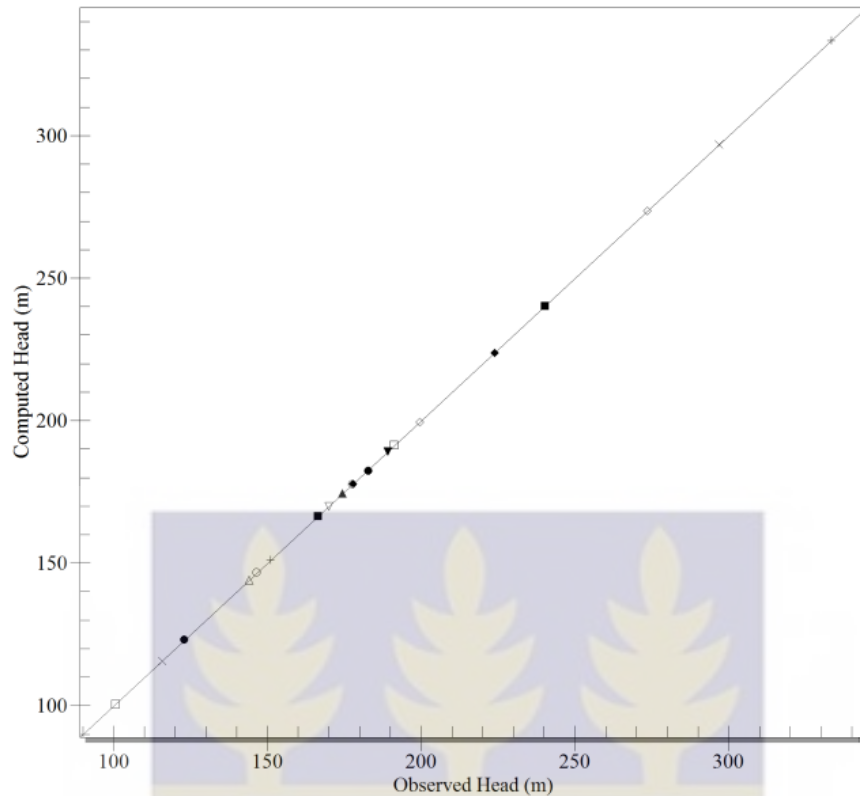


Figure 4.3: A comparison between observed and model computed hydraulic heads.

The general groundwater flow directions in the modelled basin revealed cases of local flow and regional flow systems. Tóth (1963) postulated three conditions under which groundwater flow systems occur. These are local, intermediate and regional flow systems. Local systems of groundwater flow occur where the surface topography has a well-defined relief, and as such has its recharge area at a topographic high and its discharge area at an adjacent topographic low. Where there is one or more topographic highs and lows located between the discharge and recharge areas, intermediate groundwater flow systems occur. Regional flow systems have their recharge areas in the basin and their discharge areas at the bottom of the basin.

Figs. 4.4 and 4.5 provide detail description of the groundwater flow directions and their magnitudes in plan and oblique view respectively. The local and regional flow systems probably can be attributed to the variations in the topography, hydraulic conductivity fields,

structural entities, drainage patterns and the deformational events in the area. Freeze and Cherry (1979) proposed that areas of topographic highs or pronounced local relief have only local flow systems. Hence, fluctuations in topography can affect groundwater motion and create quite complex flow systems.

Also, due to the heterogeneity of the aquifers in the study area, and their dependency on secondary porosity and permeability, such as faults, fractures, joints and veins for the storage and transmission of groundwater, there are many barriers to continual groundwater flow both laterally and in depth. From the simulated models (Figs. 4.4 and 4.5), four directions of groundwater flows have been observed; a N-S direction of flow along river Kulpawn (A), E-W direction between river Sisili (B), NE-SW trend (C) of groundwater flow depicting the morphology of the White Volta River and a NW-SE (D) along the Black Volta River.

Structurally, the variations in the groundwater flow directions can be linked to the different trends of rock type occurring in the basin. Baratoux et al., (2011) explained that the Lawra belt of Ghana has general N-S trend, giving an indication of one type of flow direction (shown by A on Figs. 4.4 and 4.5) as simulated by the model. Flow directions depicting NE-SW can be attributed to the general trend of the Bole Nangodi belt, while flow directions in the east-west directions can be attributed to the Julie belt (shown by B on Figs 4.4 and 4.5). However, NW-SE flow patterns as seen towards the northern portion of the study basin (shown by D on Figs. 4.4 and 4.5) correspond to the general NW-SE trending Boromo belt in Burkina Faso whose south eastern extension is the Lawra belt in Ghana (Baratoux et al., 2011).

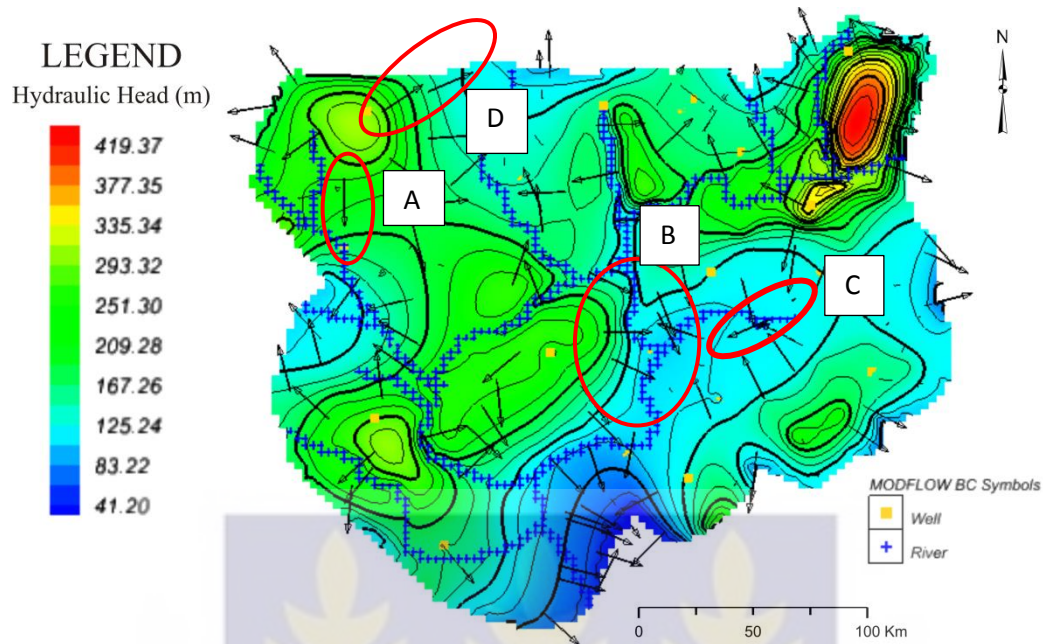


Figure 4.4: Potential field map calibrated at steady state showing the groundwater flow directions plan view.

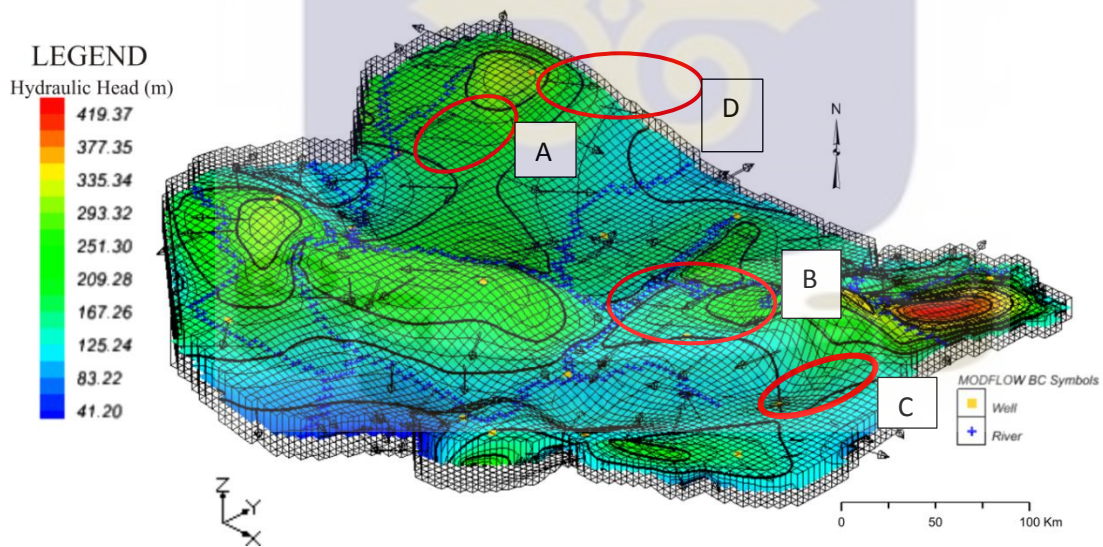


Figure 4.5: Potential field map calibrated at steady state showing the groundwater flow directions in oblique view.

## 4.1.2 General Hydraulic conductivity estimated in the numerical simulation

### 4.1.2.1. Steady State

Hydraulic Conductivity is a vital parameter in a calibrated groundwater flow model as it assists in conceptualizing the general pattern of the transmissive properties of the aquifer and the management of groundwater resources (Yidana et al., 2014). The hydraulic conductivity field in the domain was established through the pilot point method, giving a smooth map. The pattern of hydraulic conductivity distribution of the area at calibration is shown in Figs. 4.6 and 4.7. The calibrated hydraulic conductivity values range from values below 5.51 m/day to over 98 m/day with an average of 51.76 m/day. The hydrogeological properties of the aquifers in the study area are controlled by secondary permeabilities created in the wake of fracturing and/or weathering, which create ingresses for increased groundwater recharge and storage. The hydrogeological properties of the rocks are based on the pervasiveness of weathering and fracturing of the rocks. Where the degree of secondary permeability is high, the hydraulic conductivities are high, and the lithologies serve as good aquifers. Hydraulic conductivity values are highest in the north-north-western parts of the basin and lowest in the north-eastern through to the central and southern portions of the study area (Figs. 4.6 and 4.7). However, in the far north-western corner of the basin records a relatively low value of hydraulic conductivity. In comparison to the geology, the highest hydraulic conductivity values ranges between 26 m/day to over 98 m/day, and occurs in the north-north western portions of the basin, specifically, portions of the crystalline aquifers of the Birimian Structural unit. These values obtained are higher than the range of hydraulic conductivity estimates (0.99 m/day to over 19.4 m/day) attained by Yidana et al. (2011) and the ranges (1.04 m/day and 15.25 m/day) proposed by Yidana et al. (2015). However, estimates acquired for crystalline aquifers in the study basin are in concomitant to values (2 m/day to over 40

m/day) obtained by Yidana et al. (2012) in a crystalline rock aquifer system in Southern Ghana and values quoted for similar lithologies elsewhere (Fetter, 2001).

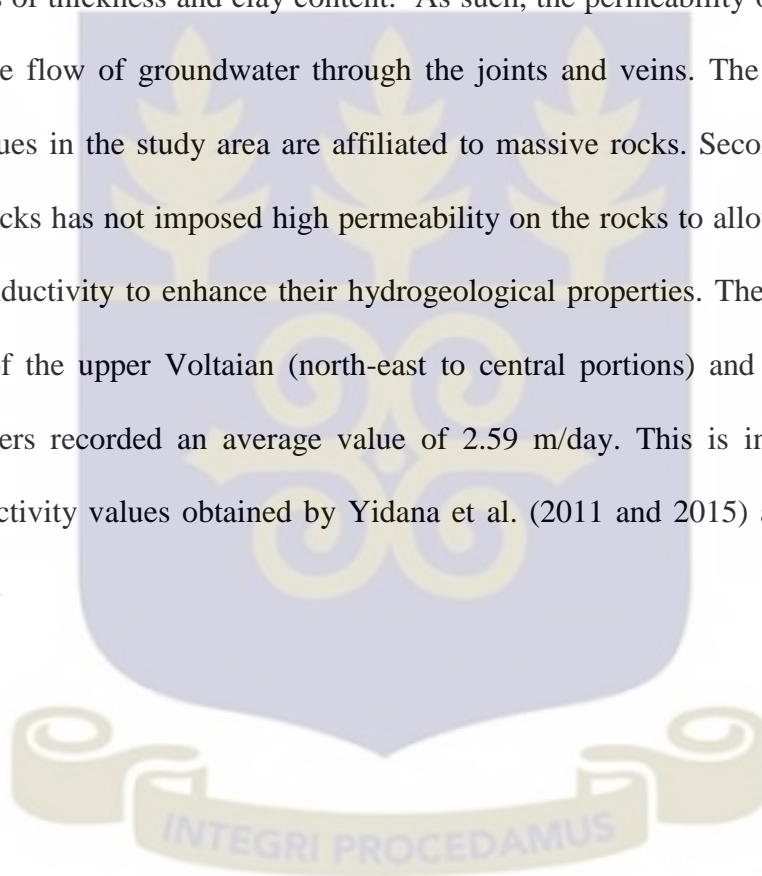
Notwithstanding, high hydraulic conductivity values obtained representing the crystalline aquifers in the study basin can be linked to the fact that aquifers of the Birimian Structural Unit in Ghana are amongst the most prolific in terms of water delivery in the country (Banoeng-Yakubo et al., 2010), where aquifer transmissivity ranges between 0.2 m<sup>2</sup>/day and 119 m<sup>2</sup>/day, with an average of 7.4 m<sup>2</sup>/day (Banoeng-Yakubo et al., 2010).

In the mid-section and southern portions of the study basin (Figs. 4.6 and 4.7), specifically, the Voltaian rock aquifers recorded hydraulic conductivity values ranging between 2.26 m/day to 13.08 m/day, with the highest values occurring in the central portions of the basin, specifically the middle Voltaian. These hydraulic conductivity values obtained are in range with estimates (0.004 m/day to 3.6 m/day) and (1.19 m/day to 6.3 m/day) proposed by Acheampong and Hess (1998) and Yidana (2011) in the Southern Voltaian aquifers respectively. Similarly, the obtained values in this study for the mid-section and the southern portions correspond with estimated values (1.9 m/day to 10.81 m/day) obtained by Attandoh et al. (2013) in the middle Voltaian aquifers.

The Middle Voltaian is slightly deformed than the Upper Voltaian Systems (Dapaah-Siakwan and Gyau-Boakye, 2000). Rocks of the Middle Voltaian are mainly flat-lying or gently dipping and are generally well consolidated and are not inherently permeable (Dapaah-Siakwan and Gyau-Boakye, 2000). An assessment of well test data by Yidana et al. (2008), suggest that some of the most prolific aquifers in the southern Voltaian are located among the fractured mudstones. Variability in the Hydraulic conductivity values obtained in the southern portion of the White Volta Basin and the crystalline aquifers are as a result of secondary porosity induced by chemical weathering and deformational processes. Thus, areas

recorded with high hydraulic conductivity values may be highly weathered and fractured. Hence, the result of the study is in harmony with the general assertion that hydrogeological properties of the aquifers in the Voltaian and crystalline basement terrains are controlled by the degree of fracturing and/or weathering of the country rock (Yidana et al., 2012).

The White Volta River Basin of Ghana is characterized by weathered and fractured materials. Most of the wells were completed in the weathered and fractured zone, which is clearly variable in terms of thickness and clay content. As such, the permeability of the materials is as a result of the flow of groundwater through the joints and veins. The lowest hydraulic conductivity values in the study area are affiliated to massive rocks. Secondary porosity of these massive rocks has not imposed high permeability on the rocks to allow for high values of hydraulic conductivity to enhance their hydrogeological properties. The Lower Voltaian, some portions of the upper Voltaian (north-east to central portions) and few areas of the crystalline aquifers recorded an average value of 2.59 m/day. This is in agreement with hydraulic conductivity values obtained by Yidana et al. (2011 and 2015) and Acheampong and Hess (1998).



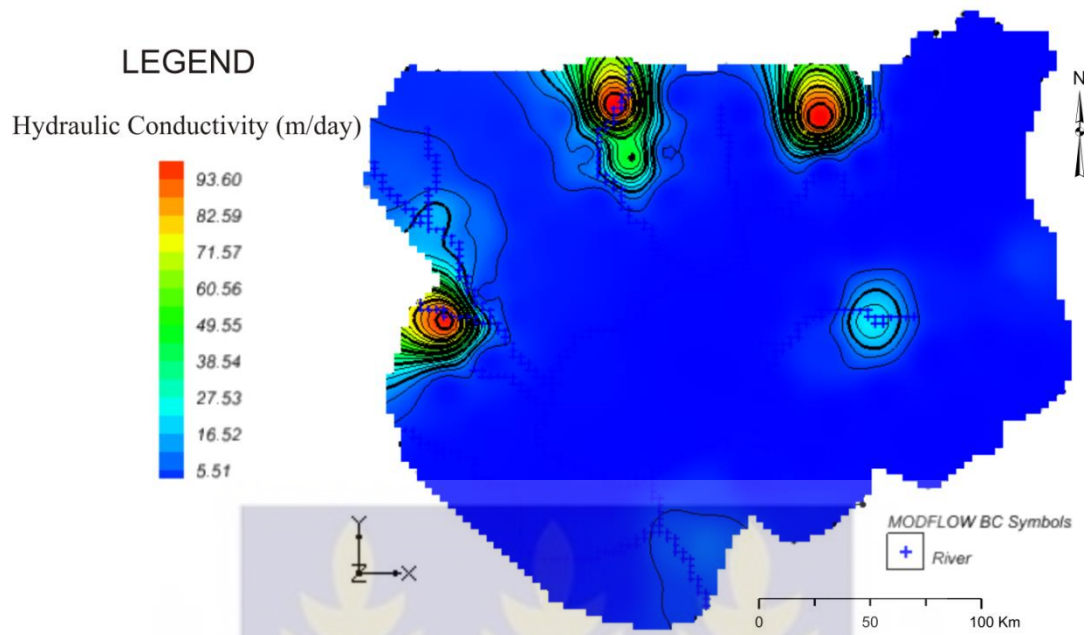


Figure 4.6: Distribution of the calibrated hydraulic conductivity (m/day) of the area in plan view

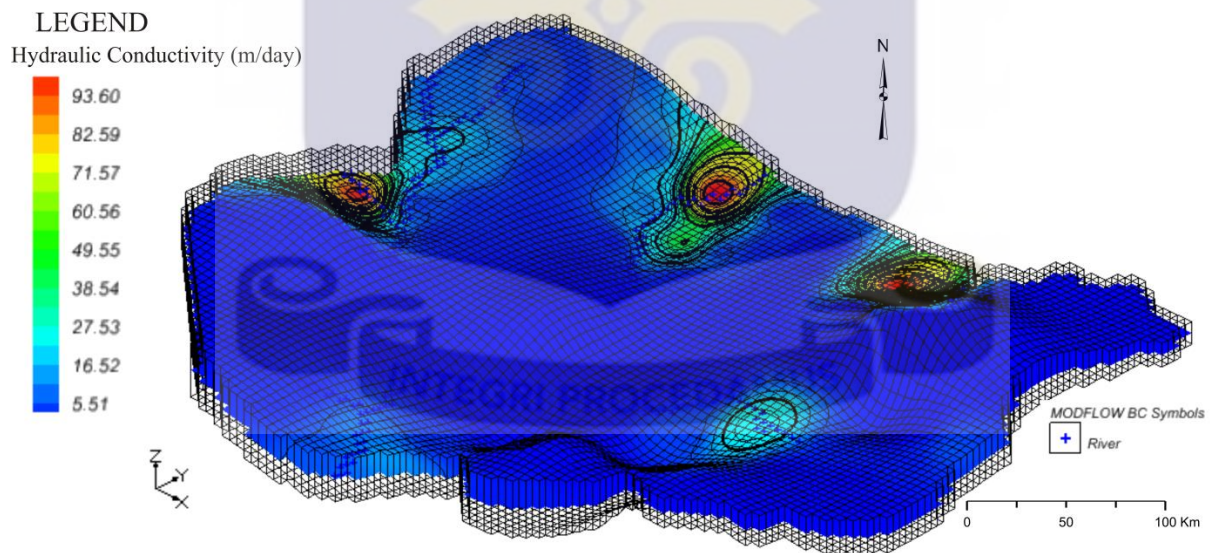


Figure 4.7: Distribution of the calibrated hydraulic conductivity (m/day) of the area in oblique view

### 4.1.3 Recharge rate estimation through the numerical simulation

#### 4.1.3.1 Steady State

One of the principal concerns in groundwater resource assessment is the quantification and model of groundwater recharge processes, as it helps in the efficient management of groundwater resources (Darko, 2002). Figs. 4.8 and 4.9 show the spatial distribution of groundwater recharge (plan and oblique views) estimated in the study area, based on the calibration of the steady state. Modelled recharge rate in the basin for the average period between 2005 to 2012 ranges between 0.0008 m/year to 0.046 m/year, with an average of about 0.023 m/year representing 0.02% and 4.0% of the average precipitation representative of the three regions which make up the entire study area. Specifically, the highest recharge rate in the basin occurred mostly within the topographic high areas in the north-western and southwestern portions of the study area, representing the Basement Complex aquifers.

Calculated recharge values (0.003 m/year to 0.046 m/year) can be translated into about 0.26% to 4.0% of the annual precipitation of 1.15 m in the Upper West Region of Ghana. This observation is consistent with the general hydrogeological knowledge that highlands and lowlands serve as recharge and discharge zones in groundwater flow systems, thus, surface topography is a replica of the groundwater table elevation ( Freeze and Cherry, 1979; Fetter, 2001; Moore, 2002).

However, a higher recharge rate of 0.035 m/year is recorded at the low topographic zones in the northern part of the study area (Birimian complex), representing 3.53% of the annual precipitation of 1m/yr. in the Upper East Region of Ghana. The highest recharge values recorded in the basin is due to the fact that rocks occurring in aquifers within the basement complex are extensively fractured, thickly foliated and highly deformed. This indicates that

there are a lot of weaker zones in those areas, facilitating the movement and flow of water in the basin.

However, the low recharge rates recorded by some of the highly conductive portions of the Crystalline aquifer within the basin can be attributed to the very low or non-existence of vertical hydraulic conductivity which restricts the vertical percolation of precipitation into the aquifer systems. Furthermore, the variations in recharge rate recorded within the Birimian Complex aquifers is due to the differences in the permeabilities and thicknesses of the unsaturated zone as well as the prevailing climatic conditions in the area.

The smallest recharge rates recorded in the Voltaian rock aquifers (central to southern part) within the study basin range between 0.0008 m/year to 0.007 m/year, translating into 0.64% to 0.07 % of the annual rainfall of 1.1 m/year for the Northern Region of Ghana. The low recharge rate estimations recorded in the Voltaian aquifers can be attributed to the fact that rocks occurring in such areas are not extensively foliated and fractured as compared to the crystalline aquifers of the basement type rocks. Also, the low recharge rate estimation within the Voltaian Sedimentary basin is due to sedimentary processes as compaction, consolidation and cementation. These processes destroy the primary porosity, thereby accounting the low recharge estimations recorded. However, intermediate estimate of 0.011m/yr. recorded in some portion of the Voltaian rock aquifers can be ascribed to secondary porosity which may be ascribed to relatively, intensely folded part of the Voltaian rock towards the east of the Togo Structural Unit ( Kesse, 1985; Affaton, 1990; Affaton, 2008) and weathering processes. Yidana and Koffie (2014) ascribed reduced groundwater recharge in the Voltaian Basin to high levels of evaporation of infiltrating precipitation whose downward trajectory is limited due to significant clay content.

Generally, the variations in the recharge rate within the study area are due to the fragmentation of the basin. This fragmentation is due to the presence of different lithological units arising from the Birimian Basement complex and the Voltaian Basin. These complexities are due to their differences in lithologies, structural overprints, ages and their evolutionary history through geologic time. These geological disparities in the basin are from poly-deformed Birimian basement complex and flat-lying Voltaian rocks with recorded deformation towards the Togo (Dahomeyides) from the Pan- African Orogenic event (Affaton et al., 1991; Affaton, 1990).

In addition, the estimated groundwater recharge distribution in the area corresponds to the distribution of the groundwater hydraulic potential as suggested in Figs. 4.1 and 4.2. However, few portions in the Crystalline Basement Complex of the study area (north-eastern corner) with high hydraulic potential recorded lower recharge rate estimate other than expected. This is because the area might have received significant horizontal flow across the general head boundary, resulting in the appreciation in hydraulic head.

Comparatively, recharge rates estimated for this study varies slightly to recharge estimates obtained from numerical simulations and other methodologies in the basin and similar terrains. For instance, Obuobie et al. (2012) estimated recharge to groundwater in the White Volta River Basin of Ghana to vary between 2.5% to 16.5% of the annual rainfall. Their estimates were higher than values obtained in this current study (0.02% and 4.0% of annual precipitation). Result obtained by Obuobie et al. (2012) is as a result of the Water Table Fluctuation approach used, and the short period of duration (2006 to 2007) for their study. However, this present study uses a mathematical approach (numerical model) over a longer duration of seven years (2005 to 2012). This gives a detail and more reliable results

considering the quality and quantity of the data used, which is paramount in every groundwater simulation model.

Furthermore, results obtained for estimates from Yidana et al. (2014) for a study conducted in a crystalline aquifer system of the Densu Basin gave an average recharge rate of 13% of the annual precipitation. Their findings are higher compared to estimates obtained in this study (0.02% and 4.0% of annual precipitation) for areas underlain by the crystalline rock aquifers. Differences in their results compared to the present study may be due to the period 2005 for which their model was simulated and the seasonal variations prevailing in the Densu Basin to that of the White Volta River Basin of Ghana.

Despite the above stated comparisons, recharge rate estimates obtained for the basin suggest good prospects for the development of groundwater resources in the basin for commercial activities such as large scale irrigation projects. Thus, identification and protection of the local groundwater recharge areas identified in this study are recommended in order to safeguard the integrity of the resource under the scenario of increased abstraction for the commercial activities in the basin.



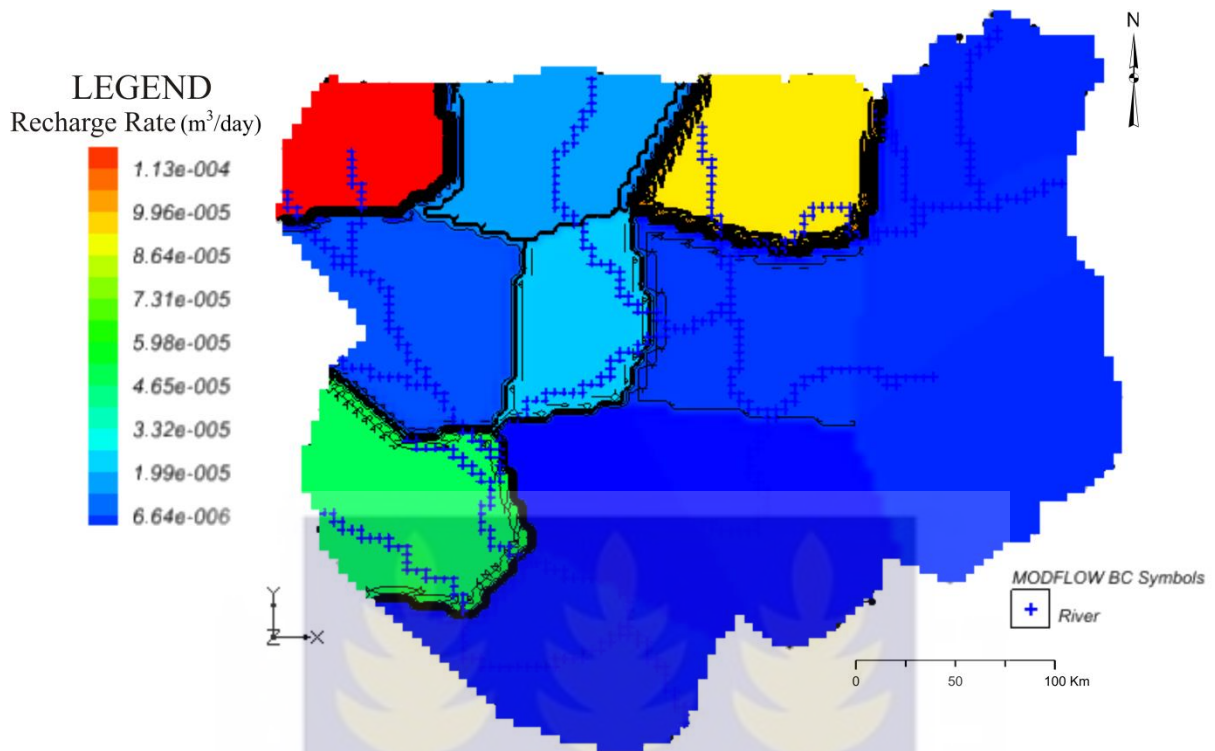


Figure 4.8: Distribution of recharge rate ( $m^3/day$ ) of the area under steady state in plan view.

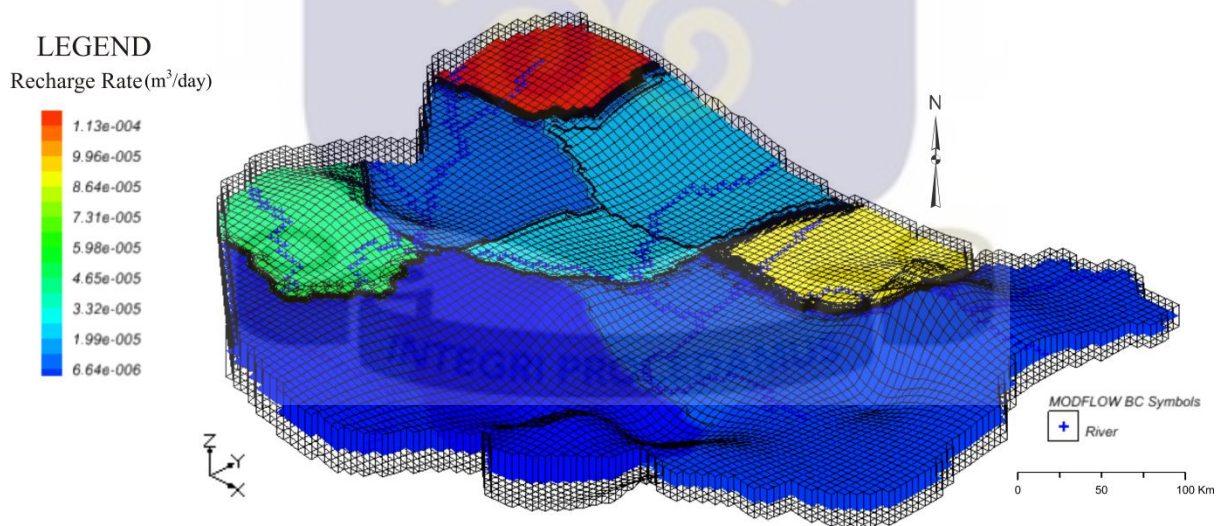


Figure 4.9: Distribution of recharge rate ( $m^3/day$ ) of the area under steady state in oblique view.

#### 4.1.4. Sensitivity analysis of calibrated steady state model

The purpose of sensitivity analysis is to determine the response of the calibrated model to subtle changes in the aquifer input parameters. In the automatic calibration mode using the automated parameter estimation approach (PEST) in MODFLOW, sensitivity analysis is performed automatically resulting in histogram plot (Fig. 4.10). From the generated histogram, recharge shows sensitivity at some portions whilst hydraulic conductivity parameter is insensitive. The sensitivity in portions of recharge is observed in the peaks of the histogram bars, with the highest in the recharge zone of 170 (Fig. 4.10). The Parameter sensitivity information is useful in identifying the parameters that have the greatest effect on the model and those parameters that have little or no effect on the model. Thus, it provides indications of whether a numerical model will be stable or not, under a given range of changes to the input parameter. In this study, sensitivity analysis was automated and performed for hydraulic conductivity and recharge. The model is stable to hydraulic conductivity and recharge parameters, except in a few locations (recharge zone 170 from Fig 4.10) where isolated pilot points for recharge field show quite high sensitivities, the model is stable recharge parameters and as such, very useful.

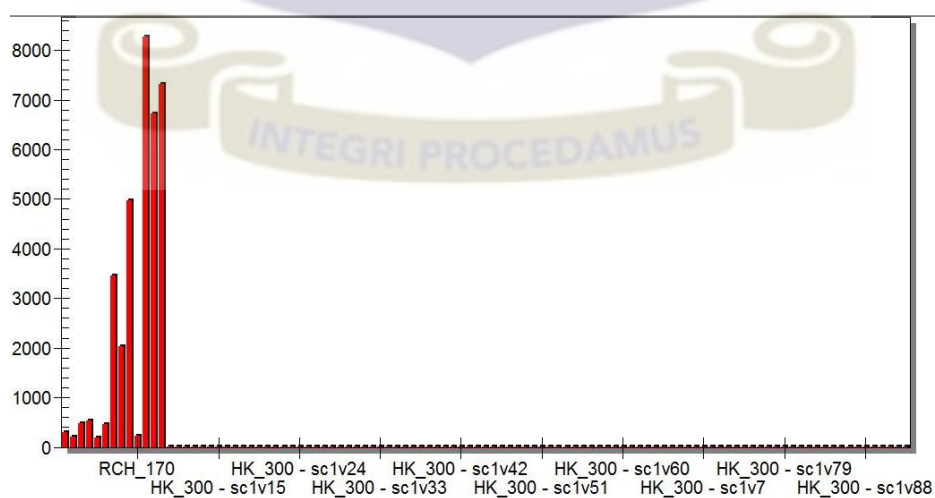


Figure 4.10: Sensitivity plot of calibrated steady state model.

#### 4.1.5 Groundwater Modelled Mass Water balance summary

##### 4.1.5. 1 Steady State

The water budget analysis is a conservation of mass approach, which accounts for all the inputs and outputs to the system. From the computed water balance of this study, the volume of water entering the basin aquifers is mainly through rainfall recharge with some recharge contribution from rivers. The simulated groundwater recharge rate in the area is 1,085,430.59 m<sup>3</sup>/day, which is a basin wide quantitative recharge of 1.1 million m<sup>3</sup>/day. The groundwater recharge rate was obtained through calibration under steady state conditions. This represents 4.0% of the annual precipitation representative of the entire model domain (Table 4.1). The base flow obtained by this simulation is 232,600.32 m<sup>3</sup>/day. The stream flow rates computed by the model in this study were therefore used as the estimated flow rates in the area. The basin wide quantitative regional groundwater flow computed from the model is 852,830.27 m<sup>3</sup>/day and was obtained by subtracting the baseflow from the recharge. The water balance shows that the river drains 286306.7 m<sup>3</sup>/day of the aquifer's water.

Table 4.1: Groundwater budget of the modelled domain under steady state condition.

Location / Source	Inflow (m <sup>3</sup> /d)	Outflow (m <sup>3</sup> /d)	Difference (m <sup>3</sup> /d)	Percent Discrepancy (%)
<b>Head Dependent Flows</b>	11781429.47	12629155.99	-847726.52	
<b>Rivers</b>	82429.02	315029.34	-232600.32	
<b>Pumping wells</b>		5280.60	-5280.60	
<b>Recharge</b>	1085430.59		1085430.59	
<b>Total</b>	12949289.08	12949465.93	-176.85	-0.001

## 4.1.6 Stochastic Simulations of Groundwater Flow

### 4.1.6.1. Parameter Randomization Approach

Stochastic simulation was carried out to determine the uniqueness of the calibrated steady state model. Parameters for recharge and hydraulic conductivity zones were sampled simultaneously for a specified distribution of 20 realizations. Though slight differences were observed from the hydraulic heads obtained from results from the stochastic simulations, there were no significant differences in the hydraulic and recharge parameters.

Thus, hydraulic conductivity and recharge rate values were similar for all twenty realizations. Again from the statistical analysis, observed standard deviations for the entire terrain (Fig. 4.11) generally shows low standard deviation heads (between the ranges of 0.05 to 0.41). However, at the southeastern corner of the study area, standard deviations, range from 0.53 to 0.85. These standard deviations indicate that the data points are very close to the mean or expected value and are not variable in space or time. Thus, little or no variations exist for the aquifer hydraulic parameters used in the steady state simulation.

This shows that the steady state model is unique for hydraulic conductivity and recharge, and hence, provides sufficient information to assist in the regional hydrogeological characterization of the aquifer. Since all the twenty solutions obtained from the stochastic modelling have similar outcome, only ten outputs are displayed as shown in Figs: 4.12- 4.21, displaying hydraulic heads and their respective hydraulic parameter per each realization.

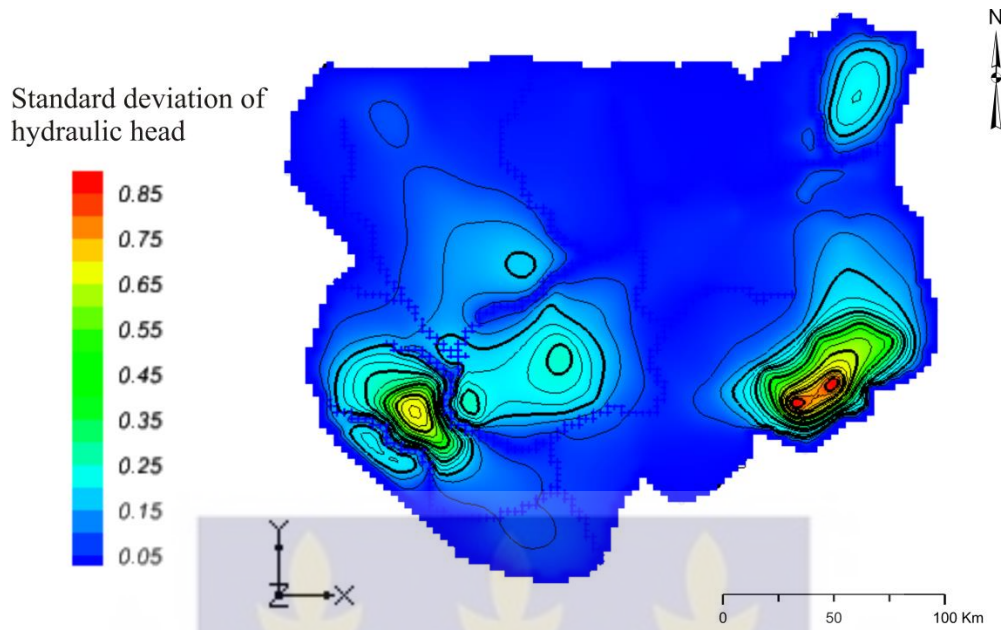


Figure 4.11: Map showing the standard deviations of hydraulic head from stochastic simulation.

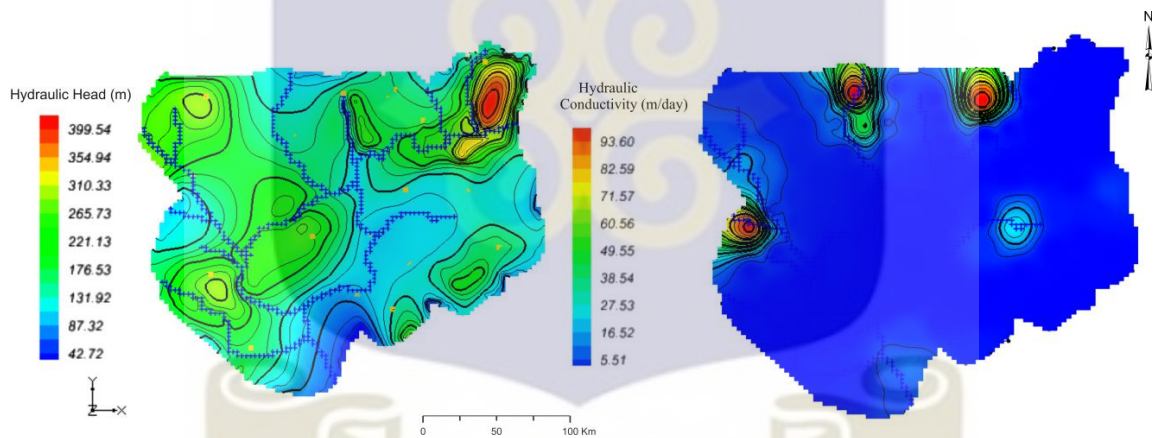


Figure 4.12: Map showing the hydraulic head and hydraulic conductivity fields from stochastic simulation for first realization.

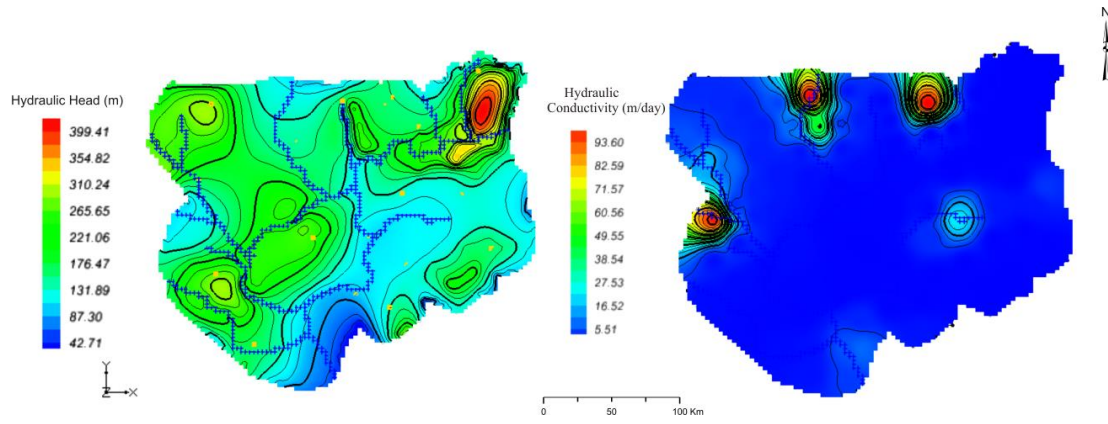


Figure 4.13: Map showing the hydraulic head and hydraulic conductivity fields from stochastic simulation for second realization.

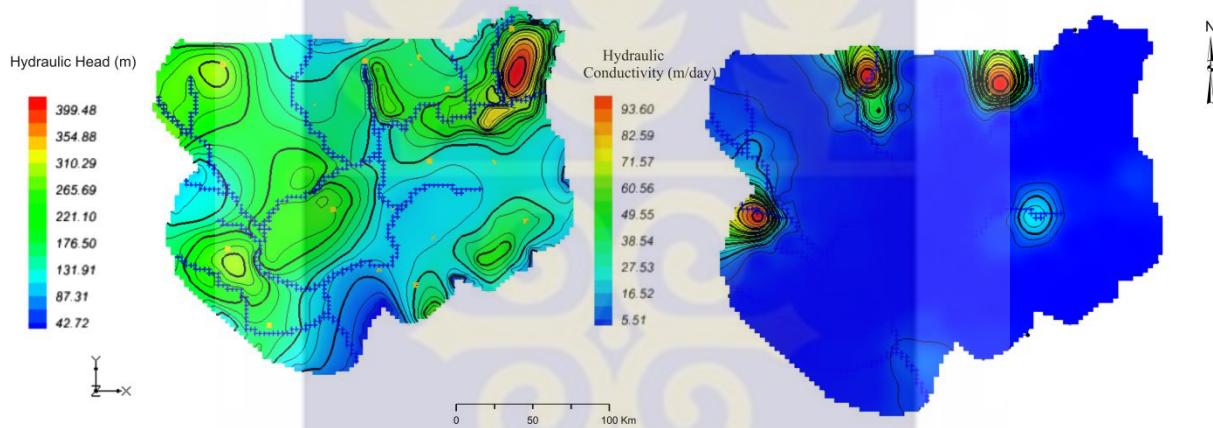


Figure 4.14: Map showing the hydraulic head and hydraulic conductivity fields from stochastic simulation for third realization.

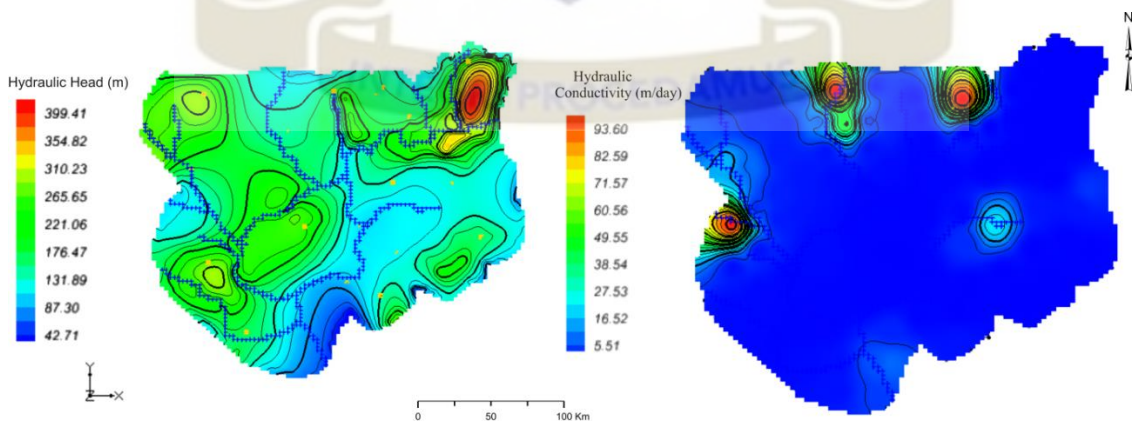


Figure 4.15: Map showing the hydraulic head and hydraulic conductivity fields from stochastic simulation for fourth realization.

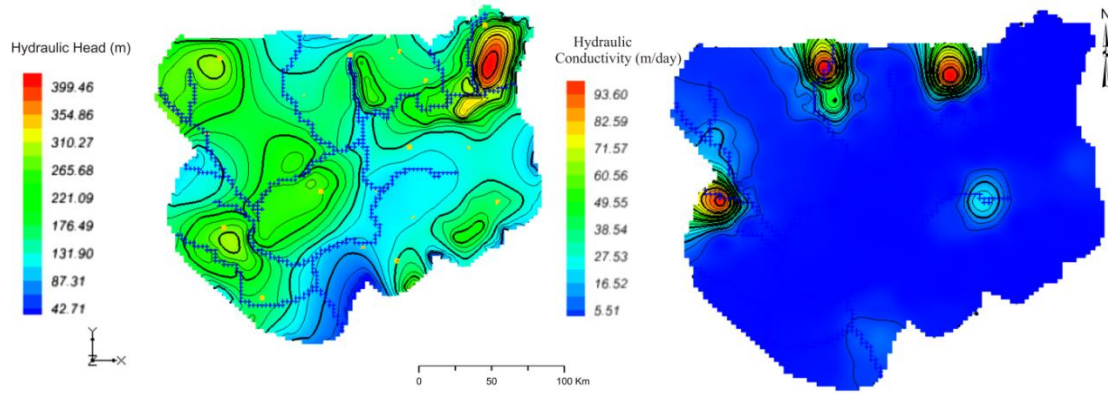


Figure 4.16: Map showing the hydraulic head and hydraulic conductivity fields from stochastic simulation for the fifth realization.

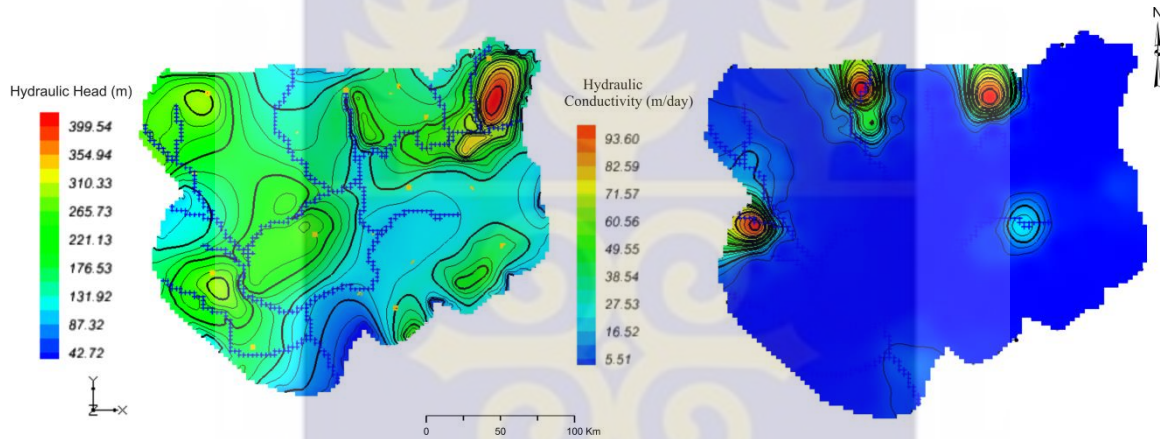


Figure 4.17: Map showing the hydraulic head and hydraulic conductivity fields from stochastic simulation for the sixth realization.

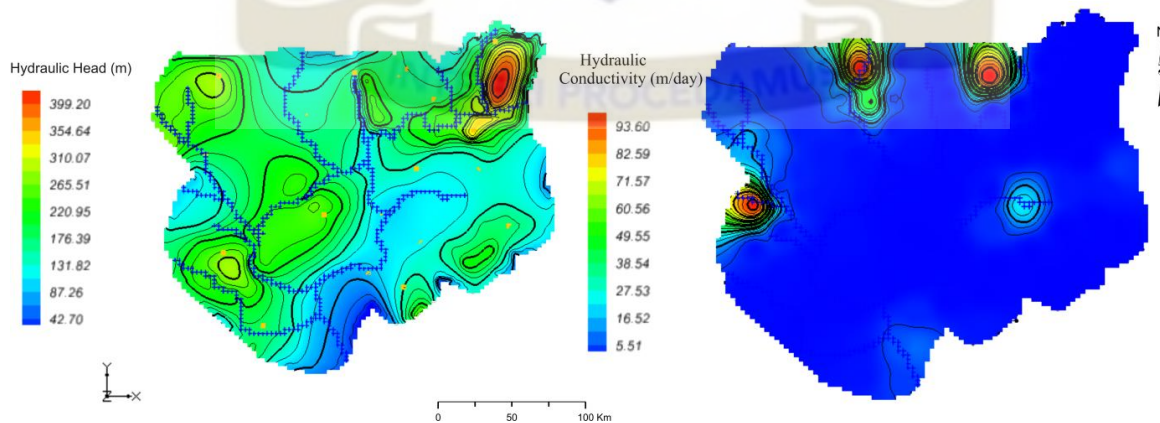


Figure 4.18: Map showing the hydraulic head and hydraulic conductivity fields from stochastic simulation for the seventh realization.

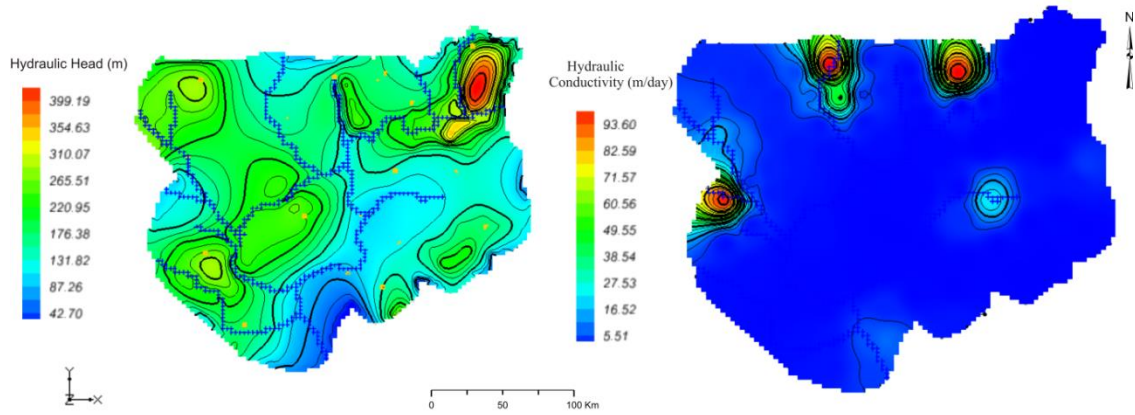


Figure 4.19: Map showing the hydraulic head and hydraulic conductivity fields from stochastic simulation for the eighth realization.

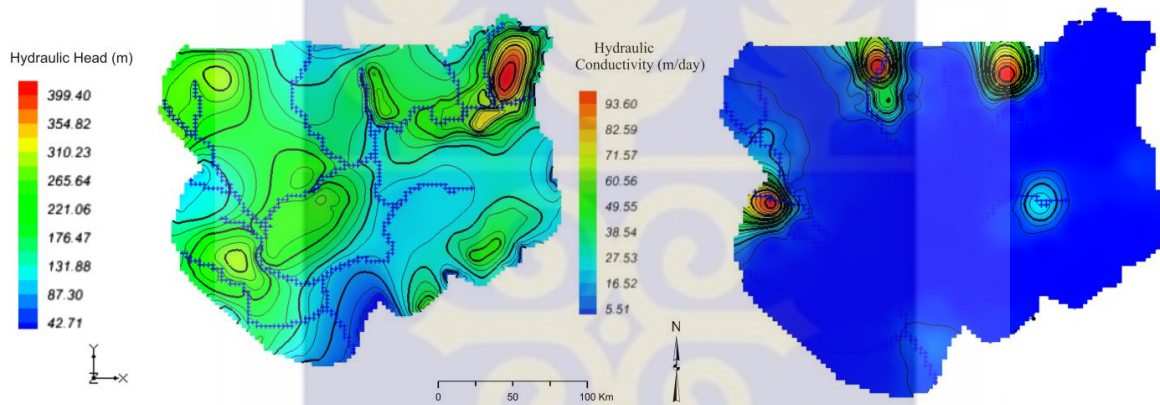


Figure 4.20: Map showing the hydraulic head and hydraulic conductivity fields from stochastic simulation for the ninth realization.

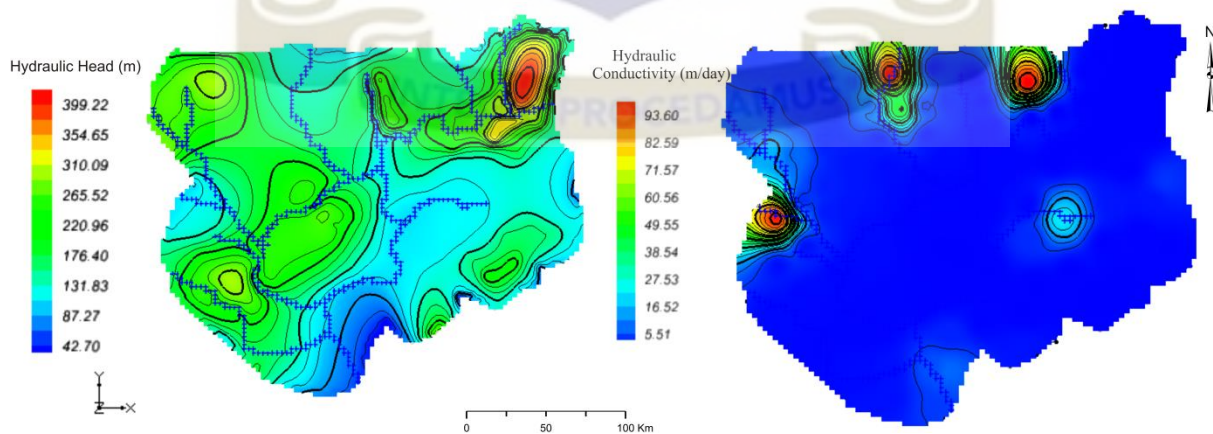


Figure 4.21: Map showing the hydraulic head and hydraulic conductivity fields from stochastic simulation for the tenth realization

#### 4.1.7 Scenario Analysis

The scenarios simulated using the calibrated steady state model in this study involved decreasing recharge and increasing groundwater abstraction from all the production wells above the current abstraction rates. These were done under stochastic mode and the effects were observed on changes in the model computed and observed heads as well as the general configuration of the flow system in the terrain. For the first scenario, recharge rates estimated at steady state were kept constant whilst increasing groundwater abstractions for all wells by 10%, 20%, 30%, 50%, 100% and 200%. The idea behind this was to determine the extent of change on the hydraulic heads with an increase in population size and groundwater over abstraction from aquifers as recharge to the basin is maintained in the subsequent years. The analysis suggested that under the current recharge rates (0.0008 – 0.046) m/year, the system can sustain increasing groundwater abstraction rates (Table 3.2) by up to 200% with minimal drawdown in the hydraulic head for the entire terrain (Figs. 4.22 - 4.28). This suggests that the system under the current conditions of groundwater recharge can sustain an increment in groundwater abstraction by up to twice the current abstraction rate with negligible effect on the system.

This scenario is obvious when all domestic and industrial water needs are served by groundwater from the pumping wells in the study area. With the present 2.5% increase in population in the Northern sector, if groundwater is being abstracted to serve the population domestic and industrial needs, the outcome suggest that the system can sustain annual incremental population demands for ten years at the current calibrated groundwater recharge rates. Furthermore, the outcome implies that the aquifer holds significant fortunes for large-scale abstraction to support irrigation schemes.

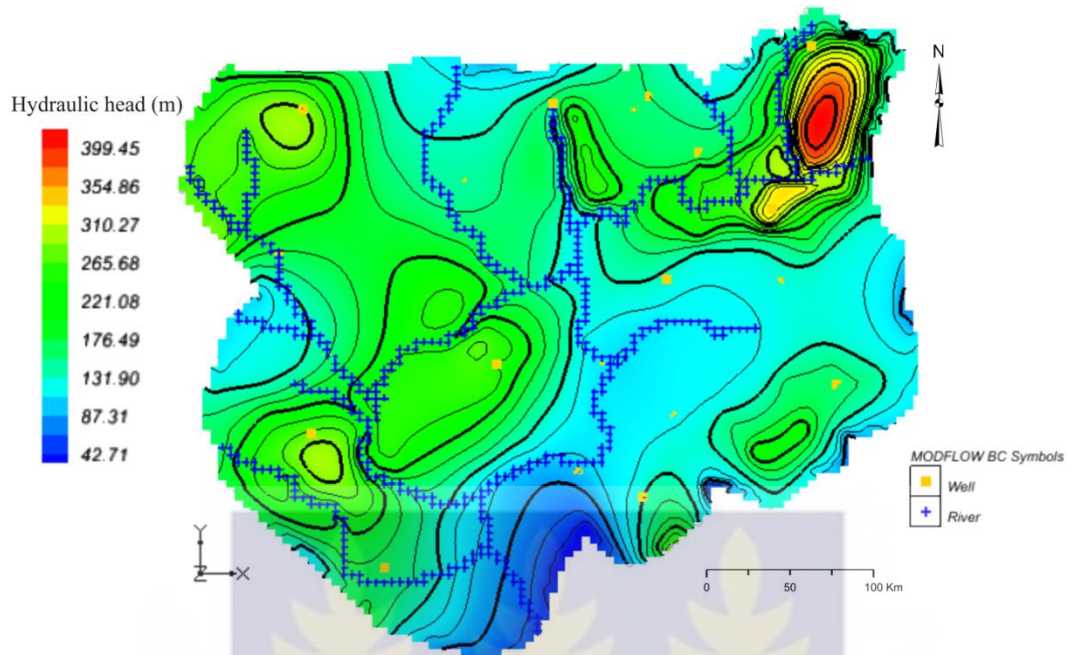


Figure 4.22: Map showing Hydraulic head distribution after 10% increment in groundwater abstraction

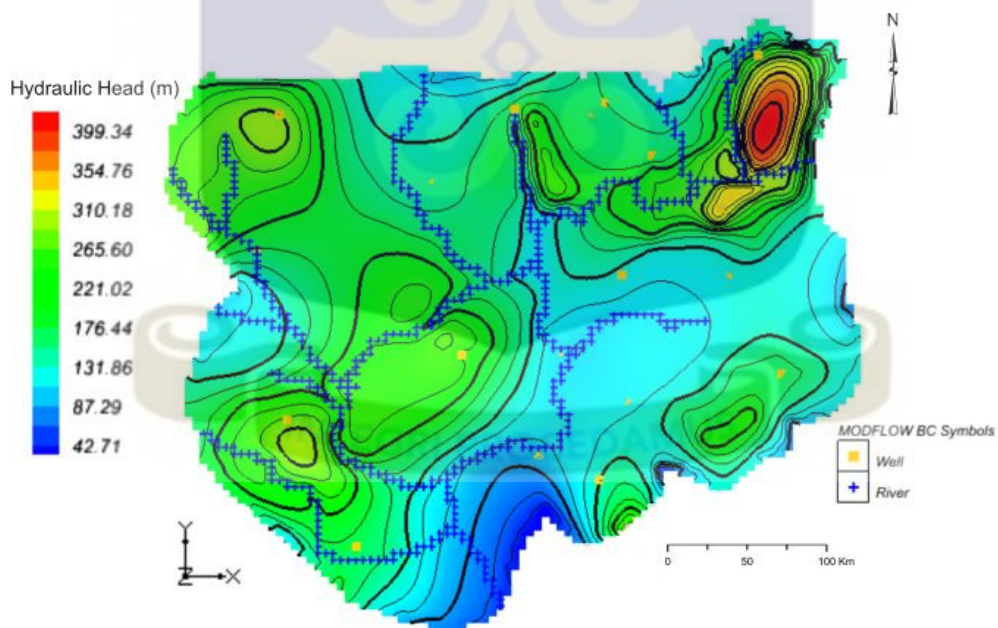


Figure 4.23: Map showing Hydraulic head distribution after 20% increment in groundwater abstraction.

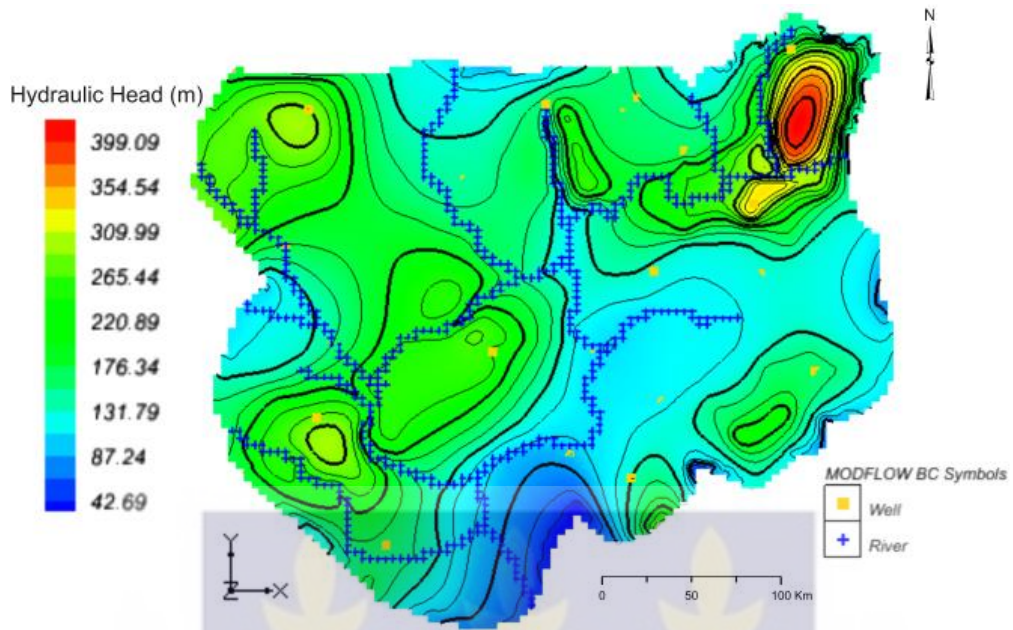


Figure 4.24: Map showing Hydraulic head distribution after 30% increment in groundwater abstraction.

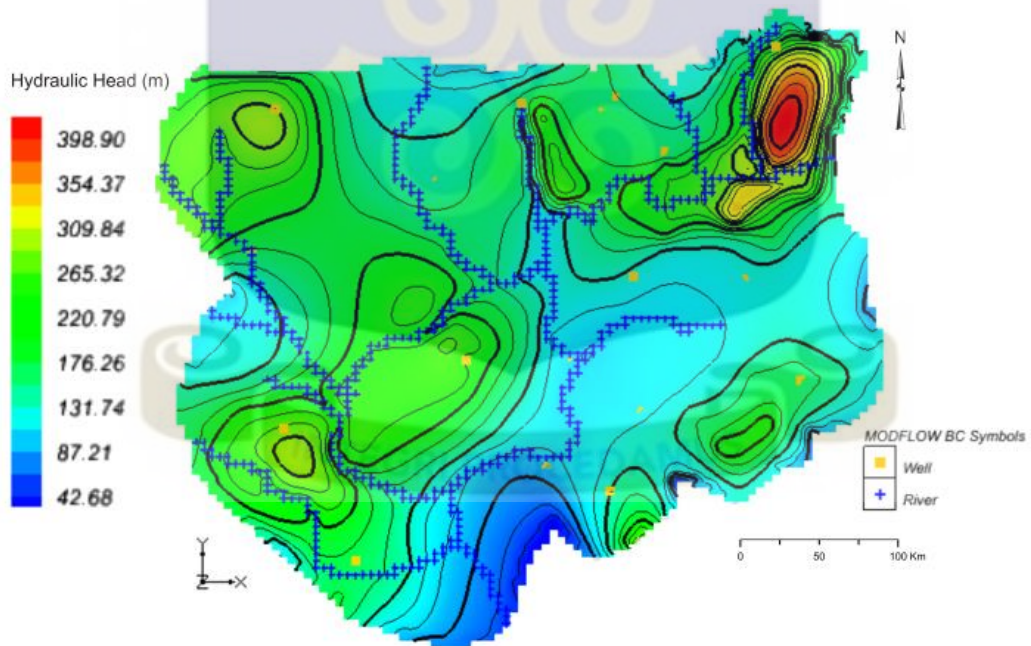


Figure 4. 25: Map showing Hydraulic head distribution after 40% increment in groundwater abstraction.

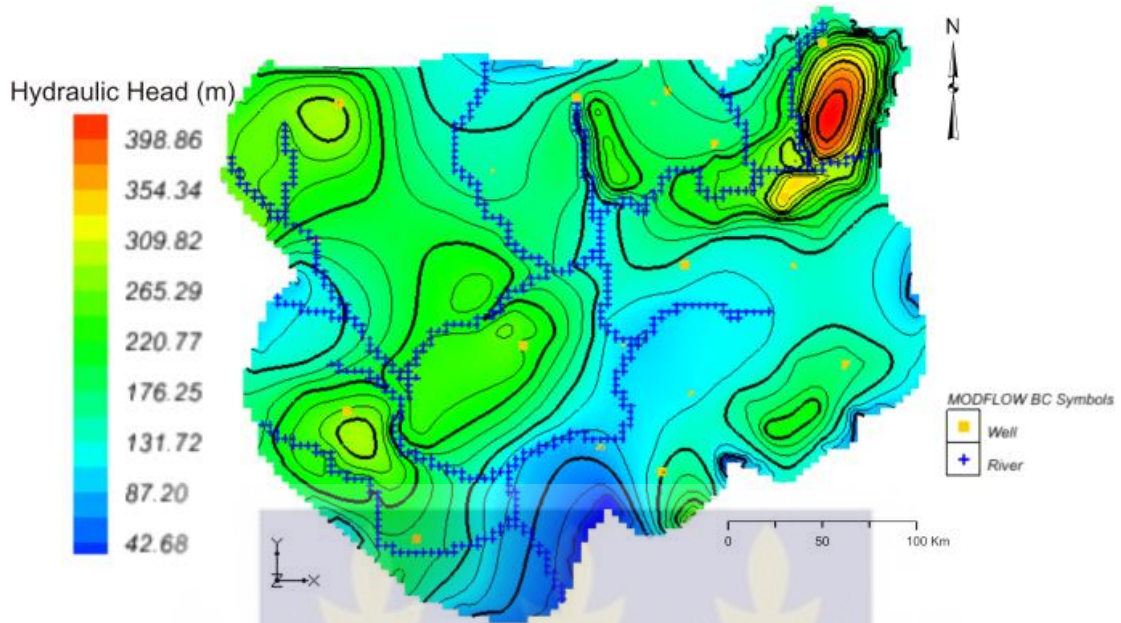


Figure 4.26: Map showing Hydraulic head distribution after 50% increment in groundwater abstraction.

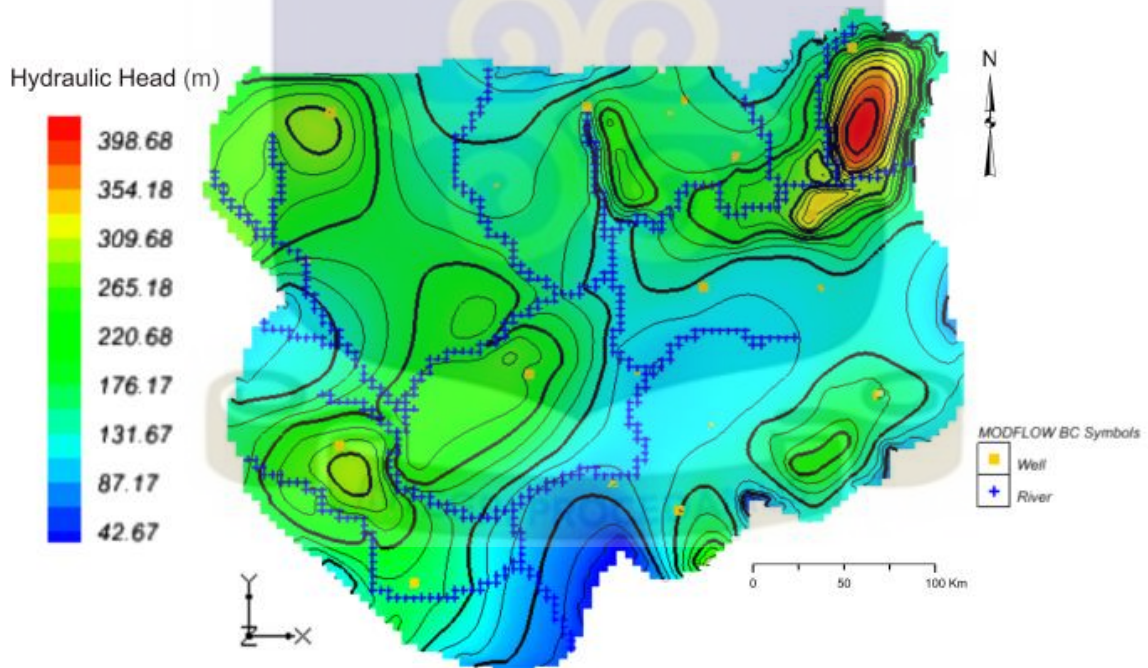


Figure 4.27: Map showing Hydraulic head distribution after 100% increment in groundwater abstraction.

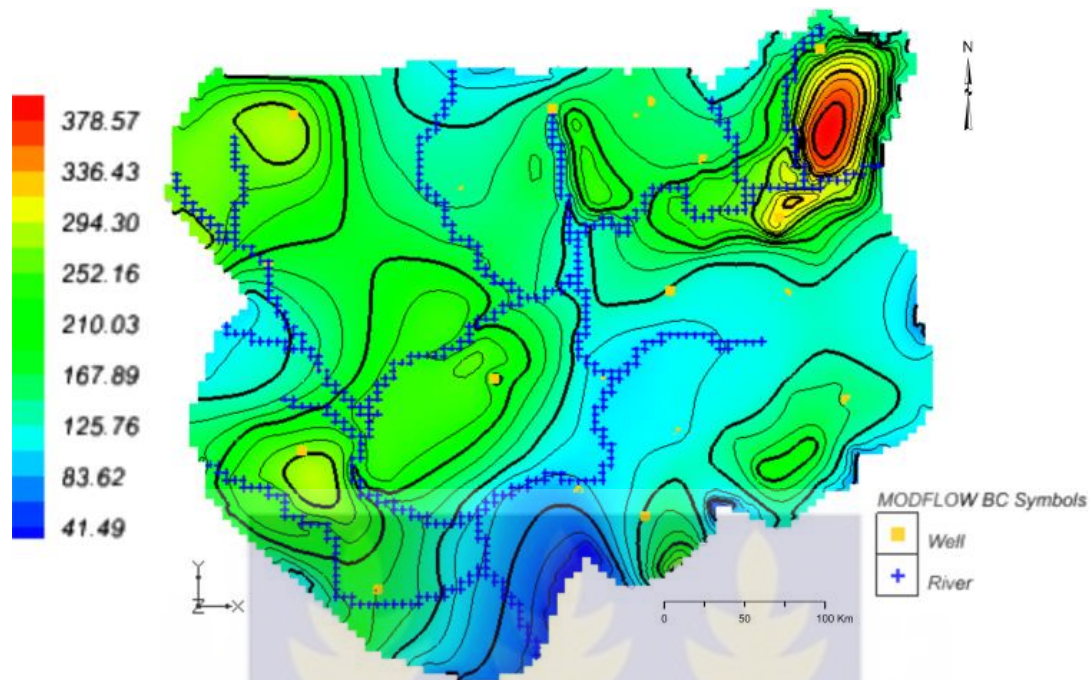


Figure 4.28: A map showing Hydraulic head distribution after 200% increment in groundwater abstraction.

For the second scenario, the groundwater abstraction rates obtained at the calibrated steady state remained constant whilst groundwater recharge was successively reduced by 10%, 20%, 30%, 50% and 85%. The implication of the observation is that it is expected that rainfall patterns will decline as a result of variability in climatic conditions which might be linked to the current erratic patterns in the spatial and temporal distribution in the rainfall patterns in the area. It is therefore expected that groundwater recharge from precipitation will decrease accordingly. When the groundwater recharge was successively reduced by 10%, 20%, 30%, 40% and 50% at the current rate of yield during calibration, there was minimal net drawdown in hydraulic potential (Figs. 4.29- 4.33).

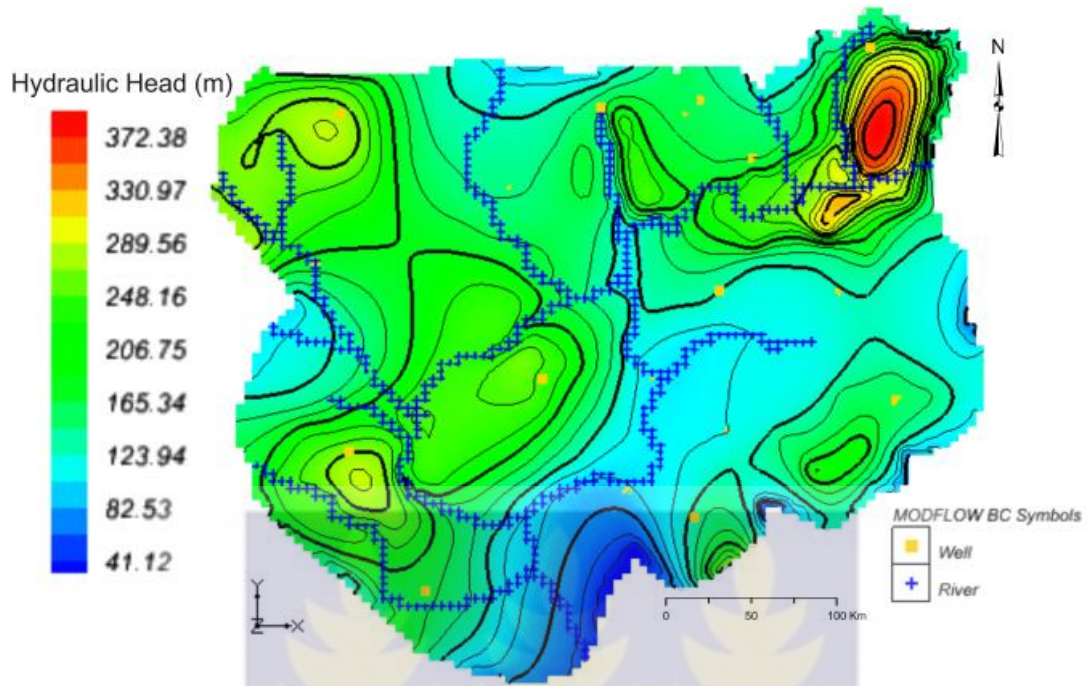


Figure 4.29: Map showing hydraulic head distribution after 10% reduction in groundwater recharge.

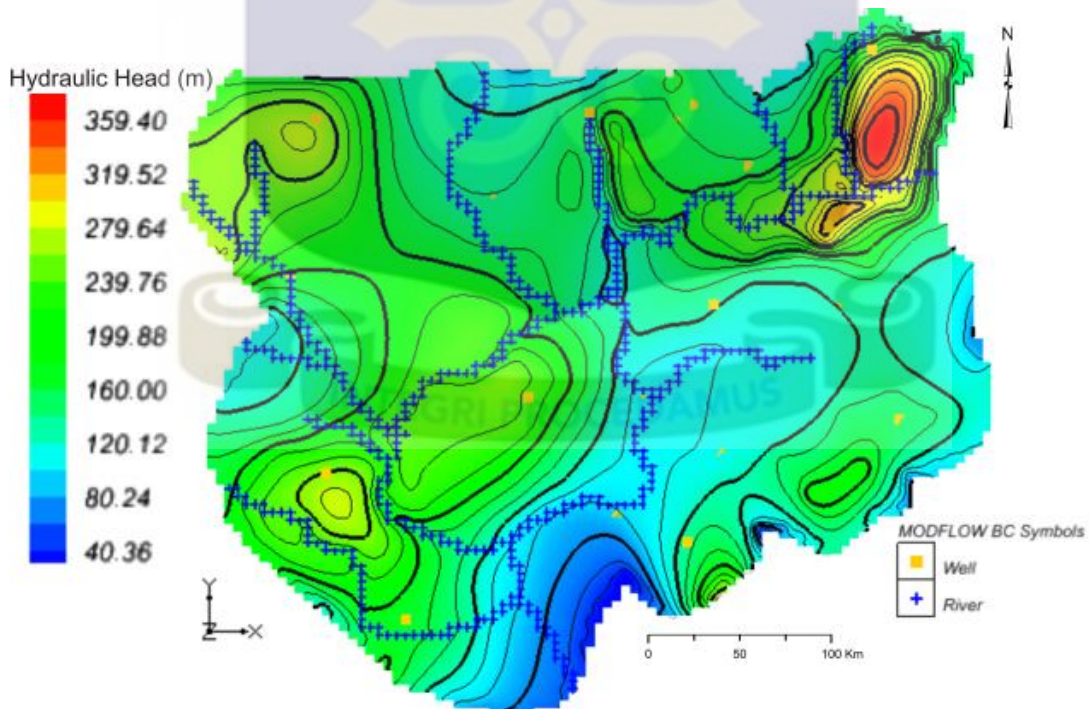


Figure 4.30: A map showing hydraulic head distribution after 20% reduction in groundwater recharge.

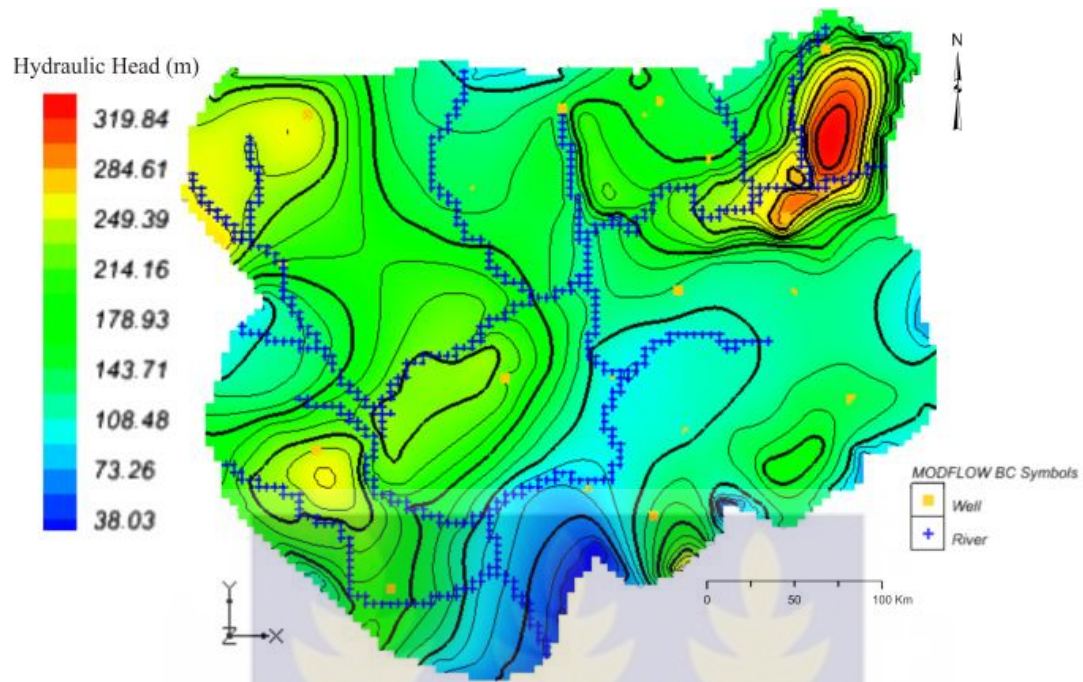


Figure 4.31: A map showing hydraulic head distribution after 30% reduction in groundwater recharge.

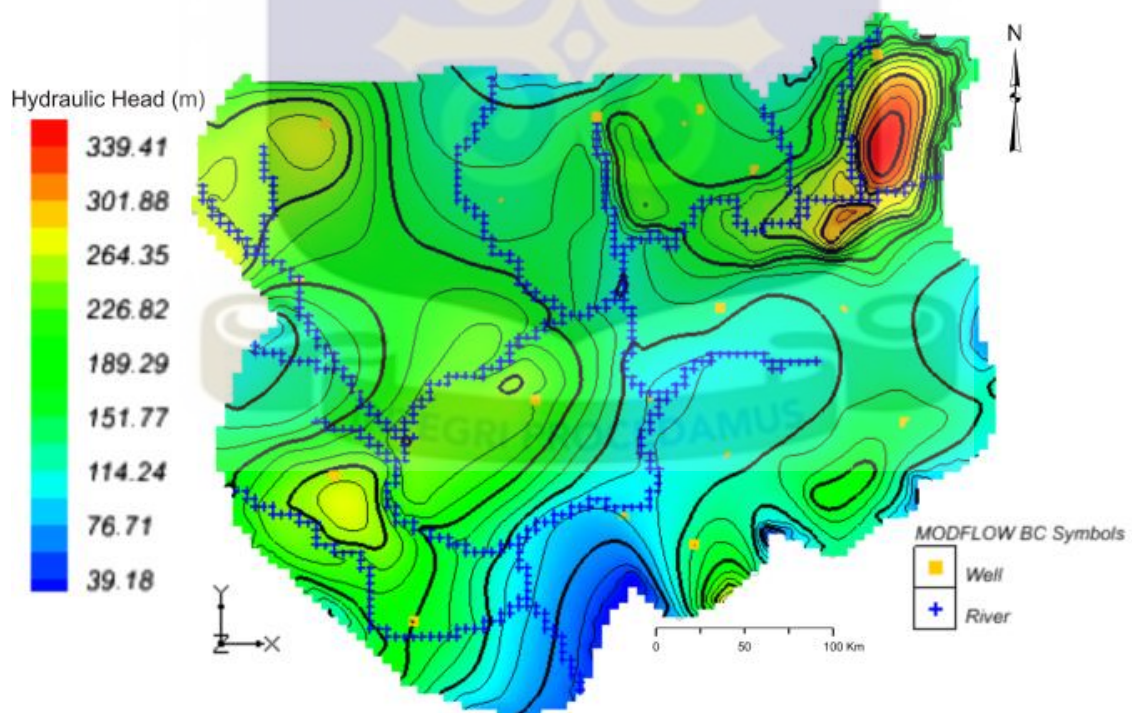


Figure 4.32: A map showing hydraulic head distribution after 40% reduction in groundwater recharge.

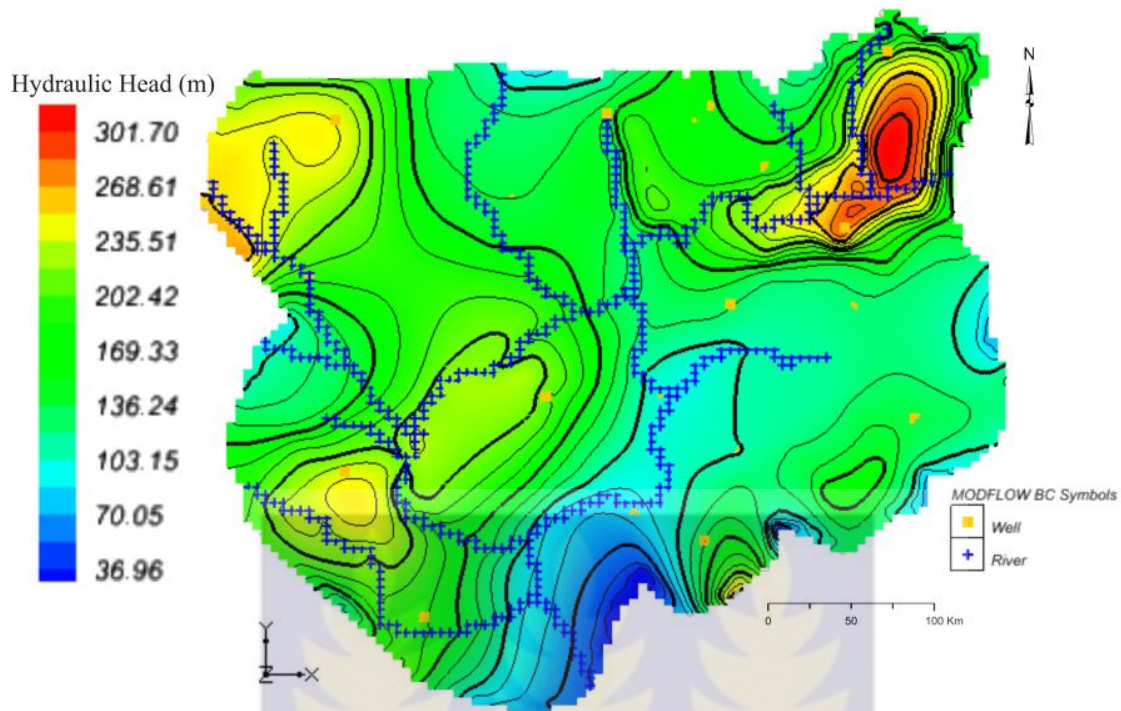


Figure 4.33: A map showing hydraulic head distribution after 50% reduction in groundwater recharge.

However, noticeable change was evident in the water level after 85% reduction in the groundwater recharge at the current groundwater abstraction rates in the terrain, while maintaining the general flow geometry. The 85% reduction in groundwater recharge resulted in drastic decline in hydraulic heads indicated by dry cells in the north-eastern and north-western portions of the study domain, specifically, the topographic highs as shown in Fig. 4.34., indicated by 'A' and 'B'. The insinuation of this observation is that climate change is likely to severely affect groundwater recharge rates from precipitation in the next few years.

Also, there are low annual relative humidities of the order 65% - 85% (Dickson and Benneh, 1995) during the raining seasons and even lower values during the dry months. These low values coupled with high temperatures encourage significant and potential evapotranspiration rates of surface impoundments and render them unsustainable as water sources for irrigation activities especially during the dry season months. Pelig-Ba (2009) using stable isotope

contents of surface and underground water for two main geological formations (Basement Complex and the Voltaian) in the Northern Region of Ghana, suggested that groundwater is recharged from local precipitation, but suffers evaporation during transit to the water table from the atmosphere. As such, infiltration to groundwater table is slow resulting in low recharge. In addition, Yidana (2013) using isotope and hydrochemical data from parts of the Voltaian Basin in northern Ghana proposed that groundwater recharge is reduced due to high evaporation of infiltrating rainwater.

Also, percolation to the aquifer is slowed by the presence of clay materials in the intervening lithologies. Results obtained from the above scenario, with regards to drastic reduction in groundwater recharge by 85% with subsequent 100% increment in abstraction will subsequently bring about significant drawdown in the hydraulic head, and thus affect the sustenance of ecosystem which depend on the on higher groundwater levels to function. With a decline in groundwater level, there is a possibility of sea water intrusion or groundwater contamination. Moreover, drastic decline in the hydraulic heads with time will consequently result in subsidence of the wells. Furthermore, with a drastic reduction in recharge to aquifers, some perennial streams which are recharged by the aquifers will dry up as there is evidence of hydraulic connection between surface flows and aquifers in the area as simulated in the steady state model.

For the third scenario, reduction in groundwater recharge by 10% with a subsequent increment in abstraction by 10%, 20%, 30%, 40%, 50% and 100% did not result in any adverse effect in the hydraulic. However, an increment in abstraction by 100% with a reduction in groundwater recharge by 85% ensued in significant hydraulic potential decline, as evident by dry cells in the north-western and north-eastern portions of the domain, specifically in the topographic highs as shown in Fig. 4.35., as 'A' and 'B'.

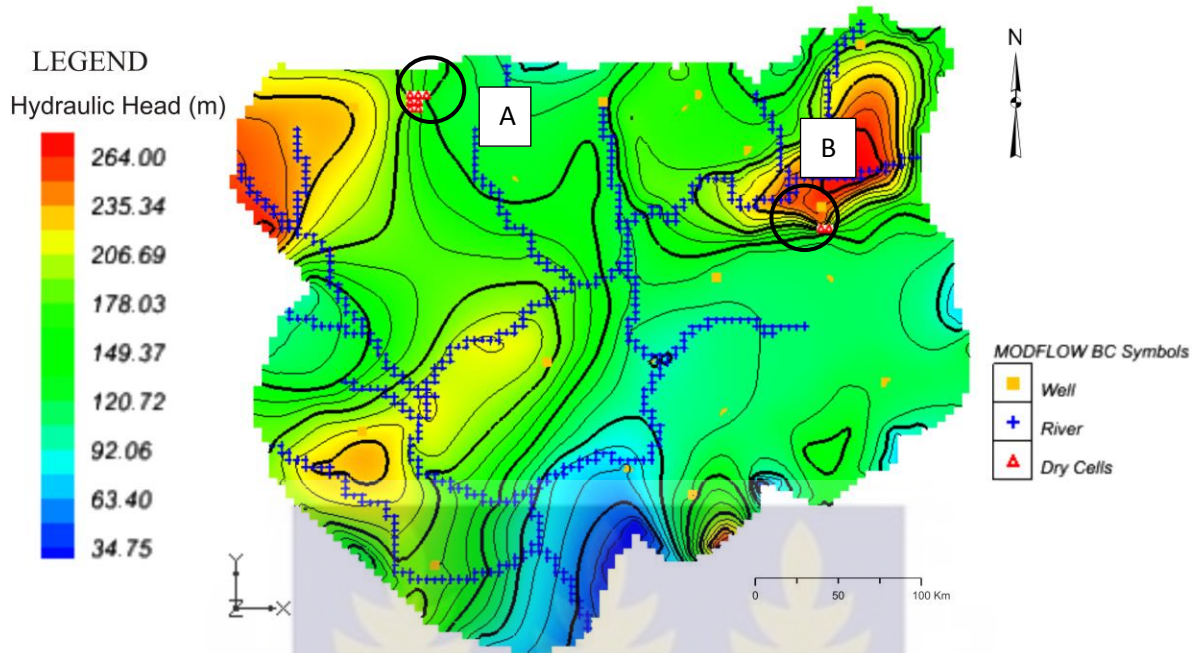


Figure 4.34: Map showing hydraulic head distribution after 85% reduction in groundwater recharge.

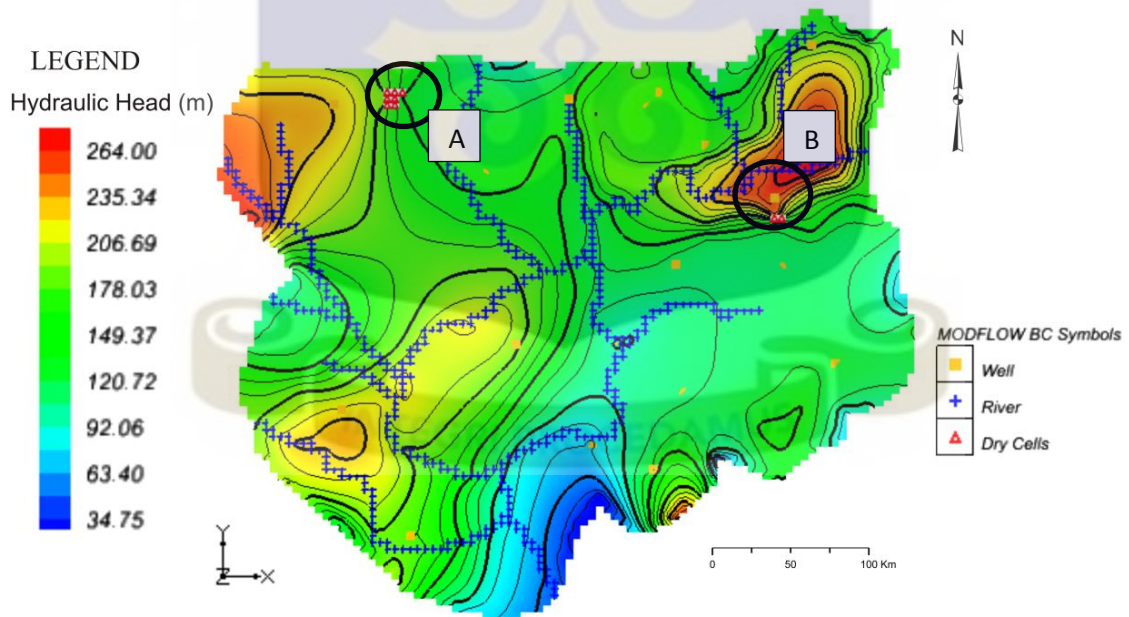


Figure 4.35: Map showing hydraulic head distribution after 85% reduction in groundwater recharge and 100% increment in abstraction.

The preceding scenarios suggest that the hydraulic potential of aquifers in the study basin exclusively relies on groundwater recharge. This shows that groundwater abstraction in the study domain is significantly limited by the duration of groundwater recharge received from precipitation. In addition, industrial and domestic water needs as well as commercial groundwater mining for irrigation purposes will be limited by the amount of water that is received as recharge from rainfall on an annual basis. Furthermore, in order to sustain commercial groundwater abstraction for irrigation activities, there is a need to encourage artificial groundwater recharge through deliberate development of dugouts and other conduits suited for such purposes in the study area.



## CHAPTER FIVE

### CONCLUSION AND RECOMMENDATION

#### 5.1. Conclusion

This current research or study on the White Volta Basin of Ghana provides new insight about its hydrogeological characterization of the basin. This is through, lithostratigraphic modelling, steady state numerical model, stochastic simulations and scenario analysis on groundwater flow. The importance of the study is to define the lithological and aquifer units of the basin, estimate aquifer hydraulic properties and provide an effective groundwater resources management of the basin. These insights are paramount both to the scientific community and policy maker concerning groundwater management. Integrating the objectives of this research, obtained results and discussion, the following conclusions are drawn;

The calibrated steady-state conditions for the average period of 2005 and 2012 suggests average recharge estimates of 0.023 m/yr. representing 4.0% of the average annual precipitation representative of the three regions (50% of northern, upper-east and 70% of upper-west). Variations in recharge rate estimates are due to the presence of different lithological units arising from the Birimian Basement complex and the Voltaian structural units with different structural overprints, evolutionary history and deformation events. Despite the differences, the average recharge of the mean annual rainfall suggests high the groundwater potential to support various irrigation projects.

The model computed aquifer hydraulic conductivity ranges between estimates lower than 5.51m/day to 98m/day. The low hydraulic conductivity is recorded in the central and southeastern portions of the study, specifically, the Voltaian aquifers, while the highest

values were observed in the northern and north-western part of the domain, representing the Birimian Basement aquifers.

Although, the groundwater recharge computed by the model suggests groundwater potential in the study area (4% of the mean annual rainfall), this groundwater resource is likely to reduce as a result of climate variability and changes as predicted by the various scenarios of reductions in the groundwater recharge.

Stochastic models simulated for recharge and hydraulic parameters produced similar results, highlighting the uniqueness and certainty of the steady state model.

## **5.2. Recommendation**

All though the estimated groundwater recharge and the various predictions suggest a promise for commercial development of groundwater resources in the White Volta River Basin, Ghana, it is recommended that abstraction from the shallow semi-confined aquifers for irrigation purposes should not exceed the estimated annual groundwater recharge of  $2.30 \times 10^4 \text{ m}^3$  across the strip, in order to maintain the reliability of the aquifer.

Furthermore, it is recommended that the groundwater recharge zones of high hydraulic head identified in the basin be protected to safeguard the quality of groundwater in the area.

It is further recommended that in order to increase reliability of recharge estimates for the development of a decision support system for the effective management of groundwater resources in the White Volta River Basin, Ghana, integrated approach (chloride mass balance, soil moisture balance technique, water table fluctuation and environmental tracer

technique) in determining for the groundwater recharge rate methodologies should be employed to confirm the values estimated in this current research.

It is also recommended that extensive investigations are carried out to identify prominent local and regional groundwater sources and buffer zones created around these sources for protection so that the current observed recharge does not reduce on account of inundation resulting from development activities and urbanization.



## References

- Acheampong, S. Y., and Hess, J. W. (1998). Hydrogeologic and hydrochemical framework of the shallow groundwater system in the southern Voltaian Sedimentary Basin, Ghana. *Hydrogeology Journal*, 6(4), 527–537.
- Acheampong, S. Y., and Hess, J. W. (2000). Origin of the shallow groundwater system in the southern Voltaian Sedimentary Basin of Ghana: An isotopic approach. *Journal of Hydrology*, 233(1-4), 37–53. [http://doi.org/10.1016/S0022-1694\(00\)00221-3](http://doi.org/10.1016/S0022-1694(00)00221-3)
- Adomako, D., Osae, S., Akiti, T. T., Faye, S., and Maloszewski, P. (2010). Geochemical and isotopic studies of groundwater conditions in the Densu River Basin of Ghana. *Environmental Earth Sciences*, 62(5), 1071–1084. <http://doi.org/10.1007/s12665-010-0595-2>
- Adu.S.D., and Asiamah. R.D. (1992). Soils of the Ayensu-Densu Basin, Central, Eastern and Greater Accra region, Ghana., *Memoir 9*.
- Affaton, P. (2008). Lithostratigraphy of the Volta Basin and related structural units. In *The Voltaian Basin, Ghana. Workshop and Excursion, March 10–17, 2008, Abstract Volume* (Kalsbeek, pp. 13–17). Geological Survey of Denmark and Greenland in Copenhagen.
- Affaton, P., Rahaman, M. A., Trompette, R., and Sougy, J. (1991). The Dahomeyide Orogen: Tectonothermal Evolution and Relationships with the Volta Basin. In: Dallmeyer, R.D., Lecorche, J.P. (Eds), *The West African Orogens and Circum-Atlantic Correlatives*. Springer-Verlag, Berlin, 107–122.
- Affaton, P., Sougy, J. and Trompette, R. (1980). The tectono-stratigraphic relationships between the Upper Precambrian and Lower Paleozoic Volta Basin and the Pan-African Dahomeyide Orogenic Belt (West Africa). *Amer. J. Sci*, 280, 224–248.

- Affaton, P. (1990). Le Bassin des Volta (Afrique de l'Ouest): une marge passive, d'âge protérozoïque supérieur, tectonisée au Panafricain ( $600 \pm 50$  Ma). *Editions de l'ORSTOM, Collection Etudes et Thèses*, 500.
- Agyenim, J. and Gupta, J. (2011). The Evolution of Ghana's Water Law and Policy. *Review of European Community and International Environmental Law*, 19(3), 339–350.
- Ahmed, S., David, K. S., and Gerald, S. (2005). Estimating water budget in a regional aquifer using HSPF-MODFLOW integrated model. *Engineering*, 1–42.
- Allison, G. B., GEE, G. W., and Tyler, S. W. (1994). Vadose-Zone Techniques for Estimating Groundwater Recharge in Arid and Semiarid Regions. *Soil Science Soc. Am. J*, 58.
- Anderson, M. P., and Woessner, W. W. (1992). *Applied Groundwater Modelling: Simulation of Flow and Advective Transport*. Elsevier.
- Annan-Yorke, R. (1971). Geology of the Voltaian Basin (Summary of the Current Ideas), Special Bulletin for oil exploration. In J. E. Cudjoe (Ed.), (p. 29). Geological Survey Department, Accra, Ghana.
- Attandoh, N., Yidana, S. M., Abdul-Samed, A., Sakyi, P. A., Banoeng-Yakubo, B., and Nude, P. M. (2013a). Conceptualization of the hydrogeological system of some sedimentary aquifers in Savelugu-Nanton and surrounding areas, Northern Ghana. *Hydrological Processes*, 27(11), 1664–1676. <http://doi.org/10.1002/hyp.9308>
- Bak, P. R. G., and Mill, A. J. B. (1989). Three dimensional representation in a Geoscientific Resource Management System for the minerals industry. In J. Raper (Ed.), *Three dimensional Application in GIS* (pp. 155–182). New York: Taylor and Francis.
- Bannerman, R. R., and Ayibotele, N. . (1984). Some critical issues with monitoring crystalline rock aquifers for groundwater management in rural areas. *IAHS-AISH*.

- Banoeng-Yakubo, B., Yidana, S. M., Ajayi, J. O., Loh, Y., and Asiedu, D. (2010). Hydrogeology and groundwater resources of Ghana: A review of the hydrogeological zonation of Ghana. In M. McMann, J. (Ed.), *Potable Water and Sanitation* (ISBN 978-1, Vol. 5, pp. 1–27). Nova Science Publishers, Inc.
- Baratoux, L., Metelka, V., Naba, S., Jessell, M. W., Grégoire, M., and Ganne, J. (2011). Juvenile Paleoproterozoic crust evolution during the Eburnean orogeny (~2.2-2.0Ga), western Burkina Faso. *Precambrian Research*, 191(1-2), 18–45. <http://doi.org/10.1016/j.precamres.2011.08.010>
- Barazzuoli, P., Nocchi, M., Rigati, R., and Salleolini, M. (2008). A conceptual and numerical model for groundwater management: A case study on a coastal aquifer in southern Tuscany, Italy. *Hydrogeology Journal*, 16(8), 1557–1576. <http://doi.org/10.1007/s10040-008-0324-z>
- Barry, F., Ophori, D., Hoffman, J., and Canace, R. (2009). Groundwater flow and capture zone analysis of the Central Passaic River Basin, New Jersey. *Environmental Geology*, 56(8), 1593–1603. <http://doi.org/10.1007/s00254-008-1257-5>
- Barry, B., Obuobie, E., Andreini, M., Andah, W., and Pluquet, M. (2005). The Volta River basin, Assessment, Comprehensive Management, Water. *Water*, 1–187.
- Bayer, E., and Dooley, K. (1990). New techniques for the generation of subsurface models. , May 7–10, 243–248.
- Bear, J. and Verruijlit, A. (1987). *Modelling Groundwater Flow and Pollution*. Dordrecht, The Netherlands: Springer.
- Bessoles, B. (1977). Géologie de l’Afrique. Le craton Ouest-Africain. (p. 88). Paris: Mémoires BRGM.
- Birner, R., Mccarthy, N., Robertson, R., Waale, D., and Schiffer, E. (2010). Increasing Access to Irrigation : Lessons Learned from Investing in Small Reservoirs in Ghana.

- Boronina, A., Renard, P., Balderer, W., and Christodoulides, A. (2003). Groundwater resources in the Kouris catchment (Cyprus): data analysis and numerical modelling. *J. of Hydrology*, 271, 130–149.
- Bozhko, N.A. (1969). Subdivision and correlation of Upper Precambrian deposits of the African Platform. *Vestnik Moscovskogo Universiteta, Geology Series N2, (in Russian)*, 21–34.
- Bredehoeft, J. (2005). The conceptualization model problem-surprise. *Hydrogeology Journal*, 13(1), 37–46.
- Brookfield, A. E., Blowes, D. W., and Mayer, K. U. (2006). Integration of field measurements and reactive transport modelling to evaluate contaminant transport at a sulfide mine tailings impoundment. *Journal of Contaminant Hydrology*, 88(1-2), 1–22. <http://doi.org/10.1016/j.jconhyd.2006.05.007>
- Carney, J., Jordan, C., Thomas, C., and McDonell, P. (2008). A revised lithostratigraphy and geological map for the Volta Basin, derived from image interpretation and field mapping. In *Voltain Basin, Ghana Workshop and Excursion, Ghana*. (pp. 19–24). Geological Survey of Denmark and Greenland in Copenhagen.
- Carrier, M., Lefebvre, R., Racicot, J., and Asare, E. . (2008a). Groundwater recharge assessment in northern Ghana using soil moisture balance and chloride mass balance, 1437–1444.
- Carrier, M., Lefebvre, R., Racicot, J., and Asare, E. B. (2008b). Northern Ghana hydrogeological assessment project.
- Clark, I., and Fritz, P. (1997). *Environmental Isotopes In Hydrogeology*. New York: Lewis Publishers.

- Codjoe, S. N. A. (2004). Population and land use/cover dynamics in the Volta River Basin of Ghana, 1960–2010. PhD Thesis. *Ecology and Development Series, No. 15*(Cuvillier Verlag Göttingen), p. 184.
- Cole, B. E., and Silliman, S. E. (2000). Utility of Simple Models for Capture Zone Delineation in Heterogeneous Unconfined Aquifers. *Ground Water*, 38(5), 665–672. <http://doi.org/10.1111/j.1745-6584.2000.tb02702.x>
- Cook, P. G., and Herczeg, A. L. (2000). *Environmental Tracers in Subsurface Hydrology*. Kluwer Academic Publishers. Boston.
- Cooper, M. (2010). Advanced Bash-Scripting Guide An in-depth exploration of the art of shell scripting Table of Contents. *Okt 2005 Abrufbar Uber Httpwww Tldp orgLDPabsabsguide Pdf Zugriff 1112 2005*, 2274(November 2008), 2267–2274. <http://doi.org/10.1002/hyp>
- Crosbie, R. S., Binning, P., and Kalma, J. D. (2005). A time series approach to inferring groundwater recharge using the water table fluctuation method. *Water Resources Research*, 41(1), 1–9. <http://doi.org/10.1029/2004WR003077>
- Dapaah-Siakwan, S. and Gyau-Boakye, P. (2000). Hydrogeologic framework and borehole yields in Ghana. *Hydrogeology Journal*, 8(4), 405–416. <http://doi.org/10.1007/PL00010976>
- Darko, P. K. (2002). Estimation of Natural Direct Groundwater Recharge in Southwest Ghana Using Water Balance Simualtions, (1300 mm), 198–212.
- Darko, P. K., Dua, A. A., and Dapaah-Siakwan, S. (2003). Groundwater Assessment: An element of integrated Water Resources Management: the case of Densu River Basin. In *Technical Report for the Water Resources Commission, Accra, Ghana*.
- Deynoux, M., Affaton, P., Trompette, R., and Villeneuve, M. (2006). Pan-African tectonic evolution and glacial events registered in Neoproterozoic to Cambrian cratonic and

- foreland basins of West Africa. *Journal of African Earth Sciences*, 46(5), 397–426.  
<http://doi.org/10.1016/j.jafrearsci.2006.08.005>
- Dickson, K. A., and Benneh, G. (1995). *A New Geography of Ghana*. Longman Group UK Ltd. P. (Revised Ed).
- Don, C. N., Hang, N. T. M., Hiroyuki, A., Hiroyuki, Y., and Kenichi, K. (2006). Groundwater resources management under environmental constraints in Shiroishi of Saga plain, Japan. *Environmental Geology*, 49(4), 601–609.
- Dorm-Adzobu, C., and Ampomah, B. Y. (2013). Legislative and institutional reforms for water resources management in Ghana. *International Journal of Water Resources Development*, 00(0), 1–13. <http://doi.org/10.1080/07900627.2013.837359>
- Drellack, Jr. S. L., Prothro, L. B., and Gonzales, J. L. (2002). A Hydrostratigraphic Model of the Pahute Mesa - Oasis Valley Area, Nye County, Nevada. Retrieved from <http://www.osti.gov/bridge/purl.cover.jsp;jsessionid=2CEA54642832A20ECC0DC0B2F87C0A22?purl=/790074-mXJWJn/native/>
- Ebraheem, A. M., Garamoon, H. K., Riad, S., Wycisk, P., and Seif El Nasr, A. M. (2003). Numerical modeling of groundwater resource management options in the East Oweinat area, SW Egypt. *Environmental Geology*, 44(4), 433–447.  
<http://doi.org/10.1007/s00254-003-0778-1>
- Eisenlohr, B. N., and Hirdes, W. (1992). The structural development of the early Proterozoic Birimian and tarkwaian rocks of southwest Ghana, West Africa. *Journal of African Earth Sciences (and the Middle East)*, 14(3), 313–325. [http://doi.org/10.1016/0899-5362\(92\)90035-B](http://doi.org/10.1016/0899-5362(92)90035-B)
- El-Kadi, A. I., Oloufa, A. A., Eltahan, A. A., and Malik, H. U. (1994). Use of Geographic Information System in Site-Specific Ground-Water Modelling. *Ground Water*.

- Fabryka-Martin, J., Davis, S. N., and Elmore, D. (1987). Applications of  $^{129}\text{I}$  and  $^{36}\text{Cl}$  to hydrology. *Nucl. Instrum. Methods Phys. Res.*, B29, 361–371.
- FAO-UNESCO. (1994). *Soil map of the world – Revised Legend*. ISRIC, Roma: FAO; Technical paper 20. Wageningen, the Netherlands.
- Fayer, M. J., Gee, G. W., Rockhold, M. L., Freshley, M. D., and Walters, T. B. (1996). Estimating Recharge Rates for a Groundwater Model Using a GIS. *Journal of Environmental Quality*, 25(3), 510–518.
- Fetter, C. W. (2001). *Applied Hydrogeology* (4th ed.). Prentice Hall, New Jersey: Merrill Publishing Company.
- Fisher, T. R., and Wales, R. Q. (1990). 3D solid modeling of sandstone reservoirs using NURBS. *Geobyte* 5(1), 39–41.
- Fleming, S. W., and Haggerty, R. (2001). Modeling solute diffusion in the presence of pore-scale heterogeneity: Method development and an application to the Culebra dolomite Member of the Rustler Formation, New Mexico, USA. *Journal of Contaminant Hydrology*, 48(3-4), 253–276. [http://doi.org/10.1016/S0169-7722\(00\)00182-0](http://doi.org/10.1016/S0169-7722(00)00182-0)
- Freeze, R. A. and Cherry, J. A. (1979). *Groundwater*. Englewood Cliffs, New Jersey: Prentice-Hall.
- Ghana Statistical Service (GSS). (2002). 2000 Population and Housing Census. Summary Report on Final Results. *Medialite Co. Ltd., Accra*.
- Giesen, N. V. D., Andreini, M., Edig, A. V., and Vlek, P. (2001). Competition for water resources of the Volta basin. *Regional Management of Water Resources*, 1964(268), 199–205.
- Gjoystdal, H., Reinhardsen, J. E., and Astebol, K. (1985). Computer representation of complex 3-D geological structures using a new solid modeling technique. *Geophysical Prospecting*, 33, 1195–1211.

- Grubb, S. (1993). Analytical Model for Estimation of Steady-State Capture Zones of Pumping Wells in Confined and Unconfined Aquifers. *Ground Water*, 31(1), 27–32.
- Gyau-Boakye, P. (2001). Sources of Rural Water Supply in Ghana. *Water International*, 26(1), 96–104. <http://doi.org/10.1080/02508060108686890>
- Gyau-boakye, P. (2009). Sources of Rural Water Supply in Ghana Sources of Rural Water Supply in Ghana, (June 2015), 37–41. <http://doi.org/10.1080/02508060108686890>
- Gyau-Boakye, P., Kankam-Yeboah, K., Darko, P., K., and Dapaah-Siakwan, S. (2008). Groundwater as a vital resource for rural development: An example from Ghana. Water Research Institute, Accra, Ghana.
- Gyau-Boakye, P., and Tumbulto, J. W. (2006). Comparison of rainfall and runoff in the humid south-western and the semiarid northern savannah zone in Ghana.
- Hall, D. W., and Risser, D. W. (1993). Effects of agricultural nutrient management on nitrogen fate and transport in Lancaster county, Pennsylvania. *Water Resour, Bull* 29, 55–76.
- Harbaugh, A. W., Banta, E. R., Hill, M. C., and McDonald, M. G. (2000). *MODFLOW-2000, The United State Geological Survey Modular Ground-Water Model–User Guide to Modularization Concepts and the Groundwater Flow Processes. U.S. Geological Survey Open-File 00-92.*
- Harte, P. T., Konikow, L. F., and Hornberger, G. Z. (2006). Simulation of solute transport across low-permeability barrier walls. *Journal of Contaminant Hydrology*, 85(3-4), 247–270. <http://doi.org/10.1016/j.jconhyd.2006.02.012>
- Hastings, D. A. (1982). On the tectonics and the metallogenesis of West Africa: A model incorporating new geophysical data. *Geoexploration* 20, 295–327.

- He, B., Takase, K., and Wang, Y. (2008). Numerical simulation of groundwater flow for a coastal plain in Japan: Data collection and model calibration. *Environmental Geology*, 55(8), 1745–1753. <http://doi.org/10.1007/s00254-007-1125-8>
- Healy, R. W., and Cook, P. G. (2002). Using groundwater levels to estimate recharge. *Hydrogeology Journal*, 10(1), 91–109. <http://doi.org/10.1007/s10040-001-0178-0>
- Herzog, B. L., Larson, D. R., Abert, C. C., Wilson, S. D., and Roadcap, G. S. (2003). Hydrostratigraphic modeling of a complex, glacial-drift aquifer system for importation into MODFLOW. *Ground Water*, 41, 57–65.
- Houston, J. (1988). Rainfall - Runoff - Recharge Relationships in the Basement rocks of Zimbabwe. In I. Simmers (Ed.), *Estimation of Natural Groundwater Recharge* (pp. 349–365). Reidel, D. Publishing Company.
- Hu, L., Chen, C., and Chen, X. (2011). Simulation of groundwater flow within observation boreholes for confined aquifers. *Journal of Hydrology*, 398(1-2), 101–108. <http://doi.org/10.1016/j.jhydrol.2010.12.013>
- Hussein, M., and Schwartz, F. W. (2003). Modeling of flow and contaminant transport in coupled stream-aquifer systems. *Journal of Contaminant Hydrology*, 65(1-2), 41–64. [http://doi.org/10.1016/S0169-7722\(02\)00229-2](http://doi.org/10.1016/S0169-7722(02)00229-2)
- Igboekwe, M. U., and Achi, N. J. (2011). *Finite Difference Method of Modelling Groundwater Flow. Journal of Water Resource and Protection* (Vol. 03). Umudike, Nigeria. <http://doi.org/10.4236/jwarp.2011.33025>
- Illman, W. A., Liu, X., and Craig, A. (2007). Steady-state hydraulic tomography in a laboratory aquifer with deterministic heterogeneity: Multi-method and multiscale validation of hydraulic conductivity tomograms. *Journal of Hydrology*, 341(3-4), 222–234. <http://doi.org/10.1016/j.jhydrol.2007.05.011>

- Ivanovich, M., and Harmon, R. S. (1992). *Uranium Series Disequilibrium: Applications to Earth, Marine, and Environmental Sciences*. Oxford Science Publ.
- IWRMP. (2008). *Water Resources Commission White Volta River Basin. Integrated Water Resources Management Plan*.
- Jones, N. L., and Wright, S. G. (1993). Subsurface characterization with solid models. *American Society of Civil Engineers, Geotechnical Engineering Journal*, 119(11), 1823–1839.
- Junner, H. R. (1940). Geology of the Gold Coast and Western Togoland (with revised geological map). Gold Coast Geol. Surv. (Vol. Bull., I 1, p. p.40).
- Junner, N. R. (1935). *Gold in the Gold Coast*. (Vol. Mem., 4).
- Junner, N. R., and Hirst, T. (1946). The geology and hydrogeology of the Volta Basin. Gold Coast Geological Survey, Memoir 8. Accra.
- Kalbus, E., Reinstorf, F., and Schirmer, M. (2006). Measuring methods for groundwater – surface water interactions: a review. *Environmental Research*, 873–887.
- Karahanoglu, N., and Doyuran, V. (2003). Finite element simulation of seawater intrusion into a quarry-site coastal aquifer, Kocaeli-Dar?ca, Turkey. *Environmental Geology*, 44(4), 456–466. <http://doi.org/10.1007/s00254-003-0780-7>
- Kassenaar, D., Holysh, S., and Gerber, R. E. (2001). Integrated 3D hydrostratigraphic interpretation in complex aquifer systems. *Interpretation A Journal of Bible And Theology*.
- Kattan, Z. (2001). Use of hydrochemistry and environmental isotopes for evaluation of groundwater in the Paleogene limestone aquifer of the Ras Al-Ain area (Syrian Jazirah). *Journal of Environmental Geology*, 41, 128–144.
- Kazda, I. (1990). *Finite element techniques in groundwater flow studies with application in hydraulic and geotechnical engineering*. Amsterdam: Elsevier.

- Kendall, C., and McDonnell, J. J. (1998). *Isotope Tracers in Catchment Hydrology*. Elsevier, New York., 839.
- Kesse, G. O. (1985). *The Mineral and Rock Resources of Ghana*. (p. 9,44). Balkema, Rotterdam.
- Khan, S., Rana, T., Gabriel, H. F., and Ullah, M. K. (2008). Hydrogeologic assessment of escalating groundwater exploitation in the Indus Basin, Pakistan. *Hydrogeology Journal*, 16(8), 1635–1654. <http://doi.org/10.1007/s10040-008-0336-8>
- Kinzelbach, W. (1986). *Groundwater modelling: an introduction with sample programs in BASIC*. New York: Elsevier B.V.
- Konikow, L. F., and Reilly, T. E. (1998). Groundwater modelling . In *The handbook of groundwater engineering* (Delleur J., Vol. 20, pp. 1–20). CRC, Boca Raton.
- Kortatsi, B. K. (1994). Groundwater utilization in Ghana (pp. 149–156).
- Krautstrunk, M. L. (2012). An Estimate of Groundwater Recharge in the Nabogo River Basin , Ghana Using Water Table Fluctuation Method and Chloride Mass Balance.
- Kumar, C. (2002). Groundwater Flow Models. *Scientist “E1” National Institute of Hydrology Roorkee, 247667*.
- Kwei, C. A. (1997). Evaluation of groundwater potential in the Northern Region of Ghana. In *Report for the CIDA* (p. 66).
- Kyei-Baffour, N., and Ofori, E. (2005). *Irrigation Development And Management In Ghana : Prospects And Challenges*.
- Laube, W., Awo, M., and Schraven, B. (2008). Erratic Rains and Erratic Markets: Environmental change, economic globalisation and the expansion of shallow groundwater irrigation in West Africa., 18.

- Lemon, A. M., and Jones, N. L. (2003). Building solid models from boreholes and user-defined cross-sections. *Computers and Geosciences*, 29(5), 547–555. [http://doi.org/10.1016/S0098-3004\(03\)00051-7](http://doi.org/10.1016/S0098-3004(03)00051-7)
- Leprun, J. C., and Trompette, R. (1969). Subdivision du Voltaïen du massif de Gobnangou (République de Haute-Volta) en deux séries discordantes séparées par une tillite d'âge éocambrien probable. *Comptes Rendus de l'Académie Des Sciences, Paris*, 269, 2187–2190.
- Lerner, D. A., Issar, A. S., and Simmers, I. (Eds.). (1990). Groundwater Recharge. A guide to understanding and estimating natural recharge. *International Contributions to Hydrogeology, Vol. 8*, 245.
- Leube, A., Hirdes, W., Mauer, R., and Kesse, G. O. (1990). The early Proterozoic Birimian Supergroup of Ghana and some aspects of its associated gold mineralization. *Precambrian Research*, 46(1-2), 139–165. [http://doi.org/10.1016/0301-9268\(90\)90070-7](http://doi.org/10.1016/0301-9268(90)90070-7)
- Lin, J., Snodsmith, J. B., Zheng, C., and Wu, J. (2009). A modeling study of seawater intrusion in Alabama Gulf Coast, USA. *Environmental Geology*, 57(1), 119–130. <http://doi.org/10.1007/s00254-008-1288-y>
- Lutz, A., Thomas, J. M., Pohll, G., and McKay, W. A. (2007). Groundwater resource sustainability in the Nabogo Basin of Ghana. *Journal of African Earth Sciences*, 49(3), 61–70. <http://doi.org/10.1016/j.jafrearsci.2007.06.004>
- Majumdar, P. K., Ghosh, N. C., and Chakravorty, B. (2002). Analysis of arsenic-contaminated groundwater domain in the Nadia district of West Bengal (India). *Hydrological Sciences Journal*, 47(sup1), S55–S66. <http://doi.org/10.1080/02626660209493022>
- Martin, N. (2006). Development of a water balance for the Atankwidi catchment, West Africa climate. In *A case study of groundwater recharge in a semi-arid*. Cuvillier.

- Martin, N., and Van de Giesen, N. (2005). Spatial Distribution of Groundwater Production and Development Potential in the Volta River basin of Ghana and Burkina Faso. *Water International*, 30(2), 239–249. <http://doi.org/10.1080/02508060508691852>
- McDonald, M.G. and Harbaugh, A. W. (1988). A modular three dimensional finite difference flow model. In *Techniques of water resources investigations of the U.S. Geological Survey, Book 6* (p. 586).
- Mensah, F. O., Alo, C., and Yidana, S. M. (2014). Evaluation of Groundwater Recharge Estimates in a Partially Metamorphosed Sedimentary Basin in a Tropical Environment : Application of Natural Tracers, 2014.
- Moon, S., Woo, N. C., and Lee, K. . (2004). Statistical analysis of hydrographs and water-table fluctuation to estimate groundwater recharge, 292, 198–209. <http://doi.org/10.1016/j.jhydrol.2003.12.030>
- Moore, J. E. (2002). *Field Hydrogeology*. Florida: Lewis Publishers.
- Mukherjee, A., Fryar, A. E., and Howell, P. D. (2007). Regional hydrostratigraphy and groundwater flow modeling in the arsenic-affected areas of the western Bengal basin, West Bengal, India. *Hydrogeology Journal*, 15(7), 1397–1418. <http://doi.org/10.1007/s10040-007-0208-7>
- Murphy, E. M., Ginn, T. R., and Phillips, J. L. (1996). Geochemical estimates of paleorecharge in the Pasco Basin: Evaluation of the chloride mass balance technique. *Water Resources Research*, 32, 2853– 2968.
- MWH. (1998). Water Resources Management Study, Information “Building Block” Study. In *Volta Basin System, Groundwater Resources* (Vol. Part II). Ministry of Works and Housing, Accra.
- Namara, R. ., Horowitz, L., Nyamadi, B., and Barry, B. (2011). Irrigation Development in Ghana : Past experiences , emerging opportunities , and future directions.

- Nimmo, J., Stonestrom, D. A., and Healy, R. W. (2008). Aquifers:Recharge. *Encyclopedia of Water Science*, 61(3), 122. <http://doi.org/10.1081/E-EWS>
- Obuobie, E. (2008). Estimation of groundwater recharge in the context of future climate change in the White Volta River Basin, West Africa, (62), 164.
- Obuobie, E., and Barry, B. (2012). General Description of Ghana. In *Groundwater availability and use in sub-Saharan Africa: a review of 15 countries*. <http://doi.org/10.5337/2012.213>
- Obuobie, E., Diekkrueger, B., Agyekum, W., and Agodzo, S. (2012). Groundwater level monitoring and recharge estimation in the White Volta River basin of Ghana. *Journal of African Earth Sciences*, 71-72, 80–86. <http://doi.org/10.1016/j.jafrearsci.2012.06.005>
- Obuobie, E., Diekkrueger, B., and Reichert, B. (2010). Use of chloride mass balance method for estimating the groundwater recharge in northeastern Ghana. *International Journal of River Basin Management*, 8(3-4), 245–253.
- Ofori-Addo, D., Jianmei, C., and Dong, S. (2008). Groundwater Development and Evaluation of the White Volta Basin (Ghana) using numerical Simulation. *The Journal of American Science*, 4(4), 64–71.
- Ophori, D. U. (1998). Flow of groundwater with variable density and viscosity, Atikokan Research Area, Canada. *Hydrogeology Journal*, 6(2), 193–203. <http://doi.org/10.1007/s100400050144>
- Ophori, D. U. (1999). Constraining permeabilities in a large-scale groundwater system through model calibration. *Journal of Hydrology*, 224(1-2), 1–20. [http://doi.org/10.1016/S0022-1694\(99\)00083-9](http://doi.org/10.1016/S0022-1694(99)00083-9)
- Owen, S. J., Jones, J. P., and Holland, J. P. (1996). A comprehensive modelling environment for the simulation of groundwater flow and transport. *Engineering with Computers*, 12(3-4), 235–242.

- Pelig-Ba, K. B. (2009). Analysis of stable isotope contents of surface and underground water in two main geological formations in the Northern Region of Ghana. *West African Journal of Applied Ecology*, 15. <http://doi.org/10.4314/wajae.v15i1.49430>
- Ross, M., Parent, M., and L. R. (2005). 3D geologic framework models for regional hydrogeology and land-use management: a case study from a Quaternary basin of southwestern Quebec, Canada. *Hydrogeology Journal*, 13 (5-6), 690–707.
- Sami, K., and Hughes, D. a. (1996). A comparison of recharge estimates to a fractured sedimentary aquifer in South Africa from a chloride mass balance and an integrated surface-subsurface model. *Journal of Hydrology*, 179(1-4), 111–136. [http://doi.org/10.1016/0022-1694\(95\)02843-9](http://doi.org/10.1016/0022-1694(95)02843-9)
- Saunders, R. S. (1970). Early Paleozoic Orogeny in Ghana: Foreland Stratigraphy and Structure. *Geological Society of America.*, 81(1), 233–240.
- Scanlon, B. R., Healy, R. W., and Cook, P. G. (2002). Choosing appropriate techniques for quantifying groundwater recharge. *Hydrogeology Journal*, 10(2), 347. <http://doi.org/10.1007/S10040-002-0200-1>
- Seaber, P. R. (1988). Hydrostratigraphic Units. *Geological Society of America.*, O-2, 9–14.
- Senthilkumar, M., and Elango, L. (2004). Three-dimensional mathematical model to simulate groundwater flow in the lower Palar River basin, southern India. *Hydrogeology Journal*, 12(2), 0–11. <http://doi.org/10.1007/s10040-003-0294-0>
- Shahin, M. (2002). *Hydrology and Water Resources of Africa*. Dordrecht, The Netherlands: Kluwer Academic.
- Sharma, M. L. (1986). Measurement and prediction of natural groundwater recharge-An overview. *Journal of Hydrology*, 25(1).

- Simmers, I. (1998). Groundwater recharge: an overview of estimation “problems” and recent developments. *Geological Society, London, Special Publications*, 130(1), 107–115. <http://doi.org/10.1144/GSL.SP.1998.130.01.10>
- Slater, L. (2002). Electrical-hydraulic relationships observed for unconsolidated sediments. *Water Resources Research*, 38(10), 1–13. <http://doi.org/10.1029/2001WR001075>
- Sophocleous, M. (2004). Groundwater Recharge, in Groundwater. In and E. J. U. Luis Silveira, Stefan Wohnlich (Ed.), *Encyclopedia of Life Support Systems (EOLSS)*, Developed under the Auspices of the UNESCO. Oxford, UK: Eolss Publishers.
- Sophocleous, M. A. (1991). Combining the soil-water balance and water-level fluctuation methods to estimate natural groundwater recharge: practical aspects. *J Hydrol*, 124, 229–241.
- Soupios, P. M., Kouli, M., Vallianatos, F., Vafidis, A., and Stavroulakis, G. (2007). Estimation of aquifer hydraulic parameters from surficial geophysical methods: A case study of Keritis Basin in Chania (Crete - Greece). *Journal of Hydrology*, 338(1-2), 122–131. <http://doi.org/10.1016/j.jhydrol.2007.02.028>
- Subyani, A., M. (2004). Use of chloride-mass balance and environmental isotopes for evaluation of groundwater recharge in the alluvial aquifer, Wadi Tharad, western Saudi Arabia. *Springer-Verlag*, 46, 741–749.
- Tiwary, R. K., Dhakate, R., Ananda Rao, V., and Singh, V. S. (2005). Assessment and prediction of contaminant migration in ground water from chromite waste dump. *Environmental Geology*, 48(4-5), 420–429. <http://doi.org/10.1007/s00254-005-1233-2>
- Todd, D. K. and Mays, L. W. (2005). *Groundwater Hydrology* (3rd ed.). John Wiley and Sons, Inc.
- Tóth, J. (1963). A theoretical analysis of groundwater flow in small drainage basins. *Journal of Geophysical Research*, 68(16), 4795–4812.

- Trompette, R. (1969). Les stromatolites du “Pre’cambrien supe’rieur” de l’Adrar de Mauritanie (sahara occidental). *Sedimentology*, 13, 123–154.
- Tyler, S. W., Chapman, J. B., Conrad, S. H., Hammermeister, D. P., Blout, D. O., Miller, J. J., and Ginanni, J. M. (1996). Soil-water flux in the Southern Great Basin, United States: Temporal and Spatial variations over the last 120,000 years. *Water Resources Research*, 32(6), 1481–1499.
- Van Der Hoven, S. J., Solomon, D. K., and Moline, G. R. (2002). Numerical simulation of unsaturated flow along preferential pathways: Implications for the use of mass balance calculations for isotope storm hydrograph separation. *Journal of Hydrology*, 268(1-4), 214–233. [http://doi.org/10.1016/S0022-1694\(02\)00178-6](http://doi.org/10.1016/S0022-1694(02)00178-6)
- Van der Sommen, J. J., and Geirnaert, W. (1988). On the continuity of aquifer systems on the crystalline basement of Burkina Faso. In I. Simmers (Ed.), *Estimation of Natural Groundwater Recharge* (pp. 29–45). Dordrecht, Netherlands: Reidel Publishing Company.
- Vandenbohede, A., Hermans, T., Nguyen, F., and Lebbe, L. (2011). Shallow heat injection and storage experiment: Heat transport simulation and sensitivity analysis. *Journal of Hydrology*, 409(1-2), 262–272. <http://doi.org/10.1016/j.jhydrol.2011.08.024>
- Walker, G. R., Jolly, I. D., and Cook, P. G. (1991). A new chloride leaching approach to the estimation of diffuse recharge following a change in land use. *J. Hydrol. (Amsterdam)*, 128, 49–67.
- Wang, S., Shao, J., Song, X., Zhang, Y., Huo, Z., and Zhou, X. (2008). Application of MODFLOW and geographic information system to groundwater flow simulation in North China Plain, China. *Environmental Geology*, 55(7), 1449–1462. <http://doi.org/10.1007/s00254-007-1095-x>

- Wang, H.F. and Anderson, M. P. (1982). *Introduction to Groundwater Modeling: Finite Difference and Finite Element Methods*. W.H Freeman and Co. New York.
- Weiss, J. S., and Williamson, A. K. (1985). Subdivision of Thick Sedimentary Units into Layers for Simulation of Ground-Water Flow. *Ground Water*. Blackwell Publishing Ltd.
- Wood, W. W., and Sandford, W. E. (1994). Chemical and Isotopic Methods for Quantifying Ground-Watre Recharge in a Regional, Semarid Environment.
- WRI. (2003). Watersheds of Africa: Water Resources eAtlas Land Cover and Use Variables: A19 Volta. *World Resources Institute*.
- Wright, E. P. (1992). The Hydrogeology of crystalline basement aquifers in Africa. <http://doi.org/10.1144/GSL.SP.1992.066.01.01>
- WRI-Water Resources Research Institute / DANIDA. (1993). “Rural Drinking Water Supply and Sanitation Project in the Volta Region - Final Report on the Inventory and Assessment of Potential for Hand Dug Wells in the Volta Region, Volume I - Main Report.” Accra: WRI.
- Yang, Y., Lerner, D. N., Barrett, M. H., and Tellam, J. H. (1999). Quantification of groundwater recharge in the city of Nottingham, UK. *Environmental Geology*, 38(3), 183–198. <http://doi.org/10.1007/s002540050414>
- Yeh, G. T., Hansen, S. ., Lester, B., Strobl, R., and Scarbrough, J. (1992). 3D FEMWATER/3DLEWASTE: Numerical codes for delineating wellhead protection area in agricultural regions based on the assimilative capacity criterion. US Environmental Protection Agency.
- Yidana, S. M. (2010). Groundwater classification using multivariate statistical methods: Southern Ghana. *Journal of African Earth Sciences*, 57(5), 455–469. <http://doi.org/10.1016/j.jafrearsci.2009.12.002>

- Yidana, S. M. (2011). Groundwater flow modeling and particle tracking for chemical transport in the southern Voltaian aquifers. *Environmental Earth Sciences*, 63(4), 709–721. <http://doi.org/10.1007/s12665-010-0740-y>
- Yidana, S. M. (2013). The Stable Isotope Characteristics of Groundwater in the Voltaian Basin – An Evaluation of the Role of Meteoric Recharge in the Basin. *Hydrogeology and Hydrologic Engineering*, 2(2), 1–3. <http://doi.org/10.4172/2325-9647.1000106>
- Yidana, S. M., Alfa, B., Banoeng-Yakubo, B., and Obeng Addai, M. (2014). Simulation of groundwater flow in a crystalline rock aquifer system in Southern Ghana - An evaluation of the effects of increased groundwater abstraction on the aquifers using a transient groundwater flow model. *Hydrological Processes*, 28(3), 1084–1094. <http://doi.org/10.1002/hyp.9644>
- Yidana, S. M., and Chegbeleh, L. P. (2013). The hydraulic conductivity field and groundwater flow in the unconfined aquifer system of the Keta Strip, Ghana. *Journal of African Earth Sciences*, 86, 45–52. <http://doi.org/10.1016/j.jafrearsci.2013.06.009>
- Yidana, S. M., Essel, S. K., Addai, M. O., and Fynn, O. F. (2015). A preliminary analysis of the hydrogeological conditions and groundwater flow in some parts of a crystalline aquifer system: Afigya Sekyere South District, Ghana. *Journal of African Earth Sciences*, 104, 132–139. <http://doi.org/10.1016/j.jafrearsci.2014.12.011>
- Yidana, S. M., Fynn, O. F., Chegbeleh, L. P., Loh, Y., and Obeng, M. A. (2014). Analysis of recharge and groundwater flow in parts of a weathered aquifer system in Northern Ghana. *Journal of Applied Water Engineering and Research*, 2(2), 91–104. <http://doi.org/10.1080/23249676.2014.954009>
- Yidana, S. M., Fynn, O. F., Chegbeleh, L. P., Nude, P. M., and Asiedu, D. K. (2013). Hydrogeological Conditions of a Crystalline Aquifer: Simulation of Optimal Abstraction Rates under Scenarios of Reduced Recharge, 2013.

- Yidana, S. M., Ganyaglo, S., Banoeng-Yakubo, B., and Akabzaa, T. (2011). A conceptual framework of groundwater flow in some crystalline aquifers in Southeastern Ghana. *Journal of African Earth Sciences*, 59(2-3), 185–194. <http://doi.org/10.1016/j.jafrearsci.2010.10.005>
- Yidana, S. M., and Koffie, E. (2014). The groundwater recharge regime of some slightly metamorphosed neoproterozoic sedimentary rocks: an application of natural environmental tracers. *Hydrological Processes*, 14.
- Yidana, S., Ophori, D., and Banoeng-Yakubo, B. (2008). Groundwater availability in the shallow aquifers of the southern voltaian system: A simulation and chemical analysis. *Environmental Geology*, 55(8), 1647–1657. <http://doi.org/10.1007/s00254-007-1114-y>
- Yihdego, Y., Danis, C., and Paffard, A. (2014). 3-D numerical groundwater flow simulation for geological discontinuities in the Unkheltseg Basin, Mongolia. *Environmental Earth Sciences*, 73(8), 4119–4133. <http://doi.org/10.1007/s12665-014-3697-4>
- Zhang, Q., Volker, R. E., and Lockington, D. A. (2004). Numerical investigation of seawater intrusion at Gooburrum, Bundaberg, Queensland, Australia. *Hydrogeology Journal*, 12(6), 674–687. <http://doi.org/10.1007/s10040-004-0333-5>
- Zhu, L., Zhang, C., Li, M., Pan, X., and Sun, J. (2012). Building 3D solid models of sedimentary stratigraphic systems from borehole data: An automatic method and case studies. *Engineering Geology*, 127, 1–13. <http://doi.org/10.1016/j.enggeo.2011.12.001>