Pan African University
Institute of Water
and Energy Sciences

PAN-AFRICAN UNIVERSITY
INSTITUTE FOR WATER AND ENERGY SCIENCES
(including CLIMATE CHANGE)

Master Dissertation

Submitted in partial fulfillment of the requirements for the Master degree in

[Water Engineering]

Presented by

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(PAUWES/2016/MWE/01)

IMPACT OF CLIMATE CHANGE ON GROUNDWATER RESOURCES OF THE ATANKWIDI BASIN IN GHANA, WEST AFRICA.

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Academic Year: 2017-2018

DECLARATION

I, Albert Elikplim Agbenorhevi, hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

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ABSTRACT

The Atankwidi basin is a sub-basin of the Volta River basin, which is located in West Africa. It is a transboundary basin shared by Ghana and Burkina Faso and has a drainage area of about 286 km^2. The basin dwellers depend heavily on groundwater sources abstracted through boreholes and hand-dug wells for domestic water supply, dry season irrigation of vegetables, livestock watering and limited industrial activities. However, considering the discrete nature of groundwater in the basin coupled with changing climate, increasing population, and expansion in irrigation activities, it is unclear how future water demands will impact on the groundwater resources.

The study utilized a modelling approach to assess the impacts of climate change and future abstraction scenarios on the groundwater resources of the Atankwidi basin, with the aim of contributing to sustainable management of the basin's groundwater resources. The approach consisted of adapting a groundwater modelling software (GMS 10.3- MODFLOW) to the study basin to simulate the groundwater system including groundwater levels and driving the adapted groundwater model with estimated future recharge and water demands to quantify their impacts on the groundwater system. The future recharge estimate was obtained from outside of this study as input. It was developed using the Soil and Water Assessment Tool (SWAT) and four future climate projections driven by the medium low-end and high-end IPCC emission scenario, RCP4.5. and RCP 8.5. The reference period for the study was set to 1986-2010 while the future horizon was set to 2051-2080. The future water demands were estimated based on a population growth rate of 1.1% between 2010 and 2080; an increase in per capita water consumption from 35 l/c/d to 50 l/c/d and 55 l/c/d to 110 l/c/d for the rural and urban population, respectively; and a doubling of the cropping intensity for irrigation.

Three future scenarios were analyzed. Scenario 1 (recharge only scenario) considered changes in recharge between 2010 and 2080 while demands remain unchanged; scenario 2 (demands only scenario) considered changes in water demands but no change in recharge; and scenario 3 considered changes in both recharge and water demands.

Based on projections of temperature and rainfall analyzed over the Atankwidi area, the basin is going to be likely warmer (5.2 °C to 6.5 °C) and slightly wetter (-0.53 % to +7.7 %). The recharge in the basin experienced a decrease by 6.2% under RCP 4.5 (2051-2081) relative to (1986-2010) but will increase slightly above the baseline to a region of 7.3%. Water demand in the basin is estimated to increase by 76.5% relative to the baseline as 40.7% of the demand coming from the agricultural sector, 39.5% from domestic demand and 19.8% from industrial. Scenario 1 showed an up rise of water table by 1747.08m^3/d under RCP 8.5 but a slightly decrease by RCP 4.5. Scenario 2 impact on the basin resulted in a stress on the water table leading to more drilling of boreholes due to 76.5% increase in demand. Scenario 3 showed a significant impact of drawdown of the water table when recharge is coupled with future demand.

These results are vital for a sustainable groundwater management in the Atankwidi basin and larger extent the White Volta Basin. But further research must be carried out for a best decision support system to be established for Atankwidi.

Key words

Atankwidi basin, Groundwater, abstraction, recharge, Climate change.

RÉSUMÉ

Le bassin d'Atankwidi est un sous-bassin du bassin de la Volta, situé en Afrique de l'Ouest. C'est un bassin transfrontalier partagé par le Ghana et le Burkina Faso avec une zone de drainage d'environ 286 km^2. Les habitants du bassin dépendent fortement des sources d'eau souterraine extraites par des forages et des puits creusés à la main pour l'approvisionnement en eau domestique, l'irrigation des légumes en saison sèche, l'abreuvement du bétail et les activités industrielles limitées. Cependant, compte tenu de la nature discrète des eaux souterraines dans le bassin, du changement climatique, de l'augmentation de la population et de l'expansion des activités d'irrigation, il est difficile de savoir comment les futures demandes en eau affecteront ces ressources en eau souterraine.

L'étude a utilisé une approche de modélisation pour évaluer les impacts du changement climatique et des futurs scénarii d'abstraction sur les ressources en eaux souterraines du bassin d'Atankwidi, dans le but de contribuer à la gestion durable des ressources en eaux souterraines du bassin. L'approche a consisté à adapter un logiciel de modélisation des eaux souterraines (GMS 10.3- MODFLOW) au bassin d'étude pour simuler le système d'eau souterraine incluant les niveaux d'eau et pilotant le modèle d'eau souterraine adapté avec estimation de la recharge future et des besoins en eau. L'estimation de la recharge future a été obtenue en dehors de cette étude en tant donnée d’entrée. Il a été élaboré à l'aide de l'outil d'évaluation du sol et de l'eau (SWAT) et de quatre projections climatiques futures, tirées par le scénario d'émissions IPCC de niveau moyen-bas et haut, RCP4.5. et 8.5 respectivement. La période de référence pour l'étude a été fixée de 1981 à 2010 alors que l'horizon futur était fixé de 2051 à 2080. Les besoins futurs en eau ont été estimés sur la base d'un taux de croissance démographique de 1,1% entre 2010 et 2080; une augmentation de la consommation d'eau par habitant de 35l/c/j à 50l/c/j et de 55l/c/j à 110l/c/j pour la population rurale et urbaine, respectivement; et un doublement de l'intensité culturale pour l'irrigation.

Trois scénarii futurs ont été analysés. Le scénario 1 (scénario de recharge seulement) a tenu compte des changements dans la recharge entre 2010 et 2080, tandis que les demandes demeurent inchangées; le scénario 2 (scénario de demandes seulement) a pris en compte les changements de la demande en eau mais pas de changement de recharge; et le scénario 3 a pris en compte les changements dans la recharge et dans les demandes d’eau.

Sur la base des projections de température et de précipitations analysées sur la zone d’Atankwidi, le bassin sera probablement plus chaud (5,2 ° C à 6,5 ° C) et légèrement plus humide (-0,53% à +7,7%). La recharge dans le bassin a diminué de 6,2% sous le RCP 4,5 de 2051-2081 par rapport à 1986-2010, mais augmentera légèrement au-dessus de la ligne de base pour atteindre une région de 7,3%. Selon les estimations, la demande en eau dans le bassin devrait augmenter jusqu'à 76,5% par rapport au scénario de référence, 40,7% de la demande provenant du secteur agricole, 39,5% de la demande intérieure et 19,8% de la production industrielle. Le scénario 1 montre une élévation de la nappe phréatique de 1747,08 m3 / j sous le RCP 8,5, mais une légère diminution de la part du RCP 4,5. L'impact du scénario 2 sur le bassin a entraîné un stress sur la nappe phréatique, dû à une augmentation des forages en raison de l'augmentation à 76,5% de la demande. Le scénario 3 a montré un impact significatif du rabattement de la nappe phréatique lorsque la recharge est associée à la demande future.

Ces résultats sont essentiels pour une gestion durable des eaux souterraines dans le bassin d'Atankwidi et plus largement le Bassin de la Volta Blanche. Mais d'autres recherches doivent être menées pour qu'un meilleur système d'aide à la décision soit mis en place pour Atankwidi.

Mots clés : Bassin Atankwidi, Eaux souterraines, captage, recharge, Changement climatique.

DEDICATION

I dedicate this project to my beloved parents Mr. & Mrs. Agbenorhevi and Bishop Dag Heward Mills, my source of inspiration, knowledge and strength.

ACKNOWLEDGEMENTS

My deepest gratitude goes to Almighty God who has provided all that was needed to complete this research project. My sincere appreciation goes to my supervisor, Dr Emmanuel Obuobie – CSIR-Water Research Institute, whose contribution and constructive criticism has pushed me to expend more efforts to make this work as original as it can be. Thanks to him, I have experienced true research and my knowledge on the subject matter has been broadened.

My special appreciation goes to the AUC for instituting Pan African University Institute of Water and Energy Science (PAUWES) and Dr. Abdellatif Zerga (the director of PAUWES) for providing me with the scholarship opportunity including research grant to study for a Degree of Master of Science in Water Engineering.

My utmost regard goes to my parents and family who have given everything possible to make sure I achieve this feat. I thank the institutions that supported me in my study – CSIR-WRI, WASCAL, CWSA, Earth Science Department of the University of Ghana, Geological Survey Department and Ghana Meteorological Agency and the staff of PAUWES especially Fatima Chaib Zohra. I also thank Amma Animwaa Opoku and all colleagues and friends whose contributions have brought me this far.

CONTENTS

LIST OF ABBREVIATIONS

International Panel on Climate change	IPCC
Global Circulation Models	GCMs
Sub Saharan Africa	SSA
Non-Governmental Organization	NGO
Environmental Protection Agency	EPA
Soil Research Institute	SRI
inner-tropical convergence	ITC
Upper East Region	UE
Water Research Institute	WRI
Static water level	SWL
Hydrogeological Assessment Program	HAP
Sustainable Development Goals	SDG
Ghana Water Company Limited	GWCL
Community Water and Sanitation Agency	CWSA
Land-use Change	LUC
Decision Support System	DSS

LIST OF TABLES

LIST OF FIGURES

1 CHAPTER 1: Introduction

1.1 Background and study rationale

Water is one of the basic necessities of life. It is essential for human survival and the sustenance of all terrestrial systems. The degree to which it is in abundance or scarce, clean or polluted is an indication of the quality of life, to a large extent. And after decades, groundwater is gaining the needed recognition as a most vital water resource globally as cited by Malekinezhad et al., 2017. Groundwater and surface water are the two most important sources of freshwater on earth. Groundwater constitutes a large proportion (60%) of the world's freshwater resources compared to surface water, which makes up only 1.3% of the world's freshwater supply (Pidwimy, 2006; Allen and Cherry, 1979). However, surface water has received much more attention as source of fresh water supply over the years most probably because it is visible to the human eye and easy to access. Groundwater, on the other hand, is hidden from the eye and requires much effort to access. In recent times, water supply in most areas in Africa is increasingly drawn from groundwater sources.

Groundwater offers water for agriculture, industry and human consumption, and several groundwater-dependent ecosystems, particularly during droughts (B. Klove et al., 2014). It is also the major freshwater reservoir acting in the hydrological cycle. Malekinezhad et al, 2017 highlighted that there is enough evidence about groundwater being a vital parameter of water supply systems in arid areas of the works. For instance, Nyagwambo, 2006, listed some importance and advantages of groundwater over surface water; accessibility to groundwater does not require having water produced on large scale before it is made available neither does it require complex engineering development to treat nor transport. Adding to the above, the capital cost for producing and treating groundwater before consuming is comparatively lower than surface water treatment and production. It is also the best option of providing a reliable quality water in connection to attaining or achieving the Sustainable development goals (SDG) 6 faster to surface water.

All these are worth knowing about how vital groundwater is but its weakness and limitations must equally be made aware and addressed as well. This is because the increasing pressures as cited by Peach et al., 2006 on groundwater resources in both the arid and semi-arid regions due increasing water demand, land use change, deteriorating groundwater quality and stricter water quality, has significant impact on groundwater. This has repeatedly affected groundwater quality and levels as said by Lachaal et al., 2010 and cited by Malekinezhad et al., 2017. Unlike surface water, abstraction of groundwater alters the water budget (Llamas, 1992). Secondly, the types of aquifer present for groundwater can be a future challenge to water availability. According to Obuobie et al. 2008, the White Volta basin presents a crystalline rock types of aquifer. This type of aquifers is in a discrete form like pocket of reservoir that has no connections. Thus, large quantity of water is usually not present in this type of aquifers and this is alarming for the future water availability.

In addition, the changing climate occurring in various parts of the world due to global warming is a challenge worth considering. According to the International Panel on Climate Change (IPCC, 2007), a probability greater than 90% that climate change due to global warming is influenced by anthropogenic factors. Others like De jager and Usoskin, 2006; Stanhill, 2007; Svensmark, 2007 raised some doubts about the role of greenhouse gas emissions in climate change. The predicted changes or impacts of climate change on groundwater includes the recharge timing and magnitude due to seasonal shift in annual or mean groundwater levels and these may be larger than the changes in precipitation or rainfall distribution (Ng et al., 2010). But because groundwater resources are related to climate change via the direct interaction with surface water, changes in hydrological parameters such as regional temperature and precipitation have great impact on the hydrological cycle. The disturbance on hydrological cycle as a result of anthropogenic activities such as mining, land use change and urbanization suppress or amplify groundwater response to climate change. It may lower water table, rainfall, recharge or increase consumption depending on the activity undertaking in a given location.

The impacts of groundwater abstraction and land use have been investigated in several studies but climate change impacts on groundwater have received a lesser amount of devotion (Taylor et al., 2012). Similarly, hydrological studies of climate change many a time addresses surface water, but fewer studies emphasis on groundwater (Kundzewicz and Döll, 2009; Green et al.,2011). Global Circulation Models (GCMs) uses greenhouse emissions to project future climates at global and regional levels. Although there is uncertainty in the outputs from GCMs, it provides good approximation of present and past climate trends for estimating future climates (Bell et al, 2003; Dearing 2006; Sloan, 2006).

Therefore, there is a need to investigate how resilience is groundwater considering the aforementioned challenges. The sustainability of groundwater is key for the future and this calls for assessing the impact of climate change and future water demand scenarios on groundwater resources.

1.2 Relevance of study

Although answers of recharge and groundwater/surface water interactions to climate change have gained few research studies and recognition in Africa, quantifying groundwater abstraction and usage remains a difficult but essential challenge (Martin-bordes et al., 2011). The interactions between climate, groundwater and surface water must also be understood in order to forecast variations in groundwater recharge (Okkonen et al., 2010). For groundwater quantity, the basic issue is how recharge will be changed with respect to climate change. The answer of plant transpiration to increased CO_2, climate warming and changes in soil moisture and groundwater elevation must be understood and involved in recharge models. Additional data is needed on groundwater recharge mechanisms, storage capacity and residence times. (Singleton and Moran, 2010 ; Martin-bordes et al., 2011 ; Bertrand et al., 2012b). Martin-bordes et al. (2011) concluded that there is a need for further scientific studies about most aquifers of the world to quantify spatial and temporal patterns of groundwater discharge, its withdrawals and uses in response to present and future climate.

Furthermore, most of the groundwater resources are non-renewable on meaningful time scales for both ecosystems and human society. As stated by Martin-bordes et al., 2011, applying the impact of climate change on groundwater will intensify the concerns globally by reducing precipitation and increasing evapotranspiration. This however, will decrease recharge and perhaps increase groundwater abstraction rates. Thus, the importance of groundwater-dependent ecosystems (GDEs) awareness must increase since it will lead to weight being placed on an improved understanding of groundwater-ecosystem interactions in a changing climate.

Adding to the above, quantification of climate change impacts on groundwater systems can be explored by running groundwater models with future meteorological boundary conditions, which may be derived from future climate scenarios computed with climate models. However, few of these approaches has been used to determine the impact of climate change on groundwater though there is a vast range of different GCMs with differing assumptions on ocean–atmosphere interaction, initial conditions and emission scenarios.

Finally, the anthropogenic experiences in the Atankwidi River Basin obviously leaves no doubt about the direct impact on the Atankwidi Basin. Although measures are being taken to curb these activities, the consequences on climate change variables have been neglected. Adding to that, the repercussion on groundwater quantity and recharge is not necessarily of concern.

1.3 Objectives of the study

1.3.1 Main objective

The main objective of this study is to contribute to the sustainable development and management of groundwater resource of the Atankwidi basin and by extension the Volta Basin by quantifying the impacts of climate change and future abstraction scenarios on the resource to inform appropriate adaptation strategies.

1.3.2 Specific objectives

The specific objectives of the study were to:

- Review literature on groundwater of the Atankwidi basin;
- Adapt a groundwater model (GMS Modflow) to the Atankwidi basin to simulate the present groundwater situation;
- Analyse climate projections over the study basin for the future (2051-2080) relative to a baseline (1986-2010) over the basin to determine changes in the climate horizon;
- Estimate future groundwater demands up to horizon 2080 in the basin and together with estimated future recharge drive the adapted Modflow model to quantify impacts on the groundwater resource; and
- Provide recommendations for sustainable management of groundwater in the Atankwidi basin based on results from the study.

1.4 Research questions

Based on the rationale and study objectives, the key research questions for this study were:

1. What is known about the hydrogeology of the Atankwidi Basin?
2. How will the key drivers of groundwater (climate and demand) in the Atankwidi basin change in the future horizon (up to 2080)?
3. How will the groundwater resource in the study basin be affected by changes in the key drivers (climate change and demand)

1.5 Thesis organization

This thesis is organized in 5 chapters plus a list of cited references. The thesis begins with chapter one, which provides a background to the study including the relevance and the objectives of the study. Chapter 2 is dedicated to the review of literature on essential topics related to water resources in general, groundwater, water demands, and climate change, amongst others. The methods, materials, and data used for analysis and modelling are described in chapter 3. The results of the study are presented and discussed in chapter 4, while key conclusions and recommendations are presented in chapter 5.

2 CHAPTER 2: Literature review

2.1 Groundwater as a vital resource

Freshwater is vital to sustain life, for which there is no substitute. This means that water has a high value to its users. The vital nature of water gives it the characteristics of a public good. Although seen as a public good, groundwater is a fugitive resource. Generally, it is difficult to assess the variations in stock and flow of the groundwater as its boundaries are not clearly defined. This complicates the planning and management of the resource. Groundwater constitutes only 1% of all water resources on Earth. However, its quantity is about 35 times more than freshwater in lakes and streams. Groundwater is the main source of water supply in many areas in Sub-Saharan Africa. In some locations especially rural settlements, it is the only source of water available (Obuobie et al., 2016). According to MacDonald and Davies (2000), groundwater supply system is very suitable for Sub-Saharan Africa for the following reasons:

- Less expensive to develop groundwater compared to surface supply system;
- It is drought resilient;
- It has a better potential of meeting water demand;
- It does not require any sophisticated treatment of microbial and chemical qualities; and
- It occurs in many places in geological formation though its yield can vary substantially.

In the Volta Basin, including the Atankwidi, groundwater plays an invaluable role in domestic water supply in rural areas, small towns and small to medium urban centers (Obuobie et al. 2016). Martin (2006) reported that about 44% of the total population of the Volta Basin depends on groundwater abstracted from boreholes (mechanized and hand-pump equipped) and modern hand dug wells. In addition to domestic water supply, groundwater is also a valuable resource for other productive uses such as small-scale irrigation, livestock watering and brick-making, all of which contributes to enhancement of livelihoods, reduction of poverty and ultimately attaining SDG 1. Groundwater also sustains vital dependent ecosystems. Martin (2006) reported the critical and significant role of groundwater contribution (baseflow) in sustaining the Black Volta river and dependent ecosystems in the dry season.

In spite of the aforementioned important roles of groundwater in the Volta basin, there are critical challenges regarding the exploration, use and management of the resource. The challenges include limited knowledge of the complex hydrogeology of the basin, poorly designed abstraction systems, and inadequate capacity of groundwater institutions and expertise which clearly expose the vulnerability, mismanagement and the lack of enforcement of the regulations on groundwater resource (Gyau-Boakye, 2001). Pavelic et al. (2012) observed that though there are improvement in the resource exploration and management in recent times due to the increasing number of funded projects, the full potential of the resources is yet to be attained.

2.2 Hydrogeology and groundwater availability

This topic presents a regional overview of groundwater basins situation in Ghana. Ghana has two major geological provinces underlain in the Basin (Obrecht et al., 2014). The basement crystalline province (crystalline and metamorphic rock formation) of the Precambrian age and associate with the West African Craton. This represents the largest part of the basin; the consolidated sedimentary province (commonly known as Voltaian formation) of the Proterozoic to Paleozoic age representing the central part of the Volta basin and consists of a flat extended depression of Cambrian sediments and has its concave edge building an escarpment towards the neighboring Precambrian rocks (Menge., 2012). Whereas the upper and lower Voltaian consist of fine grained consolidated sandstones, the Obusum which is the lower Middle Voltaian consists of shales and consolidated sandstones which are exposed to tectonic stress towards the eastern edge of the Obusum. This borders the mobile belt of the fault zone. The major fault zone covers the Southwest to the Northeast along the metamorphosed and folded metasediments of the Togo and Buem formations which is the Upper Middle Voltaian (Oti) mostly consisting of sandstone (Basin, Volta river). These Togo and Buem formations have created a hilly form build up range along the eastern border of the Volta River basin. Togo formation is mixed up with fractured and highly folded shale limestone and conglomerates. Similarly, the Buem adds up with quarzites, phyllites and sandstone; and the unconsolidated sedimentary province (sedimentary and tertiary sandstone formation), also of the Proterozoic to Paleozoic age.

The basin under research shares the same basement of the White Volta basin. 45% of the White Volta sub-basin is underlain mostly by crystalline rocks of the Birimian system of the Precambrian age with the connected granitic intrusive and isolated patches of the Tarkwaian formation. Similarly, 55% of the Voltaian systems consist of the Upper Voltaian sandstone Obosum and Oti beds and Basal sandstone. The Birimian system consist of quartzite, gneiss, migmatite, granite gneiss phyllite, and schist (Gyau-Boakye and Tumbulto, 2006). The oldest rock units in the basin from the north-eastern parts and western is the Birimian system or crystalline basement complex. This is divided into Upper and Lower Birimian. Whereas, the Lower Birimain comprises, schist, tuffs, phyllites and greywackes which is dominant in the western part of the basin, the Upper Birimian is dominant in metamorphosed lavas and pyroclastic rock formation. There are also alluvial deposits covering a narrow strip along the water course.

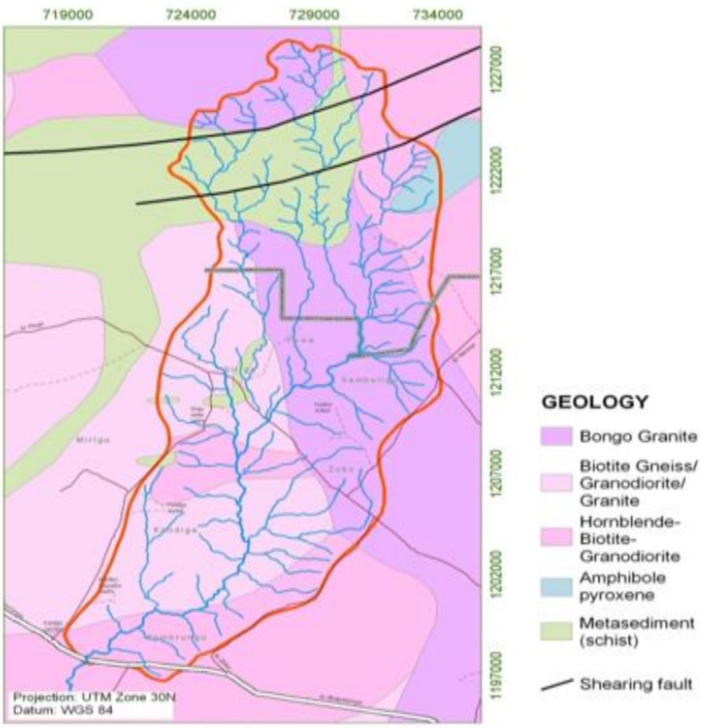


Figure 2.1: Geological map of the study area.   Source: martin, 2006

The Voltaian formation, Birimian formation and its associated granite intrusions are characterized essentially by little or no primary porosity. Due to this, groundwater occurrences are associated with fracturing, faulting, weathering and jointing occurrence distinct types of aquifers in the White Volta River Basin. These are the weathered zone aquifer and the fractured zone aquifer.

According to Abdul-Ganiyu (2014), whereas the latter tend to be more localized in nature and the degree of fracturing and its nature of groundwater recharge determines or controls the groundwater occurrences, the former usually take place at the base of the thick weathered layer and are either semi-confined or phreatic to curbed depending on the porousness of the upper weathered layer. Yields from boreholes within the fractured zone are determined by the extent and degree of fracturing. The most productive aquifer situation is determining by the formation which combines a thick weathered zone with a well fractured bedrock zone. Regolith with variation in thickness and lithology are the type of weathered layer that has overlain most of the geological formation (SNC-Lavalin/INRS., 2011). The thickness of regolith varies widely with an average ranging from 10-40m and can be up to 140m in the Precambrian formation in the southern part of the basin (Smedley, 1996). But in the North, it ranges from 15m to 40m and could be up to 100m (Groen et al., 1988).

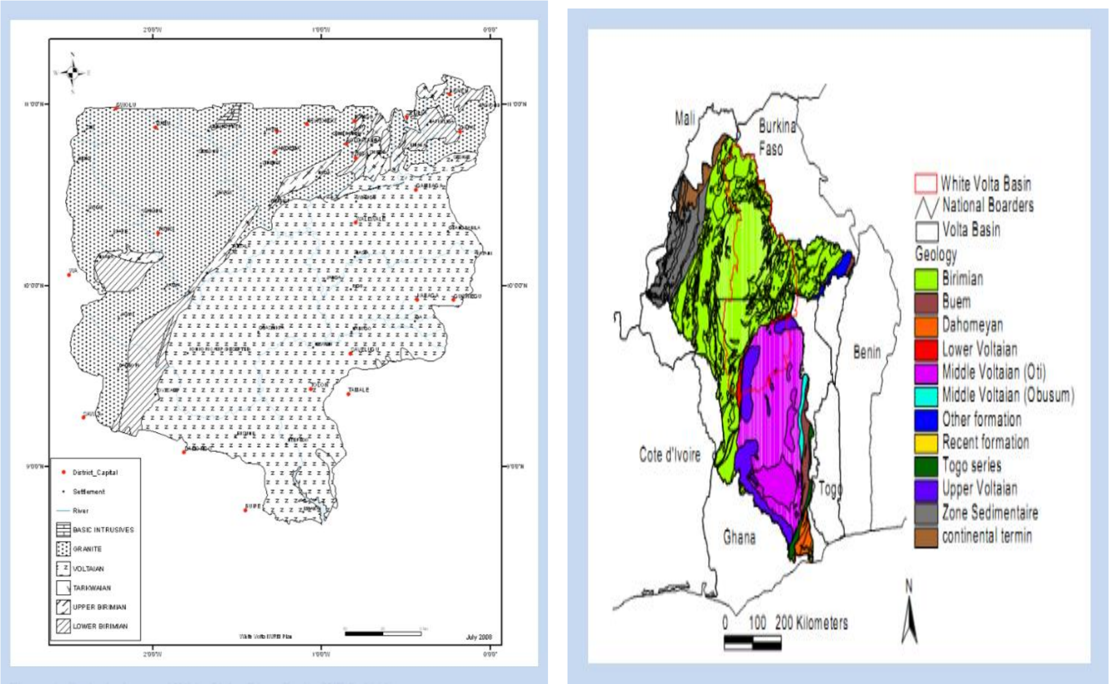


Figure 2.2: Geological map of White Volta River Basin (WRC, 2008); Geology of the Volta River Basin (GLOWA Volta Project)

2.2.1 Profile of a typical weathered mantle

They are often highly decomposed rock rich in clay or silt nigh the surface, becoming less weathered with an increasing sand fraction of rock grains and decreasing clay content with depth until the fresh rock is met.

Profile often covered with a thin, sandy layer. At times laterite or iron pisolithes are found at the interface between the sandy cover and the underlying clay. While the regolith and the fractured bedrock aquifers form an integrated aquifer system, the regolith aquifer is on average an order of magnitude more transmissive than the underlying fractured aquifer (Taylor & Howard, 2000). While basement aquifers are essentially phreatic, drilling companies often observe semi-confined conditions when constructing boreholes in regolith aquifers because of the reduced permeability in the clayey upper part of the profile. Consequently, the static water level often lies a little higher than where water was first observed during drilling.

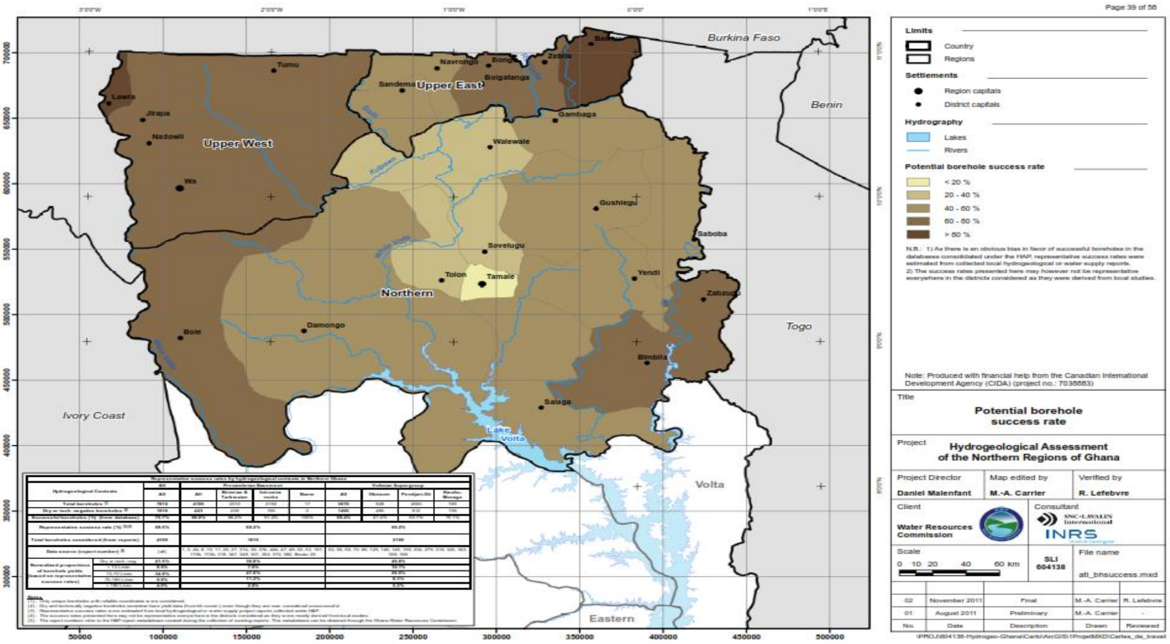


Figure 2.3: Potential borehole success rate. Source; HAP 2006

The borehole drilled for water production are used for observation due to the lack of existing monitoring boreholes in these areas. The aquifers in the basin area is referred as basement aquifers because they are in the geological environment of Precambrian granitoids which are predominant. These aquifers are developed in the weathered mantle (regolith) and the fractured bed rock.

2.2.2 Hydrogeological concept model

Three aquifers can be described in this hydrogeological system.

The discontinuous, shallow, perched aquifer

The regolith aquifer

The fracture aquifer

The regolith aquifer in the weathered mantle is the main aquifer. It forms an endless aquifer with a mean saturated thickness of 25m and a hydraulic conductivity of 2.5E-6 to 2.5E-5 m/s. The boreholes in this basin is mostly tapped into this aquifer. But bongo granite which is potassium-rich underlying this study area covering the north-eastern part is less weathered. With an average of 4E-6m/s, the lateral hydraulic conductivities and transmissivities of bongo granite is slightly lower than that of regolith. This reduces the lateral groundwater flow so that groundwater is found at shallow depths despite its topographic elevation. The records of fractures and quartz channels in numerous drilling profiles and the point that a few boreholes are unusually high yielding are indication for the presence of a fracture aquifer, which perhaps is linked to the regolith aquifer. Similarly, the existence of traditional hand dug wells which contains water at a very shallow depth that do not tally with the regional groundwater level is an indication that an unconnected shallow perched aquifer is in that location. It is normally a coarse soil texture of 0.5m-1.5m thickness covering a lesser amount of pervious, clayey layer. Usually these wells are temporal and they dry up right after the rainy season. The shallow aquifer are leaks providing water to the regolith aquifer because they generate an interflow contributing to stream runoff in the rainy season.

According to Martin 2006, sinks of groundwater from the regolith aquifers are

- Baseflow (Discharge to streams)
- Sub-surface groundwater run-off
- Recharge of the fractured bedrock aquifer
- Evapotranspiration by trees

Though infiltration from watercourses occurs at certain places, discharge from groundwater to these watercourses are more frequent.

In summary, the hydrochemical study backs the theory that both modern hand-dug wells and boreholes hit the regolith aquifer.

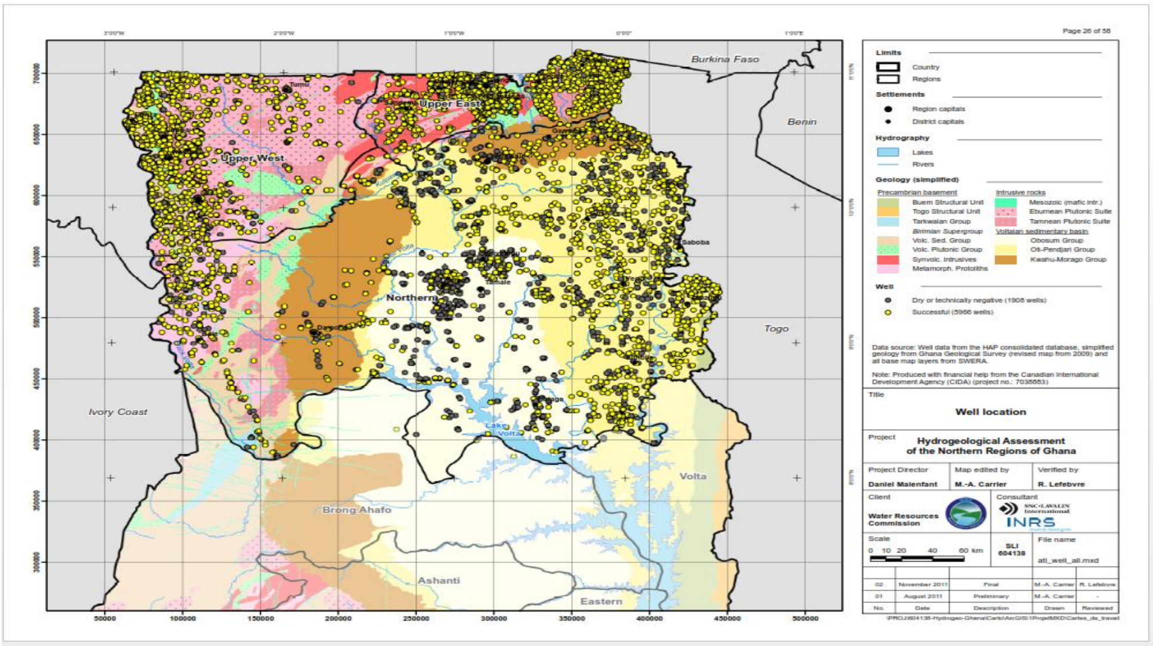


Figure 2.4: Hydrological map of Northern region of Ghana Source: HAP 2006

2.3 Groundwater recharge

Groundwater recharge gives an estimation of precipitation, landscape characteristics, human impacts and how the hydrological cycle works. For efficient and sustainable management of the groundwater resources, an understanding of the recharge processes and the quantification of natural recharge rate are basic prerequisites (Scanlon and cook, 2002, chand et al., 2005). Sanford 2002, Scalon et al., 2003 and cited by Abdul-Ganiyu et al., 2014 that quantification of the recharge is required to estimates the sustainable yield of groundwater aquifers. Recharge however, may occur naturally from rivers, canals and lakes, precipitation and by artificial means (man-induced through activities of irrigation, urbanization and precipitation (Lener et al., 1990). Similarly, the direct measurement of groundwater recharge is tough due to the complexity and heterogeneity of recharge processes according to Kinzelbach et al., 2002.

In order to determine the groundwater availability and proper management of its aquifer, it is most essential to estimate groundwater recharge (Adomako et al, 2010, MacDonald et al, 2001) cited in Forkuor, G., et al. 2014. The main factors controlling or having great influence on recharge rate include rainfall (intensity and distribution), geology, land use and soil type. Obuobie, 2008 has previously conducted research on groundwater recharge by quantifying the annual rainfall using water table fluctuation. Quantitative assessment of renewable resource dependent greatly on the knowledge of the recharge rate (Martin, 2006). Similarly, groundwater management and the impact of climate change are also dependent on the knowledge acquired in recharge rate of a particular location. However, an assumed average groundwater recharge rate of 5% of annual rainfall is currently used by water resources planners in northern Ghana. This figure is largely based on experience in other African countries.

Adding to it, data that could be used for the determination of recharge rate is extremely scarce for Volta River basin but the degree of uncertainty among water resource planners in local water authorities whether the currently figures are applicable when the wells are drying up.

Different approaches to estimating recharge in the northern region over the years have been adopted. For instance, recharge estimated by the Water Table Fluctuation method (WTF), Chloride Mass Balance (CMB) Method, WetSpass model and the Recession Curve Analysis (RCA) in Abomey et al., 2017 research for Northern Ghana concluded that:

- WTF method based on groundwater hydrograph of the 11 monitoring wells estimated a recharge rate ranging between 68mm to 163mm of the annual rainfall. Which is amounting to 6-17% and a mean recharge of 10%.
- Results from CMB estimated a range from 21mm to 191mm of the annual rainfall. This range represent 2.1 to 19.3% of the annual rainfall and a mean of 8.14%.
- WetSpass model used for estimating in the during a six (6) year period from 2003 to 2008 estimated a very high range of 519mm to 756mm representing 68 and 70% of the annual rainfall.
- Finally using the RCA methodology, the estimated ranged from 29mm (3%) to 68mm (9%) of the annual rainfall and 49mm (5%) as its mean average.

Other estimated recharge in the study region or within the crystalline basement aquifer in Africa by other researchers are summarized below.

Table 2.1: Estimated recharge within crystalline basement aquifer Source; Abomey et al., 2017

Author (s)	Year	Country	Estimated recharge of annual rainfall (mm)	Estimated recharge of annual rainfall in %
Yidana & Abomey	2014	Ghana	1.8-32	
Oteng Mensah et al	2014	Ghana	0.9-21	5.5
Obuobie	2008	Ghana	3.4-18.5	8.3
Sandwidi	2007	Burkina Faso		5.3
Martin	2006	Ghana	3-6	5.9
Nyagwambo	2006	Zimbabwe	4-25	12
Bromley et al.	1997	Niger	1.8-3.4	

Predicting the status of recharge of groundwater under climatic change is the future for integrated water management (Meixner,T., 2016). Thus, the future changes of the groundwater under climate change ought to be carefully considered more extremely by politicians and managers. From Malekinezhad et al., 2017, proved that groundwater recharge estimates are variable and rely on the designated groundwater simulation model, GCMs and geographical situation. Finally, in most of the systems studied, vadose zone storage and the dynamic interaction of surface water flows with groundwater recharge was not included. An exception to this rule is Hanson et al. (2012), which includes a very robust representation of how climate change will propagate through the hydrologic and water resource systems of Atankwidi and how those shifts will impact groundwater recharge.

2.4 Climate change and effects on groundwater resource

The Intergovernmental Panel on Climate Change (IPCC) defines climate as “the average weather in terms of the mean and its variability over a certain time-span and a certain area” and a statistically important variance of the average state of the climate or of its variability existing for decades or more, is referred to as climate change. The uncertainties climate change creates to the source and administration of water resources is alarming. Mackay, 2008 referenced IPCC demonstrating that climate change is happening on a global scale and precipitation and temperature patterns are to be experiencing these changes. The Intergovernmental Panel on Climate Change (IPCC), estimates an increase of 0.6 ± 0.2 ^{0}C since 1861 and further suggest a rise of 2 to 4 ^{0}C over the next century in reference to the global mean surface temperature. The hydrologic cycle is also affected by increase in temperature via directly increasing evaporation of existing surface water and transpiration of vegetation. Accordingly, rainfall intensity rates, timings and precipitation amounts are influenced by these changes and also indirectly impact the flux and water storage in reservoirs either surface and subsurface (i.e., lakes, soil moisture, groundwater). Adding to the above, there may be other impacts of concern, such as scarcity of potable water, sea water intrusion and water quality deterioration etc.

Significant uncertainty continues from GCMs, but there is a larger consensus on changes in precipitation and temperature extremes, which is estimated to rise with a higher degree on the global hydrological system. Longer droughts may be accompanied with more recurrent and intense rainfall events. These changes in climate may affect ground water initially and primarily through changes in irrigation demand according to Taylor et al., 2012. Projections of the direct impacts of climate change on ground water systems are highly uncertain (Scibek, J., 2005). The dominant source of uncertainty lies in climate projection derived from GCMs which typically translate the same emissions scenarios into very different climate scenarios, particularly for precipitation. Nevertheless, GCM projections of global precipitation for the 21st century generally shows pattern in which regions of moisture accumulation (or divergence) are anticipated to experience an increased or decreased rainfall

Groundwater systems are prone to climate change and variability either through directly by replenishing by recharge or indirectly through changes in the use of groundwater or both. The impact of this global changes on water resources is the one of the essential discussed basic problems in the area of water resources and climatology (Grinevsky, 2017). This impact can be severe by human activity like land-use change. According to Taylor et al (2012), natural renewal of groundwater happens from equally focused recharge and diffused rain-fed recharge via surface waters (lakes, wetlands and ephemeral streams) leakages. This however is extremely reliant on predominant climate as well as on the land cover and core geology. Climate and land cover to a higher extent is a determinant to precipitation and evapotranspiration. Similarly, the underlying soil and geology is key to whether the excess water (precipitation minus evapotranspiration) can infiltrate and stored in the subsurface. The distribution of global precipitation is primarily related to the variability in modelled recharge and over time recharge becomes intensely influenced by climate variability which includes the extremes of climate (floods and droughts) that often related to ways of climate variability such as the El Niño/Southern Oscillation (ENSO) at multiyear timescales.

Climate change has effects on hydrological cycle now or even worse in the future through climatic parameters; temperature, evapotranspiration, precipitation, soil moisture and temperature variation. There are patterns showing an increment in evaporation and precipitation and their degree of intensity. However, the major obstacle will be its unevenly distribution in the globe according to Taylor et al (2012). While some regions experience intense flood, others will be accepting severe drought. Similarly, there will be climatic seasons interference. Great changes in scheduling of wet and dry seasons. The outcome of global warming and climatic variability demands interdisciplinary research especially water resources.

A review on some of studies on the impact of climate change on groundwater resources highlighted the following;

The first is Ranjan et al., 2006, evaluated the impacts of climate change on fresh groundwater resources where he precisely focused on the salinity intrusion in five selected water resources experiencing stressed coastal aquifers. The yearly fresh groundwater resources losses clearly meant an increase long-term trend in all areas under stress excluding the northern Africa. Also, temperature and precipitation singly did not show any appreciable correlations with fresh groundwater loss. And population growth and fresh groundwater resources per capita was also realized to be the socio-economic activity impacting on groundwater resources.

Woldeamlak et al., 2007 also modelled climate change effects on the groundwater systems in the Grote-Nete basin in Belgium where annual and seasonal water balance parameters comprising groundwater recharge were simulated through WetSpass model and the discharge and average annual groundwater elevation were simulated with a MODFLOW groundwater model noted for steady-state modelling. This research indicated a reduction in level of the average annual groundwater by 50cm.

Again, Toews., 2007 also modelled the impacts of future predicted climate change on groundwater recharge for the Okanagan region (the arid and semi-arid) in Columbia. For this research the effect of climate change was analyzed stochastically from there GCMs. The use of HELP 3.80D hydrology model was used in model the spatial recharge as soil and climate data were available. The work displayed a rise of water table in future time periods when a transient MODFLOW groundwater finished simulating.

Although, climate change effect on groundwater resources are on-going, they are still at the infancy. There is a need to have more research in the said area though there are evidence of global warming threat and its consequences are alarming. From IPCC 2014, the challenges that climate change poses to water resources at the global, regional, national and local levels are increasingly better understood by the scientific community research on how to cope with them remains scattered. The planned significance of groundwater for global water and food security will probably deepen under climate change as more recurrent and intense climate extremes (droughts and floods) accelerate variability in precipitation, soil moisture and surface water.

2.5 Effects of human activities on groundwater resources

Over the past two decades, temporal shallow wells have become the most commonly adopted irrigation in the Upper East Region of Ghana specifically Atankwidi and Anyira sub-basins (Kortatsi., 1994). This commonly used wells are often used in cases where land owners lease out their lands to farmers during the dry season. After the dry seasons, farmers end up refilling the wells with soils thus explaining why they temporal shallow wells. Crops such as tomatoes, okra and pepper are cultivated from this technology and recording a yield of 60t/ha for every 500m^2 land.

Similarly, a riverine alluvial dugout practice mainly in the non-perennial streams and Atankwidi and Anyira are the famous sub basin experiencing such practices in Ghana. The farmers using this technology records a good yield and highwater productivity which eventually helps them to negotiate good market process for their products. Tomatoes and Chili pepper are the commonest crop cultivated with such practices.

Figure 2.5: Alluvial dug out under construction

In the new era of the relationship between climate and groundwater are complicated because of land-use change (LUC). LUC may exert a stronger influence on terrestrial hydrology than a climate change (Taylor et al, 2012). The expansion of rain-fed and irrigated agriculture is a major influence. The large-scale reallocation of fresh water coming from rivers, lakes and groundwater to arable land has led to

- Groundwater depletion in areas with mainly groundwater-fed irrigation
- Groundwater increase as an outcome of recharge from return flows from surface-water-fed irrigation.

Irrigation return flow is a major source of recharge in many arid and semi-arid aquifer systems (Jiménez-Martínez et al., 2010). While irrigation from groundwater pumping leads to a net reduction in aquifer storage (Stanton et al., 2011), surface water-sourced irrigation transfers water from streams to groundwater and augments natural recharge (Scanlon et al., 2007; Hanson et al., 2012). The efficiency of irrigation is particularly important, with more efficient technologies such as sprinkler and drip irrigation resulting in lower overall return flows (Scanlon et al., 2007; Dewandel et al., 2008; Kim et al., 2008), but the implementation and adoption of these techniques involves cultural and economic variables that are beyond the scope of this analysis (Steward et al., 2013). Therefore, only changes in irrigation recharge that would ensue if current farming and irrigation methods remain unchanged are considered. As irrigation leads the present-day groundwater use and depletion, the consequences of future climate variability and change on groundwater cannot be overlooked. It may be greatest through indirect effects on irrigation-water demand. Groundwater recharge forecasts are closely associated to projected changes in precipitation but the uncertainty of the current concerning climate impacts on recharge originate not from the extensive uncertainty in GCM projections of precipitation but also from that related with the downscaling of GCM projections and the hydrological models used (Taylor et al, 2012).

Urbanisation also affects the groundwater (Forster et al., 1998). Urbanization radically changes the flow paths and rates of recharge. Recharge patterns can be affected when the natural sources and infiltration routes changes by virtue of tampering with the land surface. When land-use change causes land surface to be impermeable through roads construction and buildings, it becomes mandatory for artificial drains to be built. This construction of soakaways and stormwater drains ends up collecting the rainwater from these impermeable surfaces and then creating a locally-concentrated infiltration (Lemer, 2004). The degree to which urbanization processes impacts on the underlying groundwater is a function both of the aquifer's vulnerability to contamination and its susceptibility to the significances of extreme abstraction according to Morris et al., 2003. It also initiates new abstraction regimes and adversely affect groundwater quality.

Finally, industrial and mining contributes significantly to the existence of groundwater. Activities from the mines and industry operations potentially pollutes groundwater directly or indirectly. According to Morris et al., 2003, groundwater can be polluted from acid drains. Also, deep mining results in to localize dewatering of overlying aquifer on intrusion of lower quality water on rebound.

2.6 Groundwater decision support systems

This is a knowledge base of decision-making and on tools for technical support of the decision-making process (Pierce et al., 2016). Its help decision makers to confidently make "the next to perfect" decisions in uncertain destabilize environments. The following up rising problems makes decision support system validate why they must exist**.**

- Uncertain evaluation as a result of inadequate information, system complexity,
- Number of criteria: conflicting objectives and interests,
- Heterogeneous solution possibilities,
- Interdisciplinary and complex arising situation, that is beyond the management of single person or groups of single persons,

- Easiest, reliable and immediate decisions for complex problems.

These problems are evident in water management sector and for these reasons there is a need for application of decision-support system.

According to Pierce et al., 2016, many of the support system objectives were:

- Using known and available structures, protocols, and standards to offer continuous access to an extensive body of water information;
- Provide technical support (development of processes for data procurement, metadata assistance/standards, ‘‘good practice’’ guidance, search and database integration software);
- Capacity-building in information management sector (equipping both managers and technicians through education and training);
- Facilitation of working partnerships via a physical and virtual network, the use of reliable information, and the improvement of integrated water resource management decisions;
- Creating water information database which will be available and accessible for use by decision-makers and resource managers, researchers and students and the public at large.

2.6.1 Support decisions: information needs

Because the main goal for developing a decision-support system is to be dealing with the main tasks of water management: administration, crisis management and planning. However, it is paramount that prior to the actual application development process, the actual workflow of users and their information needs ought to be collected in reference to KATER I & II. A well-structured workflow solves two most important setbacks in support decisions. Maximizing time by avoiding replica work and been the principal key for the origin of identifying the right support tools like GIS.

Owing to the nature of groundwater schemes, decision problems for natural resources like groundwater usually are in the category of growing decision context (i.e. problems that are unclearly and inaccurately defined and deficient of a known experimental approach for finding solutions). Groundwater problems from the management context will possible entail the application of a practical support of science-based planning and cooperation of DSS. Application of active DSS tools for groundwater cases are not reported, yet research studies validate transitions from passive on the way to a progressively more realistic use of DSS tools for problems. Moving forward, the context of groundwater decision support systems can be anticipated to progress toward inclining proactive types DSS.

2.6.2 Applications of decision support to groundwater cases.

Although groundwater modeling approaches have tremendously advanced, their integration in decision support processes remains imperfect, and the addition of groundwater issues within interactive and integration processes is principally absent. This section highlights the review of the use of decision analytic techniques and decision support in previous literature for groundwater problems. These problems in the past focused on relation to health and environmental quality and health concerns. For instance, groundwater problems in the area of petroleum spills, agricultural contaminants and leachate from waste site have been tackled from the risk assessment techniques (Correll and Dillon, 1993). The principal topic in groundwater researches and application is the control and management of the groundwater supply and availability, yet the number of DSS developed specifically to tackle this topic is few. Hydrogeological applications were put forth by Freeze et al.,1992 together with evaluation of decision-analysis for project evaluation. Addressing this issue, Carrerra et al., 2006, stated that to improve in connecting groundwater with geospatial utilities are restructuring methods for integrating spatially detailed models.

As said “little drops of water make mighty ocean”, Sophocleous and Ma in 1998 introduced one of the initial groundwater DSS that investigated the impact of salt water intrusion on aquifer yield. Since then, there has been much interest in decision support applications. Table 0.1 in appendix is a compilation of the literature concerning support systems and decision systems related to groundwater management. Examples comprise articles that list decision analysis applications or specific tools as well as integrated models for ecosystems decisions that includes a groundwater component.

Groundwater decision support systems should be key in providing different ways for tackling water resource management, and its operations via adaptive measures for water resources. The table 0.1 in the appendix again lists the literature under projects involving decision support and decision analysis with groundwater and other appropriate features. For example, Recio et al., 2005, on GEMCO combined a steady-state MODFLOW model to assess econometric issues arising from agricultural use on a regional scale. This example demonstrated an advancement using higher sophisticated integration of groundwater in DSS applications yet groundwater DSS have attained basically reflexive type DSS and active kind cases are emerging. Another is the MIKESHE project researched by Demetriou et al., 1999. The project addressed sustainable groundwater management problems, but failed to integrate it with optimization techniques, and rather pure scenario modeling is used. Rozos et al., 2002, in Hydroanemas incorporates stochastic programming to solve the uncertainty and investigate conjunctive usage problems by an embedded MODFLOW model to simulate groundwater response.

Pierce et al., 2016, stated that in order to achieve a forward type guidance tools for DSS, computational progression in areas such as informatics, science visualization, artificial intelligence, optimization algorithms and real-time sensing is needed. For groundwater in particular, it is usual for experts in groundwater field to pair models of groundwater response with optimization algorithms. Unfortunately, the greatest or best algorithmic support is lagging to use by expertise who are technical inclined with specific importance on applications for parameterization of numerical models instead than DSS applications.

For example, the groundwater decision support system (GWDSS) demonstrates a modern integrated example for water allocation involving both simulation-optimization and lumped parameter modelling tools according to Pierce et al. 2006. Interestingly, problems and approaches associated with support system are changing to higher levels of complexity due to improving algorithms and computation capacity. A significant obvious and visual clue of advances and maturity in the area of DSS applications which deals with groundwater related problems is recopying and implementing or and reuse of DSS methods including software application tools. A practical example can be gleaned from the implementation of Bayesian networks by Fienen et al., 2013b, Molina et al., 2013a and Moura et al., 2011, where across the multiple cases demonstrates just a carbon copy of methodology, using of software tool (WEAP-MODFLOW) which is still gaining attention across numerous applications. A lot of works have produced new tools and methods that aims at providing a more comprehensive approach to DSS for groundwater. Some of these is shown in the table below that can be grouped as active kind of DS

Based on the decision support system literature, Groundwater Modelling System (GMS) MODFLOW is the preferred software tool for this research per the available data of the study area. Groundwater model commonly used globally is MODFLOW. It stands for MODular groundwater FLOW model. It is a three-dimensional model based on finite difference technique. A code written by FORTRAN. It has a modular format and consist of a 'main' program and a series of highly independent subroutines called 'modules'. Application of the model involves the user introducing input parameters by means of data file (text file) or interfaces that help users to set-up a data file in a user-friendly way because of how tedious it setting up could be. During application of the model, the study area is divided up in finite difference cells which vary in size depending upon the desired accuracy. In delineating the boundary of the study area, cells can be put inactive as shown in the figure below. Vertical dimension of groundwater modelling is represented as layers.

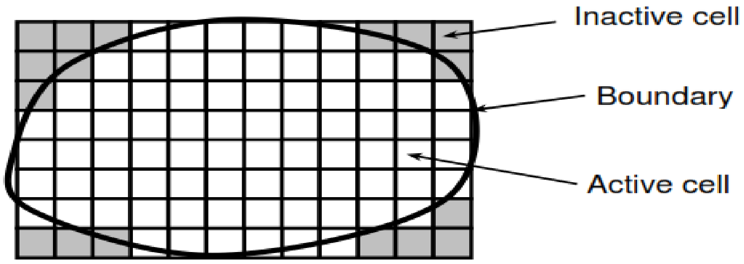


Figure 2.6: Horizontal discretisation of a study area in computational cells.

An aquifer can be represented by several layers in order to increase the vertical resolution. Basically, each computational cell can be represented by its column, row and layer number

3 CHAPTER 3: Materials and Methods

3.1 Study Area Description

3.1.1 Physical geography

The study area is the Atankwidi basin. The Atankwidi river is a tributary of the White Volta river, which is one of the three major tributaries of the Volta river system in West Africa. Located between latitude 12°30’N and 10°48’N and between longitude 0°49’W and 1°2’W, the Atankwidi basin is a transboundary basin shared by Ghana and Burkina Faso, with the upper to the middle reaches in Burkina Faso and the middle to the lower reaches in Ghana (Figure 3.1). The basin has a drainage area of about 286 km^2 (Barry et al., 2010). The elevation of the basin ranges from about 150m at the outlet in the south to about 352m in the upper reach in the north of the basin, with an average elevation of about 220m.

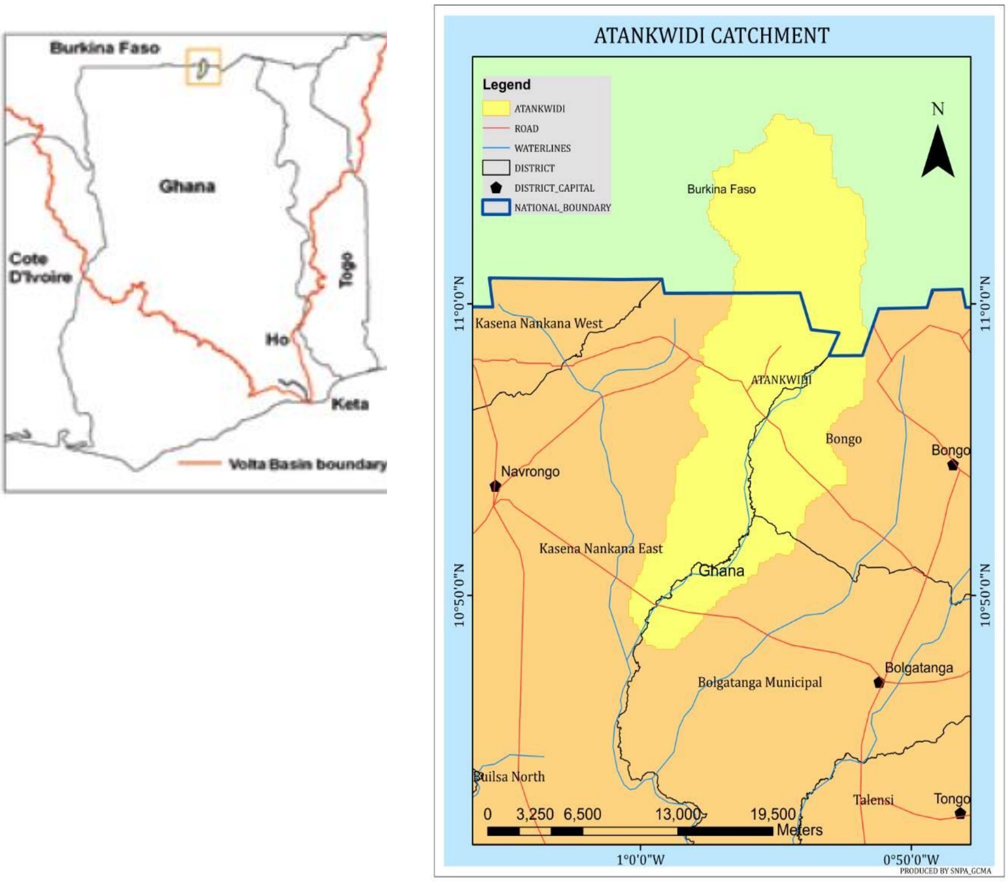


Figure 3.1: Map of the Atankwidi River

3.1.2 Climate

The climate of the Atankwidi basin can be classified based on the Köppenclimate classification as tropical savanna, which is generally characterized by monthly mean temperatures above 18°C in every month and a pronounced dry season (McKnight et al. 2000). Similar to the rest of the Volta Basin, the climate of Atankwidi is controlled by the movement of the Intertropical Convergence Zone (ITCZ) during the course of the year. The nature and period of movement of the ITCZ over the Atankwidi area is responsible for the distinct dry (October – April) and wet seasons (May – September) as well as the mono-modal rainfall pattern experienced in the basin.

Rainfall increases from the north of the basin in Burkina Faso to the south in Ghana and peaks in August. There are no observational weather stations in the basin but based on data from the nearest synoptic station (Navrongo), which is about 15 km away from the center of the basin, the long term (1986-2010) mean annual rainfall is about 980 mm. The rainfall exhibits high spatial and temporal variability (Figure 2). The long-term mean daily temperature (Tmean) varies from 26°C in August (month of peak rainfall) to 32°C in March/April (the peak of the dry season). The mean maximum temperature (Tmax) is constantly above 30°C while the mean minimum temperature (Tmin) is always above 18°C (Figure 3.2).

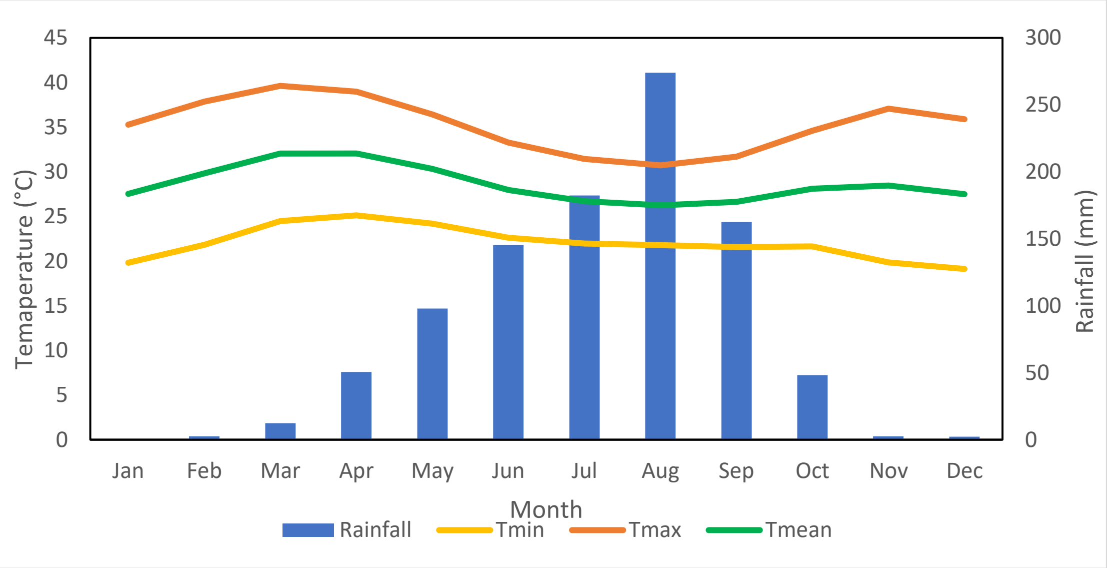


Figure 3.2: Long-term (1986-2010) mean month rainfall and temperature over Atankwidi basin, based on the Navrongo synoptic weather station (Data source: Ghana Meteorological Agency). Relative humidity varies between 10% in December/January to about 65% in August (Martin 2005) while potential evapotranspiration ranges between 2200 mm and 1800 mm (Johnston & McCartney 2010).

3.1.3 Hydrogeology

The Atankwidi basin is underlain by the Birimain sub-formation of the Crystalline basement formation that dominate the geology of the Volta basin (Obuobie et al., 2016; Martin, 2006). Martin (2006) identified three Birimian formations in the basin, namely, Granitoids, Birimian metasediments, and intrusive Bongo granite. The granitoids underlain most parts of the basin. They are of Paleoproterozoic in age and consist of hornblend-biotite granodiorite, biotite granite and biotite gneiss. The Birimian metasediments exist as small patches among the granitoids. They are made up of phyllite, schist and quartzite. The intrusive Bongo granite is the most recent geological formation in the Atankwidi basin (Murray, 1960 cited in Martin, 2006) and underlain the eastern portion of the basin. It has high quartzite content and very resistant to weathering, resulting in frequent outcrops. The Birimian bedrocks are overlain by weathered layers of varying thickness (Martin, 2006) as depicted in figure 3.3. The thickness of the weathered layers is influenced by lithology, topography, vegetation cover, structural characteristics, erosion and climate (Obuobie et al., 2016).

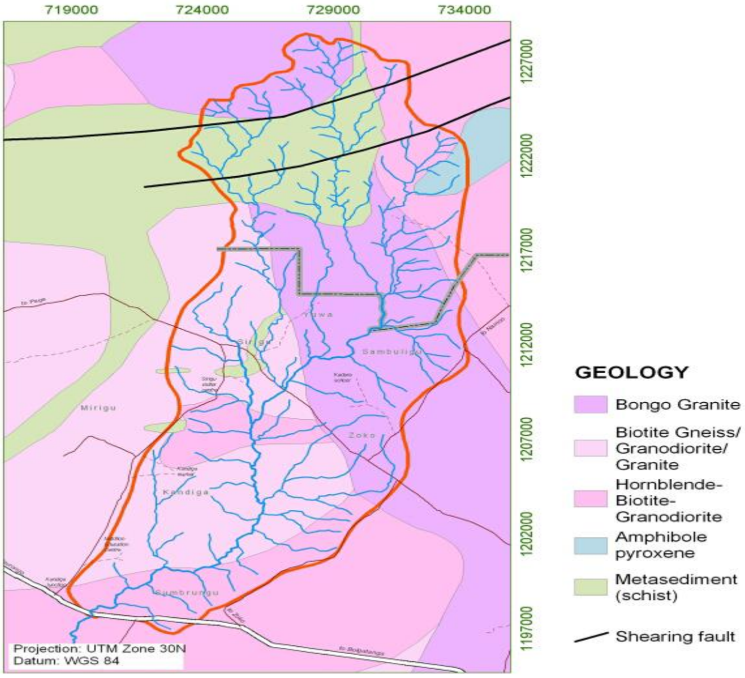


Figure 3.3: Geological formations in the Atankwidi Basin (Martin, 2006)

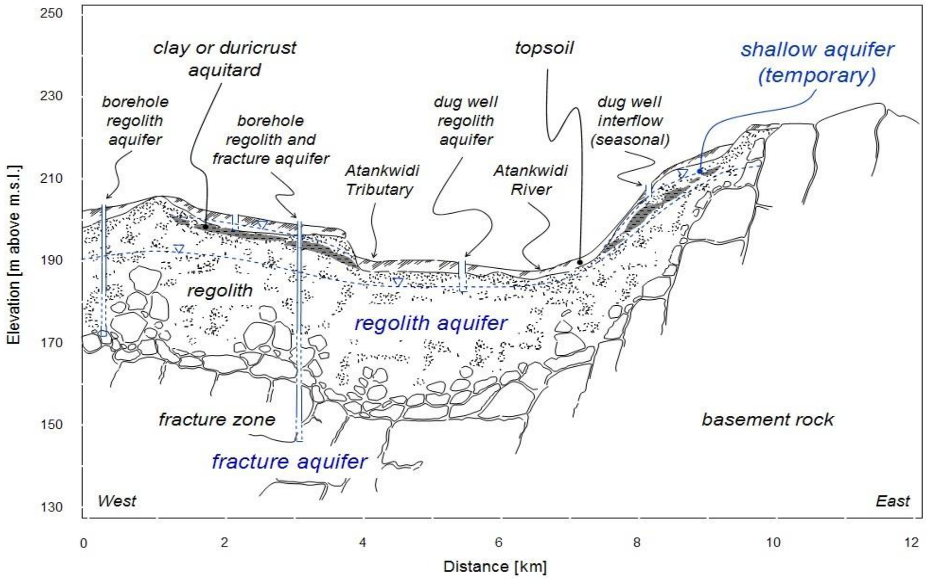


Figure 3.4: Hydrogeological cross section of the Atankwidi basin (Martin, 2006)

The Precambrian granitoids are predominant in this study area. The basement aquifer is the type of aquifers known in the study area. This is due to the fact that the basement aquifers are developed in the in the weathered mantle and the fractured bed rock (Chilton et al., 1993). Rock materials that are highly decomposed and rich in clay and silt are often the typical weathering profile. The upper layer of the weathered profile sometimes is taken of due to the age and exposure to erosion. The lower portion of the weathered region is the most appropriate for borehole exploitation because clay is often absent in the lower part.

A typical basement aquifer has the characteristics of low transmissivity but has sufficient yield. And this has caused drilling companies to often detect semi-confined situations when drilling boreholes in regolith aquifers because of the low permeability in the clayey which lies in the upper part of the profile. Subsequently, the static water level is known to be slightly higher than where water was first tapped during drilling.

Borehole reports from (Water Research institute, 2013) are accessible for 9 boreholes in the study area. Almost all the boreholes are drilled through the entire depth of the weathered zone into a few meters of the fresh rock. The reports show that in the areas where there are only slightly weathered rock contains the main water bearing region. The geological formation of the borehole moves from reddish brown clay to completely weathered brown granite to moderately weathered yellowish-brown granite to slightly weathered granite to fresh granite. Due to this the weathered zone underlying the bottom of the drilling profile is not captured or documented. This is major constraints to identifying if the borehole tapped into the fractured rock aquifer or regolith aquifer. Granite was identified as the bed rock for all the profile.

From Martin, 2006, groundwater flow is in the direction of topographic elevation of the regolith aquifer. The depth to the water table is shallowest at the highest topographic elevations like Kandiga, Sirigu and Bongo and Zoko. The reason for this surprising observation could be a combination of low lateral hydraulic conductivity and high recharge rates.

The Atankwidi basin in the Volta River Basin according to Martin, 2006 is one of the highly groundwater use area per square kilometer (Km^2). The distance between wells and the riverbed is 15-500m. The Regolith aquifer is the main aquifer type in the weathered zone of granitoids covering about two-thirds area of the Volta Basin (Martin, 2006). The thickness of the underlying aquifer varies from 2.60 to 13.7m and it has a low resistivity in the range of 3.2-55.3ohm-m which suggest a high clay content area (Adelana et al., 2008). The total volume of water stored annually in the basin is 3.7x10^{8}m^3 and an annual withdrawal for irrigation at 8.9x10^{4}m^3-2l/d/m^2 at planting stage and 5l/d/m^2 at flowering stage (Barry et al, 2010).

3.1.4 Soils

The soil types of Atankwidi basin can be distinguished into 3 main types according to the Environmental Protection Agency (EPA) of the Soil Research Institute (SRI) of Ghana; Leptosis which are predominantly along the elevated northern and eastern border; Fluvisols which are found in the flat terrain to the sides of the main stream and Lixisols which covers the rest of the basin. Lixisols typically is made up of sandy loam to sandy clay loam, high clay contents predominant in the upper layer of the profile and have increasingly coarse texture with depth. In the low-lying areas, Atankwidi river especially the small slope at the sides of the lower reach has a soil profiles down to hand auger depth consisted of compacted clay loam and can be classified as Fluvisols. The high clay content and compact nature result in a low hydraulic conductivity of the top soil.

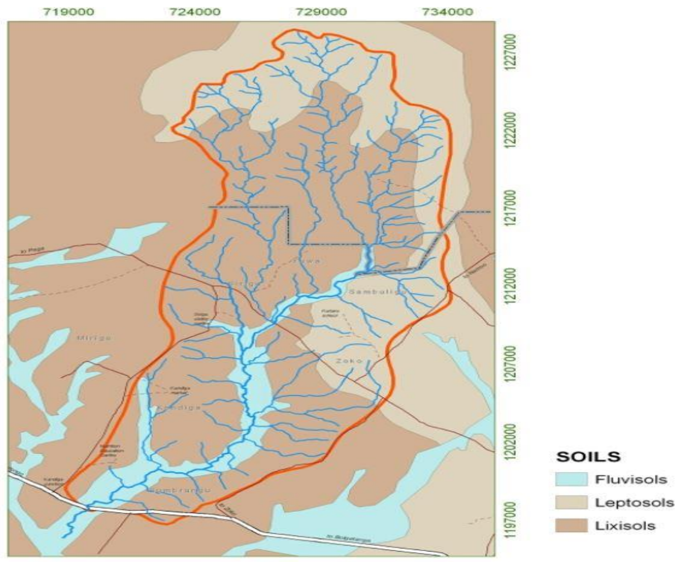


Figure 3.5: Soil map of Atankwidi (Martin, 2006)

3.2 Methods

The methodological approach used in this study consisted of adapting a groundwater model (GMS - MODFLOW) to the Atankwidi basin to simulate the present state of the groundwater system followed by driving the adapted model with future projected groundwater recharge and demands to determine impacts on the groundwater resource (Figure 3.6).

The approach consisted of adapting.

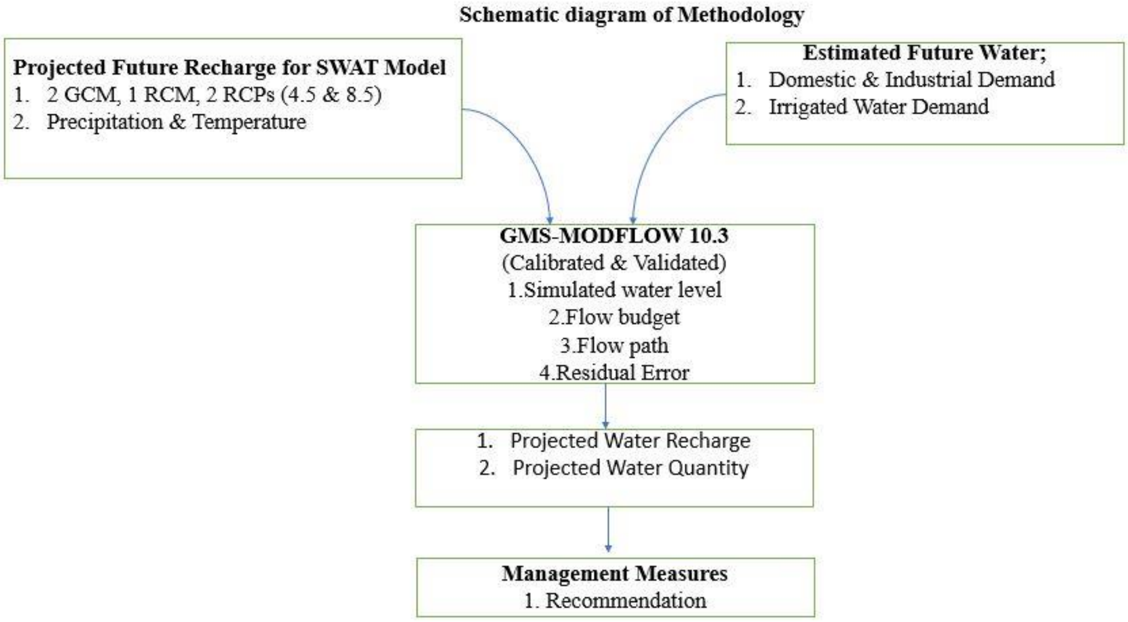


Figure 3.6: A schematic diagram of study approach

3.2.1 Groundwater Modelling in GMS-MODFLOW

The Groundwater Modelling System (GMS) is a kind of water modelling application which aims at building and simulating groundwater models. The GMS system has a graphical user interface, 2D and 3D geostatistics, analysis codes (MODFLOW, MT3D, MODPATH, SEEP2D, FEMWATER) and a unique conceptual model approach. The GMS interface initially was developed by the Engineering Computer Graphics Laboratory at Brigham Young University and sponsored by the U.S. Army Engineer Waterways Experiment Station. GMS focuses on providing interfaces for the following; Transport flow and contaminant modeling, groundwater flow model interface and MODFLOW. GMS has tools that supports model conceptualization, grid generation, site characterization, mesh etc. it also includes a suite of tools that with creating high level representations of groundwater model in the Map Model using GIS objects. Works model in GMS can be imported or exported between Arc Info or ArcView and GMS. This research uses the Modflow of GMS. MODFLOW is a computer program that simulates three-dimensional ground-water flow through a porous medium by using a finite-difference method (McDonald and Harbaugh, 1988). MODFLOW is considered an international standard for simulating and predicting groundwater conditions and groundwater/surface-water interactions. The model describes groundwater flow of constant density under non-equilibrium conditions in a heterogeneous and anisotropic medium according to the following equation:

$$\frac{\partial}{\partial x}(k_{xx}) + \frac{\partial}{\partial y(\partial h|\partial x)}\left(k_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_{zz}\frac{\partial h}{\partial z}\right) + q_s = s_s\frac{\partial h}{\partial y} - w$$

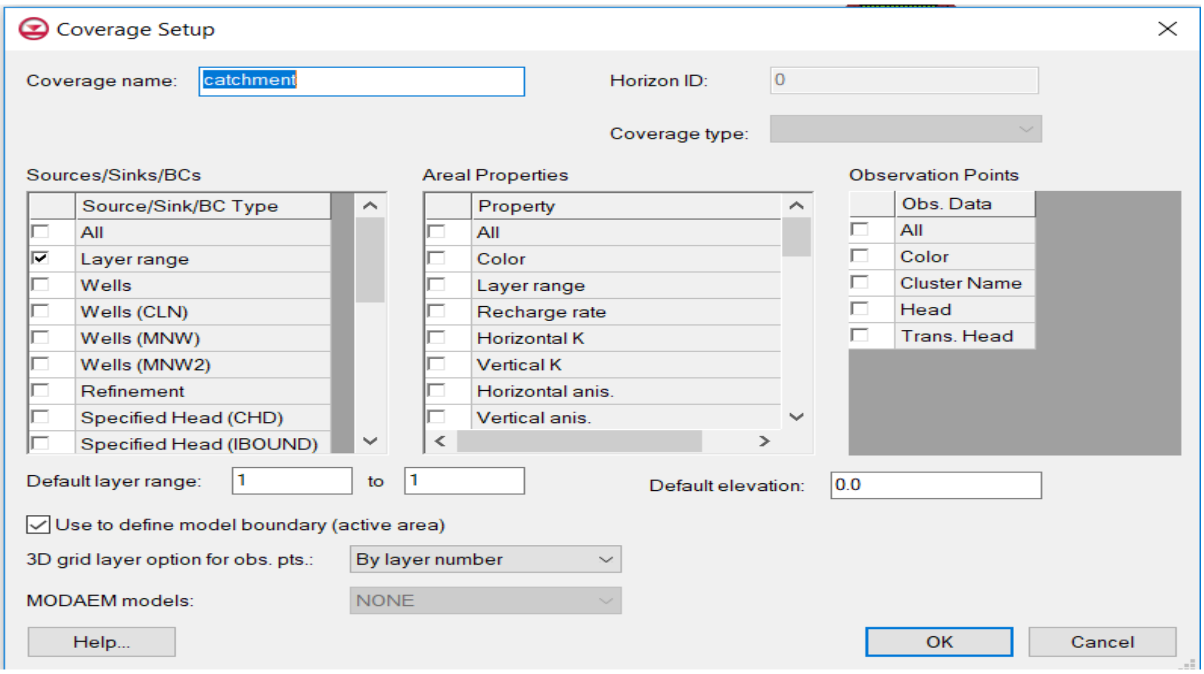
k_{xx}, k_{yy}, and k_{zz}, are values of hydraulic conductivity (L T^{-l}); along the x, y, and z coordinate axes; h is the potentiometric head (L); W is the flux per unit volume and q_s represent volumetric flux of groundwater sources and/or sinks of water (T^{-l}); Ss is the specific storage of the porous material (L^{-l}); and t is time (T). The model used the finite difference approach to solve the groundwater flow equation.

3.2.2 Model grid setup

MODFLOW requires subdividing the groundwater flow region into blocks. Each block is presumed to homogeneous and therefore average values of groundwater variables are applied to the block. The grid model of the Atankwidi aquifer covered only the portion of the basin in Ghana specifically located between latitude 10° 47'N and 11°N and longitude 0° 52'W and 1° 15'W and covers an area of about 206km^2. The grid model consisted of 70000 cells but 29358 active cells. The grids were refined in the area of wells for the layer and detailed information on the aquifer properties were provided as inputs to the model. The groundwater system was built for the layer by assigning the hydraulic conductivity, transmissivity and porosity, and to the grid cells using all information of the present work.

3.2.3 Model conceptualization

The study is about simulating a three-dimensional unsteady groundwater. In order to achieve this a detailed, accurate and reliable information with precise description of the groundwater system are needed. Database like geological data (DEM layer, shapefiles, aquifer thickness), boundary conditions (general head), hydraulic parameters (specific yield, hydraulic conductivity), budget components (observation wells, abstraction, recharge). Achieving this, the conceptualization and characterization of the Atankwidi aquifer were done in ArcGIS 10.4 software and then imported these layers into GMS 10.3 software to developing the conceptual model using a number of layers. The model was changed to MODFLOW model in a 3D grid and the software of GMS.



Coverage name: catchment

Horizon ID: 0

Coverage type:

☐ All
☑ Layer range
☐ Wells
☐ Wells (CLN)
☐ Wells (MNW)
☐ Wells (MNW2)
☐ Refinement
☐ Specified Head (CHD)
☐ Specified Head (IBOUND)

Default layer range: 1 to 1

Default elevation: 0.0

☑ Use to define model boundary (active area)

3D grid layer option for obs. pts.: By layer number

MODAEM models: NONE

Figure 3.7: Atankwidi Basin set up using GMS

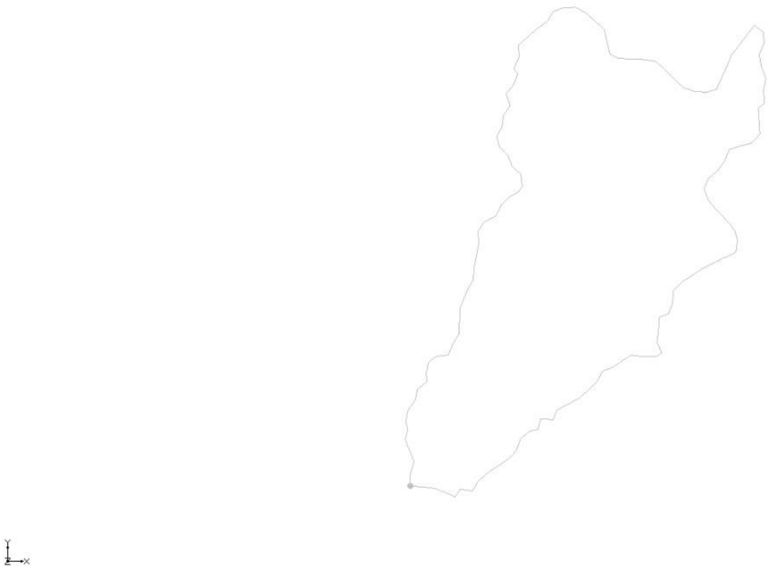


Figure 3.8: Importing of Atankwidi shapefile

3.2.4 Calibration and validation of groundwater flow model

Normally a model is a representation of a real hydrological system. A conceptual model was used in this research and calibrated. However, the first modelling results did not mimic the actual system in reality. This exercise was done by calibrating certain parameters until the goodness fit of model was achieved. Goodness of fit was seen by comparing simulated hydraulic heads with observed ones (25 observation wells) distributed in the aquifers of the sub basin. This model had the point observation type. The point observation presented the locations of the observed values in the basin area or on the field. The points corresponded with the hand dug wells and the values represented the elevation of the head (groundwater table). After the first simulation, the calculated heads for the layer were compared by the measured ones and the result was poor. As a result, the calibration of the model became critical and important to attain goodness of fit.

Calibration was carried out in two steps. First by a manual method (trial–and-error) through modifying the hydraulic parameters of the aquifer until a satisfied difference between the calculated and measured heads was reached. Manual calibration undergoes forward run and this is done to suit the observed to the computed. Additionally, a PEST calibration method was also used. Pest calibration undergoes the back-forward run. This approach is used to assign values that are not captured in the model. PEST provides an alternative for the Pilot Point Method termed Regularization. The introduction of PEST causes a supplemental measure of restriction to the parameter being interpolated. This constraint brands the inversion method more stable and violate the one of the typical constraints associated with parameter estimation. This violation is about, the number of parameters must be less than the number of observations. Regularization makes it probable for the number of parameters to surpass the number of observations and this technique provides the decision for complex hydraulic conductivity movement to be defined that results to enormously low residual error.

For this reason, the best values used are negative values since the manual calibration uses positive values. The model performance was evaluated by visual comparison of groundwater levels (observed versus simulated) and using Root Mean Square Error (RMSE) as a statistical measure. The standard for the error difference must be lowered to 0.05 m for the layer. As a result, head distribution maps resulted from the model are closely related to the actually measured maps.

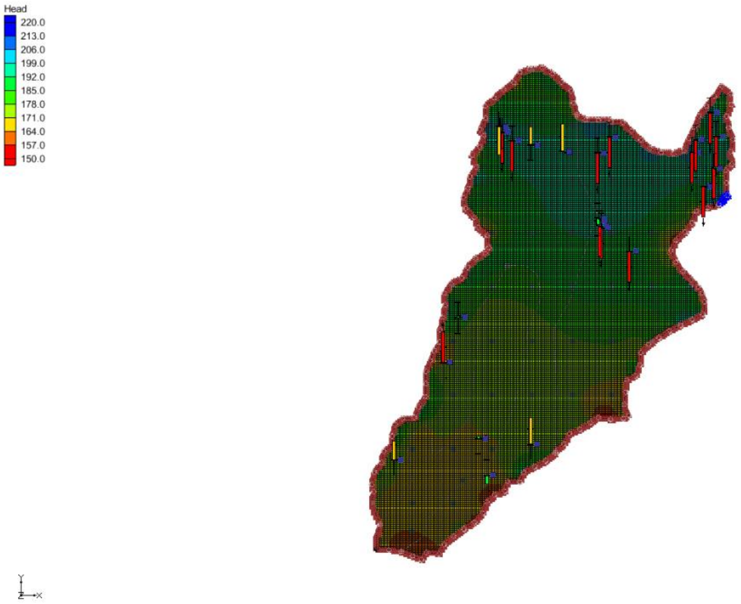
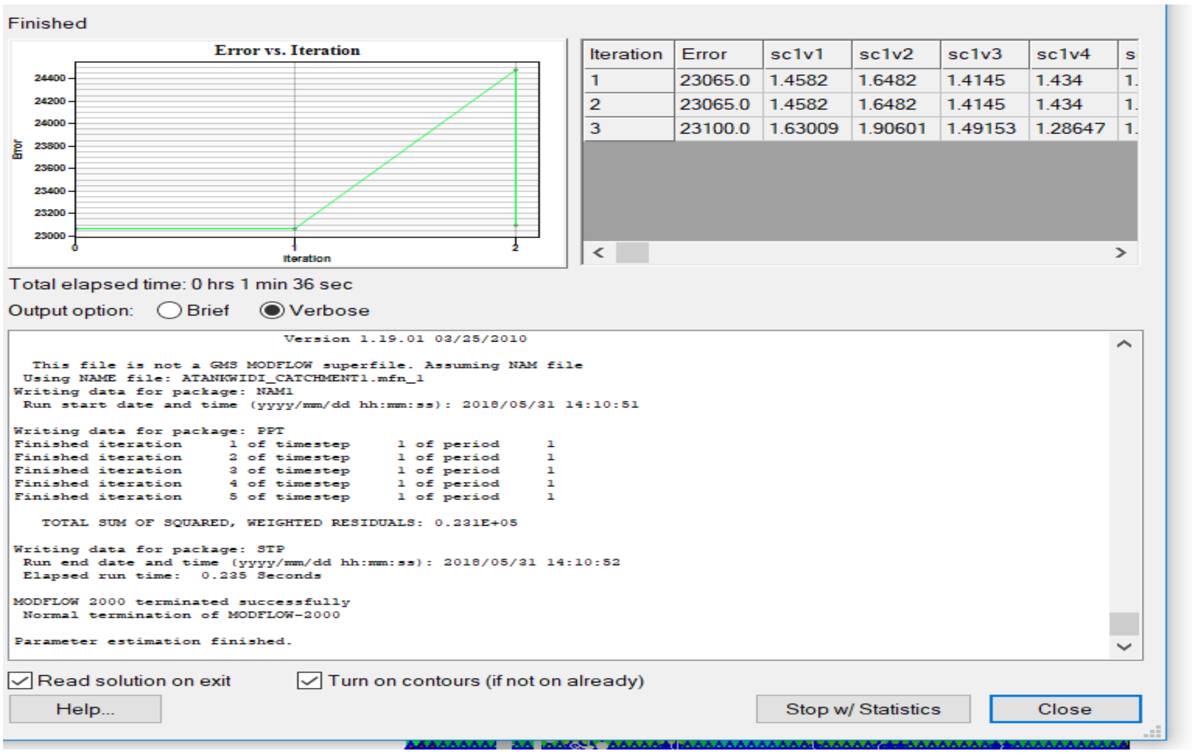


Figure 3.9: Atankwidi basin under manual (trial and error) calibration.



Iteration	Error	sc1v1	sc1v2	sc1v3	sc1v4	s
1	23065.0	1.4582	1.6482	1.4145	1.434	1.
2	23065.0	1.4582	1.6482	1.4145	1.434	1.
3	23100.0	1.63009	1.90601	1.49153	1.28647	1.

Total elapsed time: 0 hrs 1 min 36 sec

Output option: ○ Brief ● Verbose

```
                              Version 1.19.01 03/25/2010

  This file is not a GMS MODFLOW superfile. Assuming NAM file
 Using NAME file: ATANKWIDI_CATCHMENT1.mfn_1
Writing data for package: NAM1
 Run start date and time (yyyy/mm/dd hh:mm:ss): 2018/05/31 14:10:51

Writing data for package: PPT
Finished iteration     1 of timestep     1 of period     1
Finished iteration     2 of timestep     1 of period     1
Finished iteration     3 of timestep     1 of period     1
Finished iteration     4 of timestep     1 of period     1
Finished iteration     5 of timestep     1 of period     1

   TOTAL SUM OF SQUARED, WEIGHTED RESIDUALS: 0.231E+05

Writing data for package: STP
 Run end date and time (yyyy/mm/dd hh:mm:ss): 2018/05/31 14:10:52
 Elapsed run time:  0.235 Seconds

MODFLOW 2000 terminated successfully
 Normal termination of MODFLOW-2000

Parameter estimation finished.
```

☑ Read solution on exit ☑ Turn on contours (if not on already)

Figure 3.10: Calibration of Atankwidi basin using PEST Parameter estimation

3.2.5 Calibration target

During calibration, the observed values were assigned to feature object, the calibration at each object was plotted using a ‘calibration target’. This set of targets provided useful feedback on the magnitude, direction (high, low) and spatial distribution of the calibration error. Calibration targets was drawn such that the height of the target was equal to twice the confidence interval

(+interval on the top, - interval on the bottom). The figure 3.11 below illustrates the calibration target.

The top of the target corresponds to the observed value plus the interval and bottom corresponds to the observed value minus the interval. The observed interval for the system was set to 3 and it also serves as a calibration target for the observed wells in the model. The coloured bar represents the error. If the bar lies entirely within the target, the colour bar is green. If the bar is outside the target, but the error is less than 100%, the bar is drawn in yellow. If the error is greater than 200%, the bar is drawn in red.

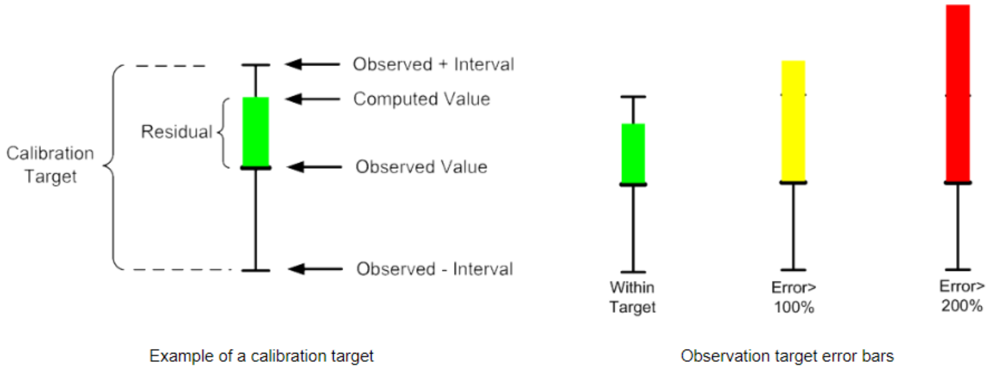


Figure 3.11: Calibration target

3.2.6 Parameter Sensitivity

A plot of parameter sensitivity was the means in showing the sensitivity of the MODFLOW parameters. The plot was created in the plot wizard by setting the Plot Type to “Parameter Sensitivity”.

3.2.7 Difference between head of flow errors and simulation

Figure 3.12 shows measurement types as well as steady-state simulations. In this case, a clear pictorial explanation for the mean error, mean absolute error and the root mean squared between the successive solution and observed data is the objective. This is because various simulation was run after changing model parameters such as recharge and hydraulic conductivity, this plot showed the trend in the solution if the model parameters changes are causing better calibration with measured field data.

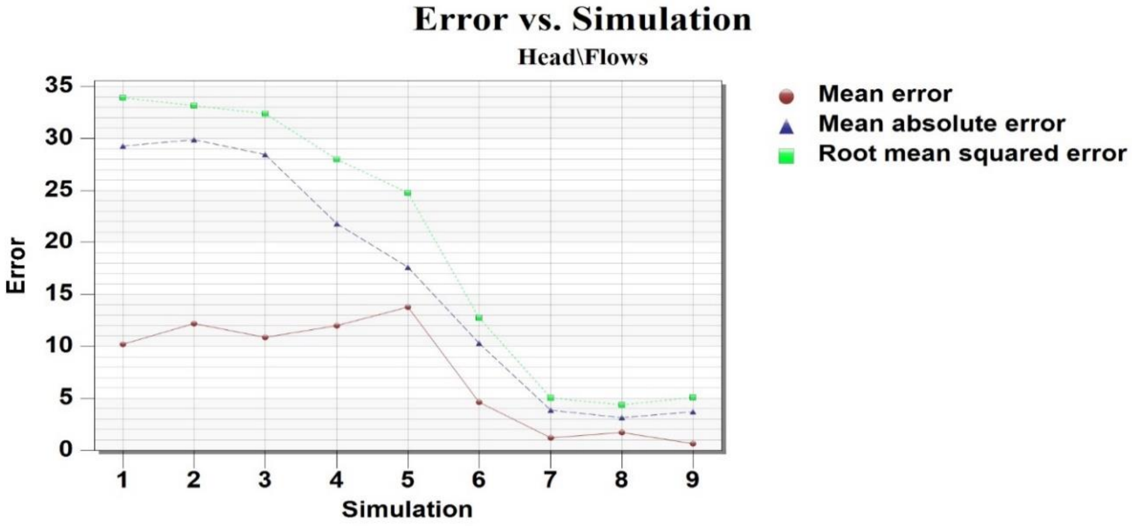


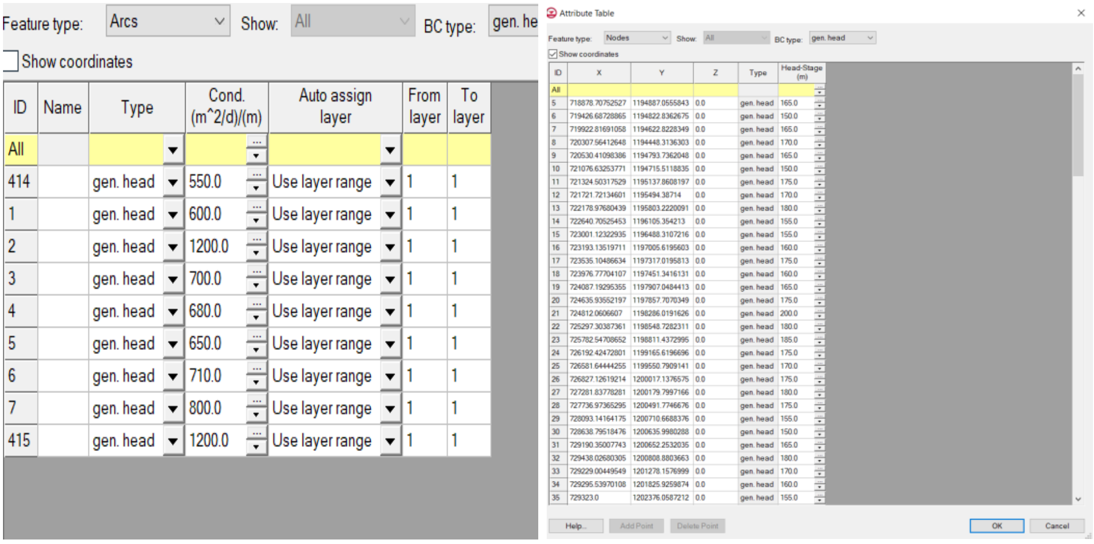
Figure 3.12: Head of flow errors against simulation of the Atankwidi basin

3.3 Data and sources

During the second visitation in April 2018, and difficulty in scheduling a suitable meeting with the borehole technician, used and unused hand dug wells suitable for measurement of static water level were located within the basin. Although the coordinates of hand dug wells measured by martin in 2002-2003 were available and were to be used as monitored wells, all the wells were replaced with different brand (modernised hand dug wells) so they were not accessible for measurement. The exact location for the suitable hand dug wells as well as elevation were determined using a GPS (Garmin GPSmap 62 handheld) and a deep meter for the groundwater level measurement. Though it was in the dry season, the hand dug wells (elevation or fluctuation) that were around the boreholes which were in use consistently had water available in them. This justified the question if boreholes and hand dug wells were tapped in the same aquifer (regolith). Due to time constraints, manual groundwater level measurement was taken once and in the dry season (mid-April) and was also limited to the Ghanaian area of the basin. This confirms a one-layer groundwater modelling setup. In total, 25 hand dug wells measured.

3.3.1 Boundary conditions

In building the numerical MODFLOW model for the study area, various boundary conditions were defined. In the case of Atankwidi basin, General Head Boundaries (GHB) as shown in figure 3.13 were applied to the southern and northern boundaries of the model domain. The hydraulic heads and hydraulic conductance of the layer were assigned to boundary cells. Based on the contour and elevation map of the Atankwidi sub basin, arbitrary values were applied for both boundaries. The values of the southern boundary were within the ranges of 150 m and 180 m as head and 520 to 800 m^2/day as hydraulic conductance while that of the northern boundary were within the ranges of 200 m and 250 m and 1000 to 2500 m^2/day as head and hydraulic conductance in the boundary respectively. These heads varied during the simulation process according to different stresses applied on the modelled area.



Feature type: Arcs Show: All BC type: gen. he

☐ Show coordinates

ID	Name	Type	Cond. (m^2/d)/(m)	Auto assign layer	From layer	To layer
All						
414		gen. head	550.0	Use layer range	1	1
1		gen. head	600.0	Use layer range	1	1
2		gen. head	1200.0	Use layer range	1	1
3		gen. head	700.0	Use layer range	1	1
4		gen. head	680.0	Use layer range	1	1
5		gen. head	650.0	Use layer range	1	1
6		gen. head	710.0	Use layer range	1	1
7		gen. head	800.0	Use layer range	1	1
415		gen. head	1200.0	Use layer range	1	1

Feature type: Nodes Show: All BC type: gen. head

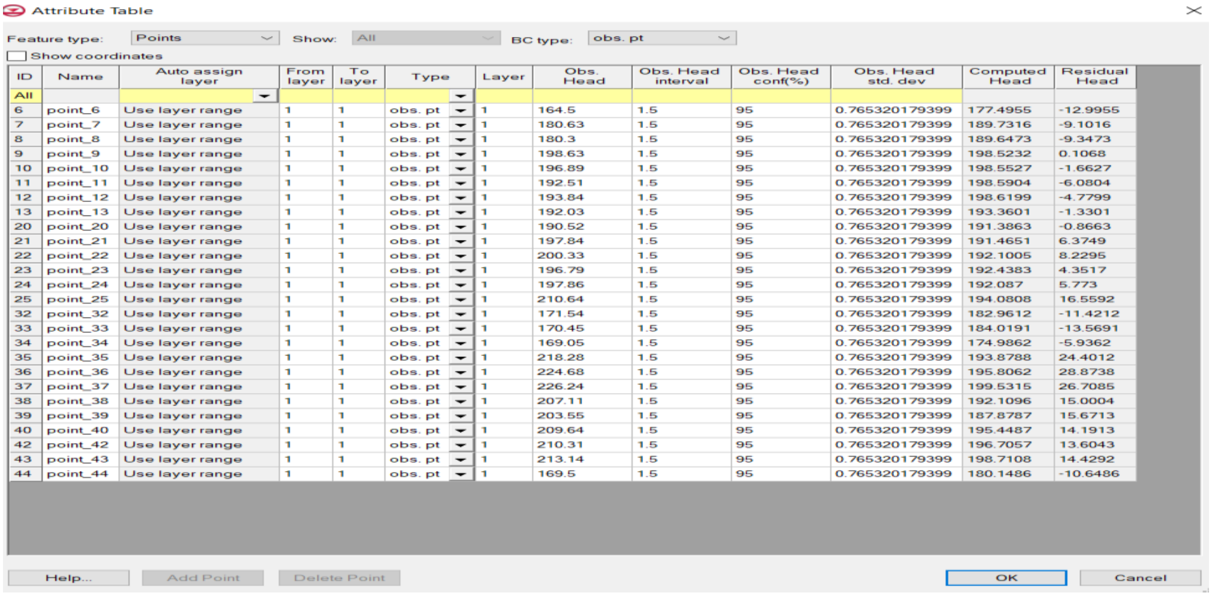
☑ Show coordinates

ID	X	Y	Z	Type	Head-Stage (m)
All					
5	718878.70752527	1194887.0555843	0.0	gen. head	165.0
6	719426.68728865	1194822.8362675	0.0	gen. head	150.0
7	719922.81691058	1194622.8228349	0.0	gen. head	165.0
8	720307.56412648	1194448.3136303	0.0	gen. head	170.0
9	720530.41098386	1194793.7362048	0.0	gen. head	165.0
10	721076.63253771	1194715.5118835	0.0	gen. head	150.0
11	721324.50317529	1195137.8608197	0.0	gen. head	175.0
12	721721.72134601	1195494.38714	0.0	gen. head	170.0
13	722178.97680439	1195803.2220091	0.0	gen. head	180.0
14	722640.70525453	1196105.354213	0.0	gen. head	155.0
15	723001.12322935	1196488.3107216	0.0	gen. head	155.0
16	723193.13519711	1197005.6195603	0.0	gen. head	160.0
17	723535.10486634	1197317.0195813	0.0	gen. head	175.0
18	723976.77704107	1197451.3416131	0.0	gen. head	160.0
19	724087.19295355	1197907.0484413	0.0	gen. head	165.0
20	724635.93552197	1197857.7070349	0.0	gen. head	175.0
21	724812.0606607	1198286.0191626	0.0	gen. head	200.0
22	725297.30387361	1198548.7282311	0.0	gen. head	180.0
23	725782.54708652	1198811.4372995	0.0	gen. head	185.0
24	726192.42472801	1199165.6196696	0.0	gen. head	175.0
25	726581.64444255	1199550.7909141	0.0	gen. head	170.0
26	726827.12619214	1200017.1376575	0.0	gen. head	175.0
27	727281.83778281	1200179.7997166	0.0	gen. head	180.0
28	727736.97365295	1200491.7746676	0.0	gen. head	175.0
29	728093.14164175	1200710.6688376	0.0	gen. head	155.0
30	728638.79518476	1200635.9980288	0.0	gen. head	150.0
31	729190.35007743	1200652.2532035	0.0	gen. head	165.0
32	729438.02680305	1200808.8803663	0.0	gen. head	180.0
33	729229.00449549	1201278.1576999	0.0	gen. head	170.0
34	729295.53970108	1201825.9259874	0.0	gen. head	160.0
35	729323.0	1202376.0587212	0.0	gen. head	155.0

Figure 3.13: General Head boundaries of the Atankwidi basin set up

3.3.2 Piezometric wells

There are over 200 wells within Atankwidi basin, however due to the constraints of reaching the borehole technician, the study relied on hand dug wells and therefore only 25 hand dug wells were applicable for the groundwater modelling as shown in figure 3.14 and appendix 0.2. Others though measured, fell outside the aquifer boundaries. 25 observation wells data were used in simulating the steady state groundwater model. These data are most important for the calibration and validation of the model.



Feature type: Points Show: All BC type: obs. pt

☐ Show coordinates

ID	Name	Auto assign layer	From layer	To layer	Type	Layer	Obs. Head	Obs. Head interval	Obs. Head conf(%)	Obs. Head std. dev	Computed Head	Residual Head
All												
6	point_6	Use layer range	1	1	obs. pt	1	164.5	1.5	95	0.765320179399	177.4955	-12.9955
7	point_7	Use layer range	1	1	obs. pt	1	180.63	1.5	95	0.765320179399	189.7316	-9.1016
8	point_8	Use layer range	1	1	obs. pt	1	180.3	1.5	95	0.765320179399	189.6473	-9.3473
9	point_9	Use layer range	1	1	obs. pt	1	198.63	1.5	95	0.765320179399	198.5232	0.1068
10	point_10	Use layer range	1	1	obs. pt	1	196.89	1.5	95	0.765320179399	198.5527	-1.6627
11	point_11	Use layer range	1	1	obs. pt	1	192.51	1.5	95	0.765320179399	198.5904	-6.0804
12	point_12	Use layer range	1	1	obs. pt	1	193.84	1.5	95	0.765320179399	198.6199	-4.7799
13	point_13	Use layer range	1	1	obs. pt	1	192.03	1.5	95	0.765320179399	193.3601	-1.3301
20	point_20	Use layer range	1	1	obs. pt	1	190.52	1.5	95	0.765320179399	191.3863	-0.8663
21	point_21	Use layer range	1	1	obs. pt	1	197.84	1.5	95	0.765320179399	191.4651	6.3749
22	point_22	Use layer range	1	1	obs. pt	1	200.33	1.5	95	0.765320179399	192.1005	8.2295
23	point_23	Use layer range	1	1	obs. pt	1	196.79	1.5	95	0.765320179399	192.4383	4.3517
24	point_24	Use layer range	1	1	obs. pt	1	197.86	1.5	95	0.765320179399	192.087	5.773
25	point_25	Use layer range	1	1	obs. pt	1	210.64	1.5	95	0.765320179399	194.0808	16.5592
32	point_32	Use layer range	1	1	obs. pt	1	171.54	1.5	95	0.765320179399	182.9612	-11.4212
33	point_33	Use layer range	1	1	obs. pt	1	170.45	1.5	95	0.765320179399	184.0191	-13.5691
34	point_34	Use layer range	1	1	obs. pt	1	169.05	1.5	95	0.765320179399	174.9862	-5.9362
35	point_35	Use layer range	1	1	obs. pt	1	218.28	1.5	95	0.765320179399	193.8788	24.4012
36	point_36	Use layer range	1	1	obs. pt	1	224.68	1.5	95	0.765320179399	195.8062	28.8738
37	point_37	Use layer range	1	1	obs. pt	1	226.24	1.5	95	0.765320179399	199.5315	26.7085
38	point_38	Use layer range	1	1	obs. pt	1	207.11	1.5	95	0.765320179399	192.1096	15.0004
39	point_39	Use layer range	1	1	obs. pt	1	203.55	1.5	95	0.765320179399	187.8787	15.6713
40	point_40	Use layer range	1	1	obs. pt	1	209.64	1.5	95	0.765320179399	195.4487	14.1913
42	point_42	Use layer range	1	1	obs. pt	1	210.31	1.5	95	0.765320179399	196.7057	13.6043
43	point_43	Use layer range	1	1	obs. pt	1	213.14	1.5	95	0.765320179399	198.7108	14.4292
44	point_44	Use layer range	1	1	obs. pt	1	169.5	1.5	95	0.765320179399	180.1486	-10.6486

Figure 3.14: Observation points for setup showing the computed head and the residual head of the Atankwidi basin

Figure 3.15: Observed wells within the Atankwidi basin

Table 3.1: Summary of data collected and tools required

Data types	Sources	Tools
Lithological data	CSIR-WRI, CWSA	GPS
Shapefiles (Basin boundary, Rivers, Roads, Towns)	CSIR-WRI	Deep meter
SRTM 30m resolution DEM	NASA	GMS software
Pumping Test Data	CSIR-WRI	Arc GIS
Observed data (static water levels, elevation)	FIELD	SWAT
Climatic Data	CORDEX Archives, Ghana Met. Agency, WASCAL	EXCEL
Projected recharge	CSIR-WRI	MICROSOFT WORD
Population Data	GSS	LAPTOP

For this reason, only the Ghanaian area of Atankwidi was considered in this research model build up. Similarly, Atankwidi do not have its recharge connected. And due to the crystalline nature of the aquifer, there is no segment flow or insignificant because they have discrete or pocket type of aquifer which pre-suggest that flows or quantity in the aquifer is mostly influenced by precipitation and there is a great decrease in water level when affected by seasonal change.

3.4 Impacts of future scenarios on the groundwater resource

After calibrating the MODFLOW model for the Atankwidi basin, the model was used to predict the response of the groundwater system to future groundwater recharge and water demands, separately and jointly. Three future scenarios were developed and compared to the present status (baseline) (Table 3.3). Scenario 1 considers a future in which groundwater recharge changes in response to climate change but groundwater demands remain significantly unchanged. Scenario 2 is built around a future in which groundwater recharge remains significantly unchanged but groundwater demand changes significantly due to increase in population, livestock numbers, cropping intensity, urbanization and slight increment in industrial activities. Scenario 3 depicts a future in which both recharge and demand changes concurrently. The future scenarios covered the time horizon of 2051-2080 while the baseline covered the period 1986-2015.

3.4.1 Future projected groundwater recharge

The future groundwater recharge projection for the Atankwidi basin was obtained from ongoing hydrological modelling work of the CSIR-Water Research Institute, Ghana, in the Atankwidi basin. The recharge was simulated using the Soil and Water Assessment Tool (SWAT) and four downscaled climate projections from a combination of two global climate models (GCM), a regional climate model (RCM), and two of the most recent IPCC emission scenarios, Representative Concentration Pathways (RCPs) as defined by CoastAdapt, n. d. (Table 4). The SWAT model was first adapted to the Atankwidi basin through calibration and validation process before it was used to simulate the future recharge. The RCM used was the SMHI-RCA4 model from the Swedish Meteorological and Hydrological Institute, while the GCMs where the CNRM-CM5 and MPI-ESM from Centre National de Recherches Météorologiques/Centre Européen de Recherche et Formation Avancée en Calcul Scientifique and Max Planck Institute for Meteorology, respectively (Obuobie et al. 2017). The two emission scenarios used were the medium-low emission (RCP 4.5) and the high-end emission (RCP 8.5). The projected recharge from the four climate projections were averaged and used as recharge input for the Atankwidi MODFLOW to simulate impact on the groundwater source. Details on the GCMs and RCM used in the study are described in

Table 3.2: GCM/RCM/RCP combinations used in the CSIR-WRI recharge study

No.	Climate projections
1	MPI-ESM/RCA4/RCP4.5
2	MPI-ESM/RCA4/RCP8.5
3	CNRM-CM5/RCA4/RCP4.5
4	CNRM-CM5/RCA4/RCP8.5

Table 3.3:Global Climate Models (GCMs) used to drive the Regional Climate Models (RCMs) in the CORDEX-Africa "Historical" (HIST) Experiment for the GCM-RCM combination that provided data for the recharge (Obuobie et al., 2017).

Model name	Model type	Modelling Centre	Reference
SMHI-RCA4	RCM	Swedish Meteorological and Hydrological Institute	Samuelsson et al., [2011]
MPI-ESM-LR	GCM	Max Planck Institute for Meteorology	Popke et al., (2013), Mascaro et al., (2015) Giorgetta et al., [2013]
CNRM-CM5	GCM	Centre National de Recherches Météorologiques/Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	Voldoire et al., (2012)

3.4.2 Projected groundwater demands

Groundwater demand for the community of Atankwidi was projected for the future. The baseline for the groundwater demand was 2015 and the future projection was for 2080. The demand was projected considering

- Domestic & industrial water demand
- Irrigation water demand and

With a population growth rate of 1.1%, baseline population of Atankwidi community from the Ghana Statistical survey (GSS), 2012 and using an exponential growth method (Equation 1) the future population was projection.

$$P_n = P_c e^{rt} \text{……………………………………………………... (Eq 1)}$$

Where:

$P_n = the\ unkown\ population$

$P_c = the\ current\ population$

$r = growth\ rate\ in\ \%$

$t = number\ of\ year$

$e = exponential$

For domestic demand, the population was sub divided into Rural and urban population as demarcated by the Ghana Water Company Limited (GWCL) statistics for water consumption from the baseline to the future projection. Rural population making up 60% of the total population and urban 40%. The water consumption per the population category was projected from 35% for rural and 65% for urban to 55% rural and 110% respectively.

Industrial water consumption was projected based on the assumption that half of the domestic water demand caters for their demand.

For irrigation demand, the assumption was based on doubling the crop water demand because of change in cropping and population increase. Thus, maintaining an area of 387ha as the area of irrigated land as cited by Barry et al. 2010 and irrigation efficiency of 0.7 and water requirement per hectare to be 6040m^3.

Livestock demand was exempted from the demand calculation due to the unavailability of head count of livestock available for the Atankwidi community and their per water consumption value.

4 CHAPTER 4: Expected Results and Discussion

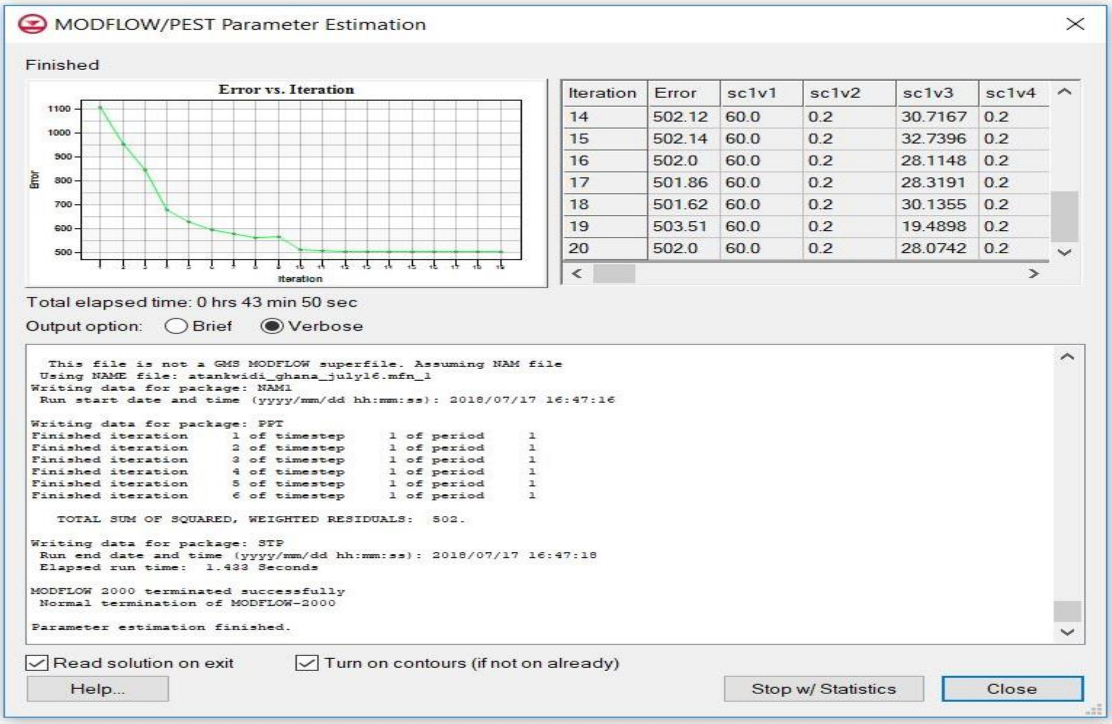
Because the methodology involved an integrated model approach, different steps were applied in simulating climate change impact on groundwater resource of Atankwidi basin. The analysis of the results was from the context of:

- Impact of scenarios on the groundwater systems
- The impact of the abstraction on the groundwater systems
- The dynamism between the impact of recharge and abstraction on the groundwater system.

However, these results are dependent on the quality of the data collected. The type of model used, the computer used, the modeller and the homogenous nature of the study area.

4.1 Calibration of GMS-MODFLOW

Groundwater level was nearly accurately simulated by the GMS-MODFLOW model. The error after calibration was 502 as shown in figure 4.1. Although the error was not at the best minimal error of 0.5, almost all prediction error was located within the calibrated target. However, with an observation value of 3 set as the calibrated target, 13 of the observed wells were within the calibrated target the model, 8 of the wells had error within 100% and 4 of the wells were with error of 200%. These wells are indicated with green, yellow and red colours respectively as shown in figure 4.2. In the calibration stage, optimal fit between observed and computed data was attained which is important for a fully calibrated model. The figure 4.2 also shows the spatial distribution of the hydraulic heads of the Atankwidi basin.



Finished

Iteration	Error	sc1v1	sc1v2	sc1v3	sc1v4
14	502.12	60.0	0.2	30.7167	0.2
15	502.14	60.0	0.2	32.7396	0.2
16	502.0	60.0	0.2	28.1148	0.2
17	501.86	60.0	0.2	28.3191	0.2
18	501.62	60.0	0.2	30.1355	0.2
19	503.51	60.0	0.2	19.4898	0.2
20	502.0	60.0	0.2	28.0742	0.2

Total elapsed time: 0 hrs 43 min 50 sec

Output option: ○ Brief ● Verbose

```
  This file is not a GMS MODFLOW superfile. Assuming NAM file
 Using NAME file: atankwidi_ghana_july16.mfn_1
Writing data for package: NAM1
 Run start date and time (yyyy/mm/dd hh:mm:ss): 2018/07/17 16:47:16

Writing data for package: PPT
Finished iteration     1 of timestep     1 of period     1
Finished iteration     2 of timestep     1 of period     1
Finished iteration     3 of timestep     1 of period     1
Finished iteration     4 of timestep     1 of period     1
Finished iteration     5 of timestep     1 of period     1
Finished iteration     6 of timestep     1 of period     1

   TOTAL SUM OF SQUARED, WEIGHTED RESIDUALS:  502.

Writing data for package: STP
 Run end date and time (yyyy/mm/dd hh:mm:ss): 2018/07/17 16:47:18
 Elapsed run time:  1.433 Seconds

MODFLOW 2000 terminated successfully
 Normal termination of MODFLOW-2000

Parameter estimation finished.
```

☑ Read solution on exit ☑ Turn on contours (if not on already)

Figure 4.1: Calibrated target for Atankwidi

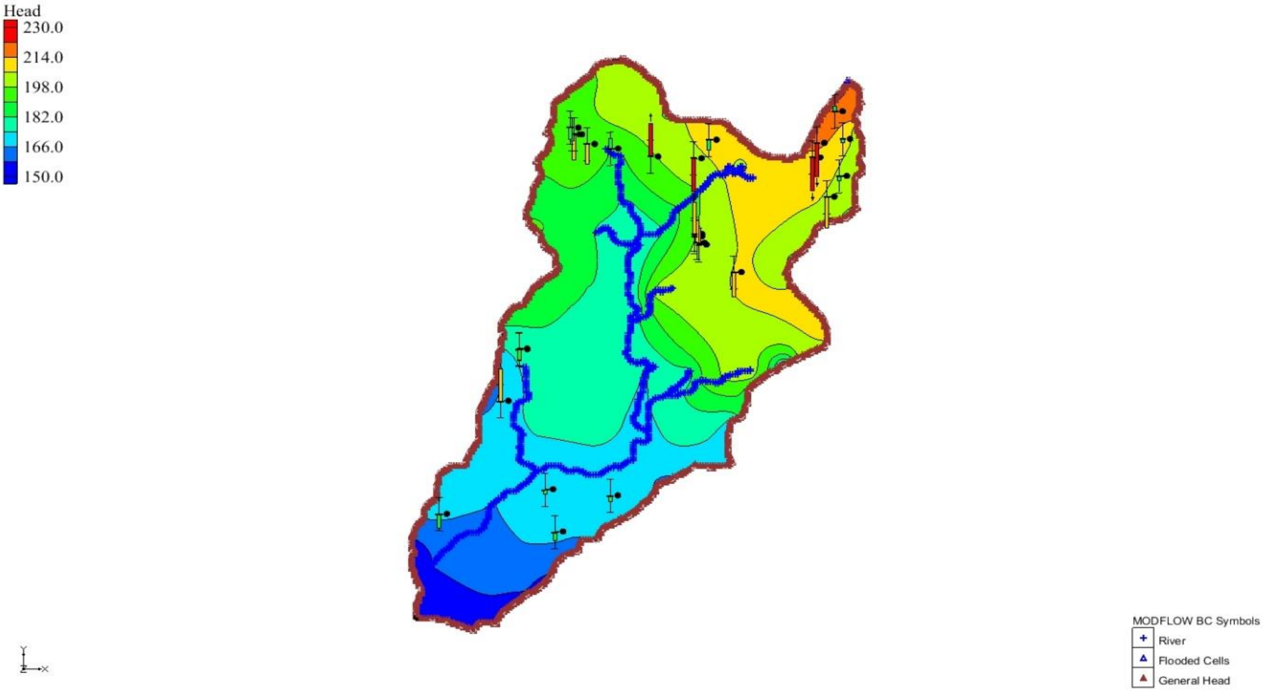


Figure 4.2: Spatial distribution of hydraulic heads (meters above mean sea level) in Atankwidi Basin

4.1.1 Comparison of computed and observed groundwater levels

The graph in Figure 4.3 shows how well the observed values matched the model solution. A 45° line generated by the model represents a perfect or precise correspondence between the observed data and solution values. Each symbol on the graph represents an observation point at the intersection of the observed against the computed values. In all, there were 25 observed points which produced the intersection between the computed and the observed. Out of these points, 22 of them had a perfect or slightly close to perfect correspondence indicating a fully calibrated model and gives an indication of the residual error in the model. Also, using a regression approach to determine the root mean square, the model produced a value of 0.942 (Table 4.1) which gives an almost perfect calibration and reliability of the software used. The R^2 value is well within the expected range of $0.5 \leq R^2 \leq 1$ of the goodness-of-fit and express a good correlation as indicated by Minitab blog editor, 2013

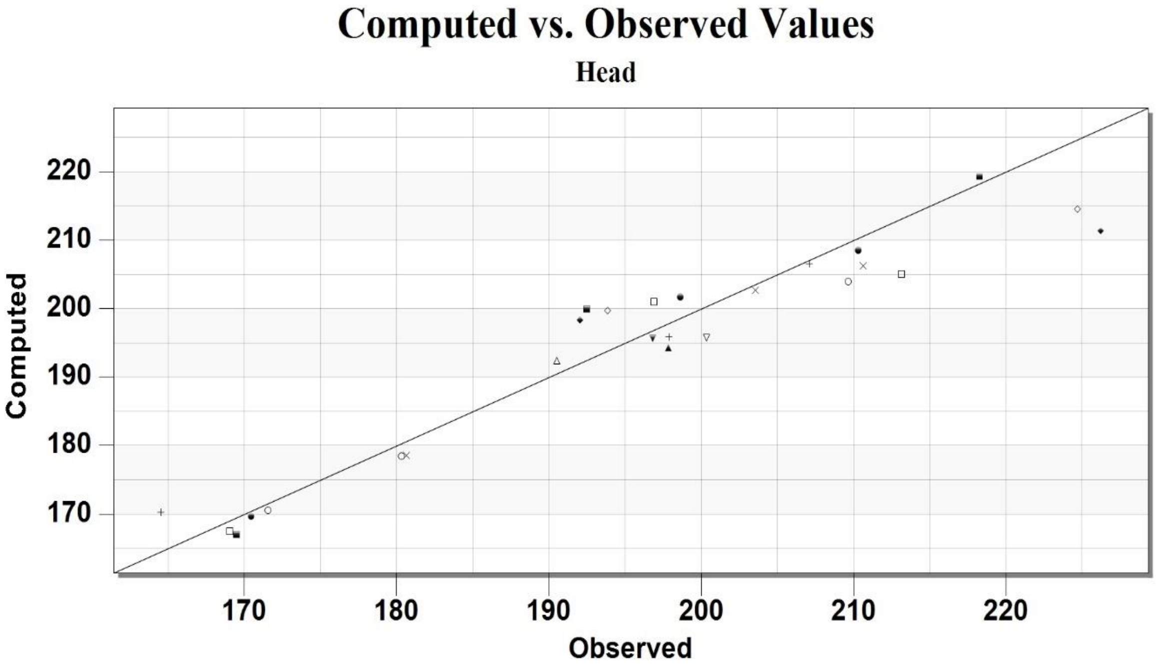
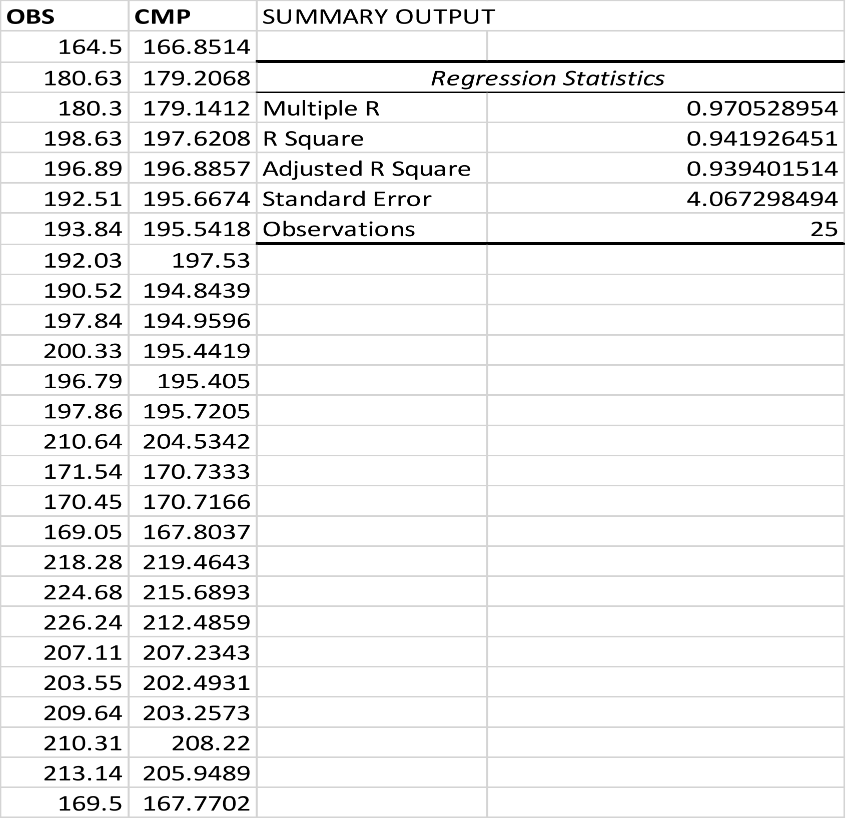


Figure 4.3: Groundwater modelling Computed and observed values head for Atankwidi basin

Table 4.1: Regression value for Atankwidi basin groundwater model



OBS	**CMP**	SUMMARY OUTPUT	
164.5	166.8514		
180.63	179.2068	*Regression Statistics*	
180.3	179.1412	Multiple R	0.970528954
198.63	197.6208	R Square	0.941926451
196.89	196.8857	Adjusted R Square	0.939401514
192.51	195.6674	Standard Error	4.067298494
193.84	195.5418	Observations	25
192.03	197.53		
190.52	194.8439		
197.84	194.9596		
200.33	195.4419		
196.79	195.405		
197.86	195.7205		
210.64	204.5342		
171.54	170.7333		
170.45	170.7166		
169.05	167.8037		
218.28	219.4643		
224.68	215.6893		
226.24	212.4859		
207.11	207.2343		
203.55	202.4931		
209.64	203.2573		
210.31	208.22		
213.14	205.9489		
169.5	167.7702		

4.1.2 Groundwater modelling Residual vs Observed values

The horizontal line along an error of zero in Figure 4.4 below represents an idea of a perfect correspondence between the observed data and the solution values. The symbols on the graph represents each observed value at the intersect and residual (computed-observed) values for the points. From the graph, the error or residual after intersection of the observed gives an indication that 3 of the total observed wells had zero residual error and 17 of the remaining 22 observed wells fell between the range ±5 and which implies a higher reliability of the model used.

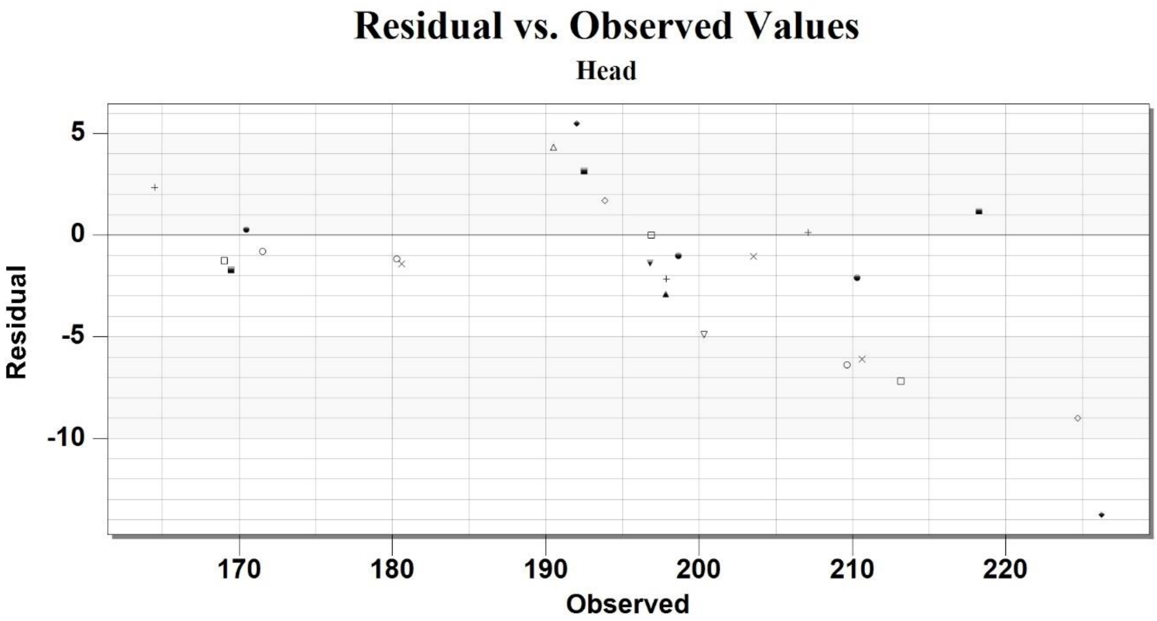


Figure 4.4: Residual vs observed head values in meters for Atankwidi basin

The above outputs confirm appropriate model calibration. The orderly outline of all simulated versus observed groundwater level graphs shown above indicate that a reasonable level of “model-to-measurement” misfit is achieved. The proposed approach will enable the quantification of groundwater recharge from the induced impact of climate change as a result of the variation of the climatic parameters or variables (temperature and precipitation).

4.2 Sensitivity analysis

The sensitivity analysis shown in Figure 4.5 for the aquifer was its hydraulic conductivity. Any increase in the horizontal and vertical anisotropy of the aquifer causes an increase in river baseflow. A small increase from 1E-5 m/s to 2E-5 m/s is enough to cause river flow from groundwater throughout the dry season. However, the extent to which a change of groundwater head at certain positions in response to the small increase in hydraulic conductivity is significantly alarming. The model as a result of this observation is regarded to be highly sensitive to aquifer hydraulic conductivity.

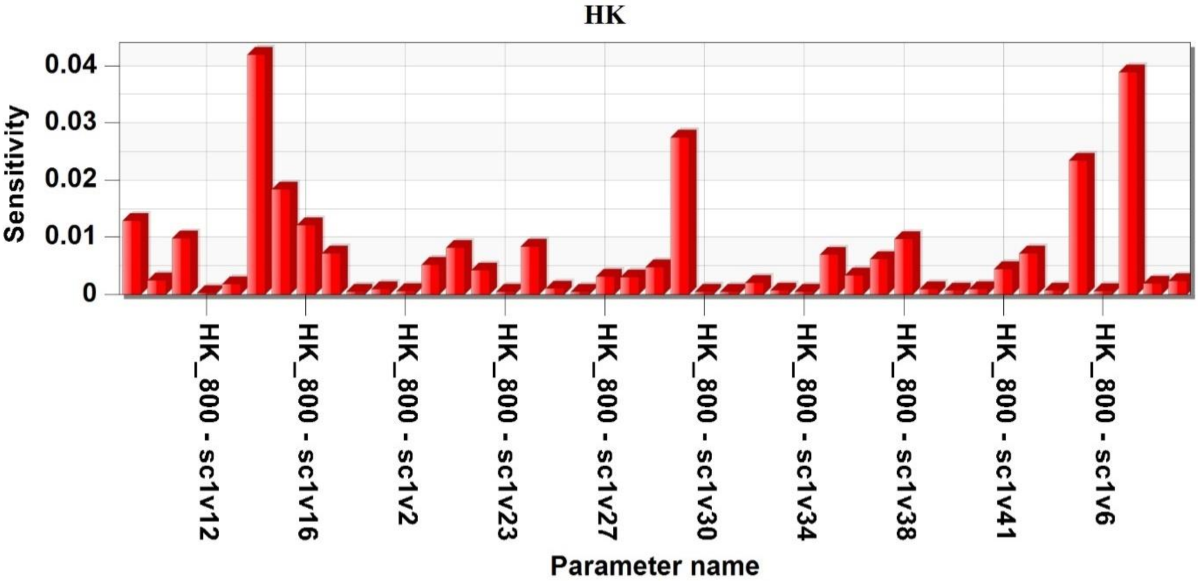


Figure 4.5: GMS-MODFLOW Sensitivity analysis for Atankwidi Basin

4.2.1 Baseline Recharge

The recharge rate for the basin is 0.00015 m/d and this translates into an average annual recharge depth of 55 mm/yr. This indicates the uniformity of the basin, and that, it is located in one aquifer and the source of recharge also from one mechanism. It also gives an indication that the soil profile and its porosity within the basin does not defer across the basin. Adding to that, the slope of the basin also contributes to the uniformity of the recharge.

4.2.2 Hydraulic conductivity

The hydraulic conductivity of the study area after calibration ranged from 0.0 to 60m/day (Figure 4.7). This could be due to the geology of the area. Generally, the area had a low conductivity and as a result indicates a low permeability. However, the North Western boundary had the highest conductivity ranging between 50-60m/day. This gives an indication of high porosity.

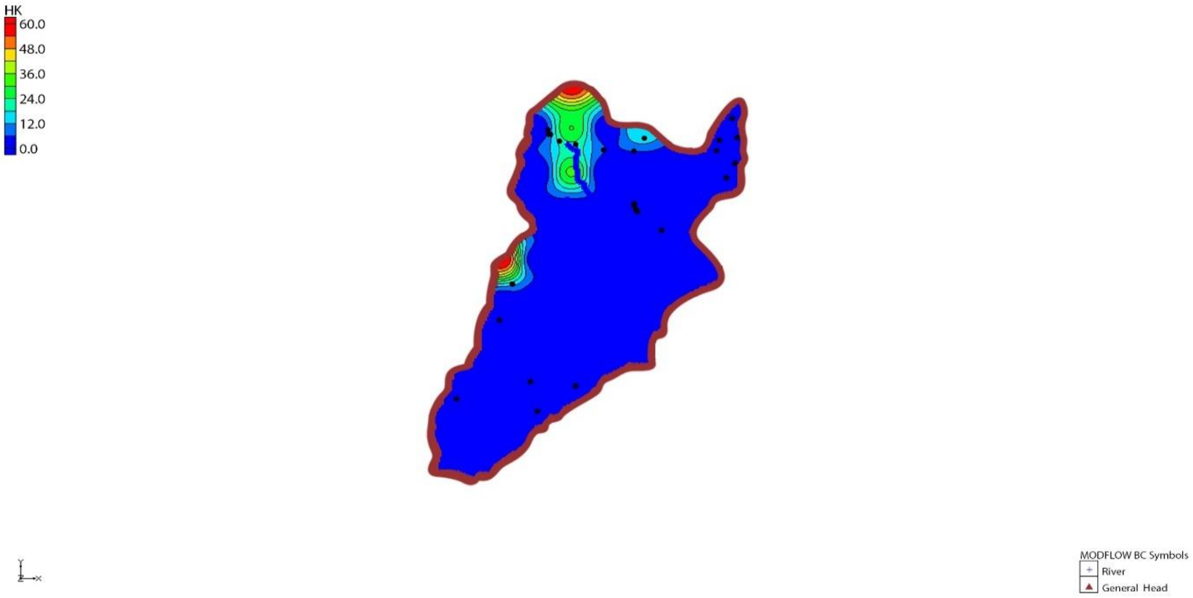


Figure 4.6: Spatial distribution of Hydraulic conductivity (m/day) in Atankwidi basin

4.2.3 Flow path

Figure 4.7 displayed the flow pattern within the Atankwidi basin. The flow path showed it flowed from the north to the south which confirms why the elevations at the top has higher values as compared to the south. Similarly, the hydraulic conductivity is highest at the north west of the area and lowest at the south. This shows how the river within the basin flows.

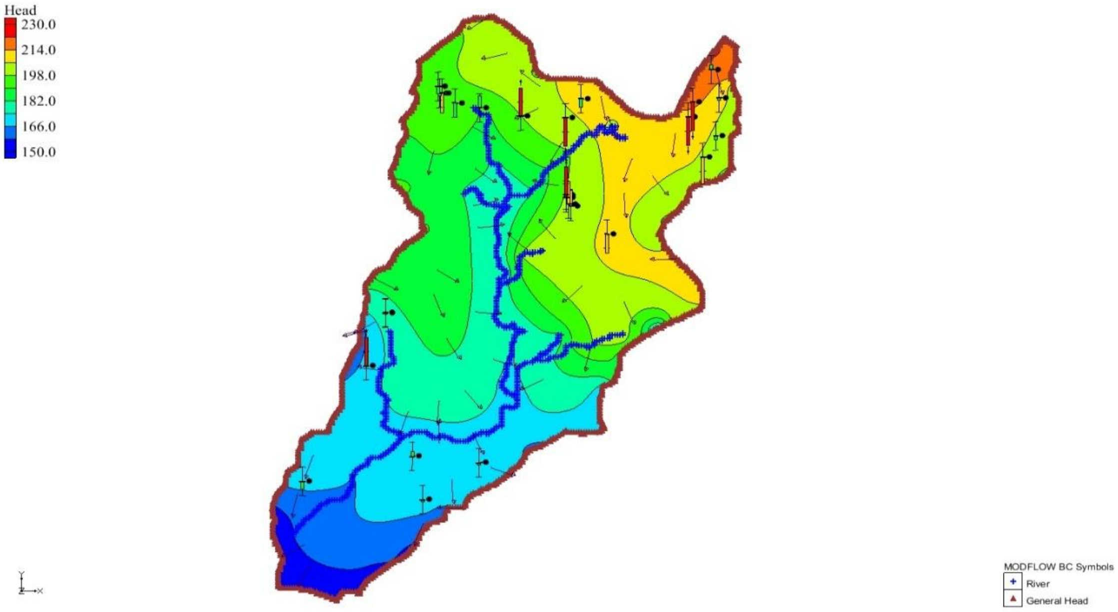
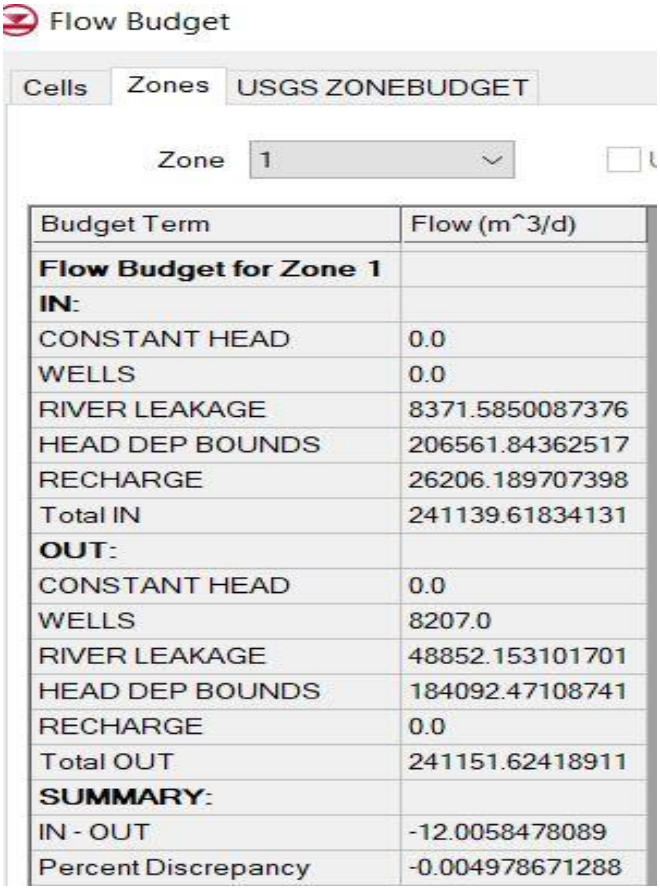


Figure 4.7: Groundwater flow path in the Atankwidi Basin

4.2.4 Flow budget

From the calibrated model, the total flow-in and flow-out is made visible. This flow budget displays the changes in the aquifer when recharged or abstracted. The total water volume available as of calibration was 237.28m^3/d and an estimated abstraction of -237.295 m^3/d with recharge estimated around 26206.2 m^3/d. This gives an indication of the water level situation in the study area before climate scenarios are applied to know the likely impacts in the future. In summary, the IN-OUT in Figure 4.8 shows a negative value of 12m^3/d. This indicates that the level of the water table has gone down “above the ground level” and also agree with the reality on grounds as the observation wells data collected in May was in the peak moment of the dry season. According to Obuobie et al., 2008, water table oscillate between 0-15m above ground level.



Zone 1

Budget Term	Flow (m^3/d)
Flow Budget for Zone 1	
IN:	
CONSTANT HEAD	0.0
WELLS	0.0
RIVER LEAKAGE	8371.5850087376
HEAD DEP BOUNDS	206561.84362517
RECHARGE	26206.189707398
Total IN	241139.61834131
OUT:	
CONSTANT HEAD	0.0
WELLS	8207.0
RIVER LEAKAGE	48852.153101701
HEAD DEP BOUNDS	184092.47108741
RECHARGE	0.0
Total OUT	241151.62418911
SUMMARY:	
IN - OUT	-12.0058478089
Percent Discrepancy	-0.004978671288

Figure 4.8: Current flow budget of Atankwidi basin

4.3 Scenarios analysis

Over a season when there is no recharge or drought and water is abstracted for daily activities, the water level decreases and in the season of recharge brings the water level back to the normal level or above. So basically, water level in the groundwater systems oscillate between a range.

4.3.1 Climate change projections

Climate change has caused variation in water balance in the river Atankwidi Sub Basin. The extent of variation under the GCMs will show that all the water balance components are projected to increase under future climatic conditions and the rate of change varies with season.

4.3.1.1 Temperature Change

To evaluate the impact temperature changes could have on recharge in the Atankwidi basin in the White Volta basin, climate series (present and future) were simulated with two GCMs and downscaled with one regional climate model based on two emission scenarios. The future annual mean temperature based on the emission scenarios RCP 4.5 and RCP 8.5 produced a positive signal (increase) with a possible warming of 5 – 5.4 ˚C and 6.3 – 6.7 ˚C with an ensemble mean of 5.2˚C and 6.5 ˚C for RCP 4.5 and RCP 8.5 respectively. The expected possible rise in temperature by 5.2ºC and 6.5ºC by the ensemble mean in table 4.2 and table 4.3 compares well with the findings of Sylla et al., 2016, where an annual mean temperature rises of 1.5 – 6.5 ˚C for West Africa at the end of the 21st century has been projected. The rise in temperature could affect precipitation, hence, the naturally occurring recharge from precipitation, rivers and lakes may be affected.

Table 4.2: Baseline (1986-2015) and future (2051-2080) projected monthly average and annual temperature (˚C) in the Atankwidi basin for RCP 4.5

		Ensemble mean		RCA4_CNRM45		RCA4_MPI45	
Month	Baseline temp	Future temp	Change in temp	Future temp	Change in temp	Future temp	Change in temp
Jan	25.6	31.0	5.4	30.4	4.8	31.7	6.1
Feb	27.6	33.2	5.6	33.3	5.7	33.1	5.5
Mar	30.6	36.5	5.8	36.5	5.8	36.5	5.8
Apr	32.7	37.4	4.6	37.1	4.4	37.6	4.9
May	31.4	35.8	4.4	35.5	4.1	36.2	4.8
Jun	29.3	33.9	4.7	33.6	4.3	34.3	5.0
Jul	26.7	31.4	4.7	31.3	4.6	31.6	4.9
Aug	25.9	30.6	4.7	30.2	4.3	30.9	5.0
Sep	27.4	32.5	5.1	32.8	5.4	32.3	4.9
Oct	28.4	33.8	5.3	33.7	5.2	33.9	5.4
Nov	26.2	32.3	6.1	32.4	6.3	32.2	6.0
Dec	24.8	30.5	5.7	30.0	5.2	31.0	6.2
Annual temp	28.0	33.2	5.2	33.1	5.0	33.4	5.4

Table 4.3: Baseline (1986-2015) and future (2051 - 2080) projected monthly average and annual temperature (˚C) in the Atankwidi basin for RCP 8.5

		Ensemble mean		RCA4_CNRM85		RCA4_MPI85	
Month	Baseline temp	Future temp	Change in temp	Future temp	Change in temp	Future temp	Change in temp
Jan	25.6	33.0	7.4	32.7	7.1	33.3	7.7
Feb	27.6	35.1	7.5	35.2	7.6	35.0	7.5
Mar	30.6	37.9	7.2	37.8	7.2	37.9	7.3
Apr	32.7	38.3	5.5	38.1	5.3	38.5	5.8
May	31.4	36.7	5.3	36.2	4.8	37.2	5.8
Jun	29.3	34.8	5.5	34.1	4.8	35.4	6.2
Jul	26.7	33.2	6.5	32.6	5.9	33.7	7.0
Aug	25.9	31.5	5.6	30.9	5.1	32.1	6.2
Sep	27.4	33.4	6.1	33.4	6.0	33.4	6.1
Oct	28.4	34.9	6.5	34.9	6.4	34.9	6.5
Nov	26.2	33.6	7.4	33.7	7.6	33.4	7.3
Dec	24.8	32.3	7.5	32.3	7.5	32.4	7.6
Annual temp	28.0	34.5	6.5	34.3	6.3	34.8	6.7

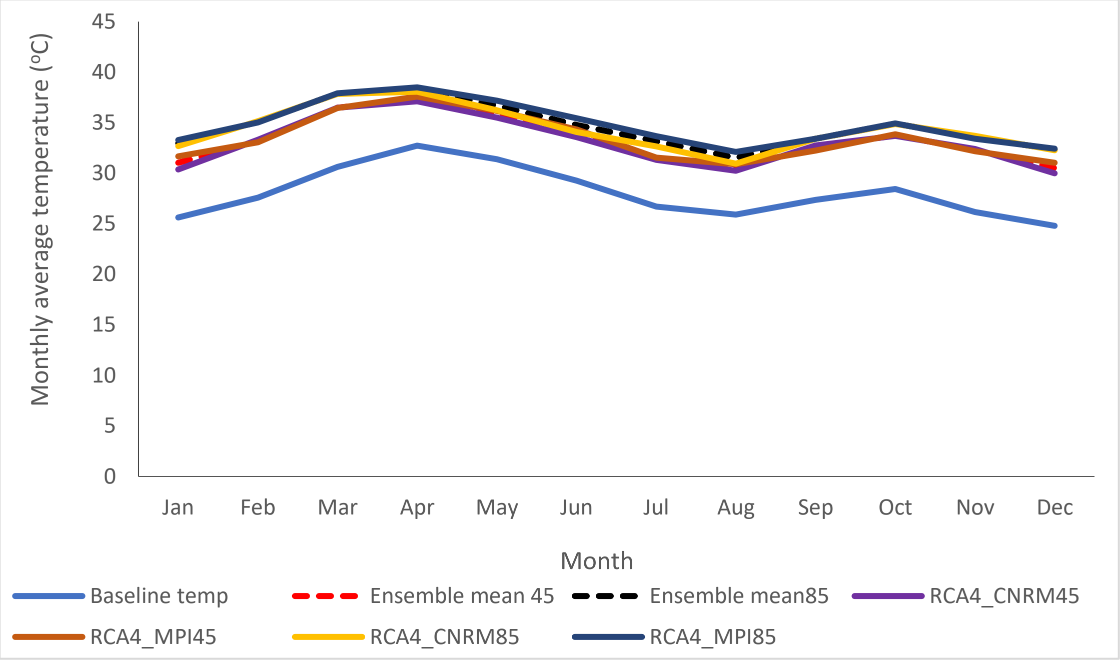


Figure 4.9: Projected monthly average temperature (˚C) for the future (2051-2080) in the Atankwidi basin for each model relative to the baseline (1986-2015) for RCP 4.5 and RCP 8.5

From Figure 4.10 above, the two models agree with a likely increase in temperature, nevertheless, the high-end emission (RCP 8.5) projects higher rise to the medium -low - end (RCP4.5). The graph indicated that, the future monthly temperatures will be high during the dry season to that of the wet season. Generally, temperature and evapotranspiration increase toward the northern part of Ghana which results in nearly 80% loss of rainfall to evapotranspiration (Kasei, 2009). Hence, the future rise in temperature could affect the sources of recharge in the Atankwidi basin.

4.3.1.2 Rainfall Change

Table 4.4 and 4.5 below provides a summary results of the analysis of the baseline and future projected rainfall over the Atankwidi basin based on the IPCC emission scenarios (RCP 4.5 and RCP 8.5). Generally, the ensemble mean change in rainfall over Atankwidi basin for RCP 4.5 shows a decline in future projected annual rainfall. Besides, the high-end emission scenario projected an increase. The range of possible rainfall changes which is indicated by the ensemble mean produced both negative and positive values, thus -0.53 % and 7.7 % with respect to RCP 4.5 and RCP 8.5. This phenomenon indicates that, the projected future rainfall will be highly uncertain over the basin. These values fall in the possible range of rainfall change mostly between -30 and 30 % (Sylla et al., 2016).

Table 4.4: Future projection (2051–2080) of monthly average and annual rainfall in the Atankwidi basin for RCP 4.5 relative to the baseline (1986 – 2015) in millimeters (mm)

Month	Baseline	Ensemble mean	RCA4_CNRM45	RCA4_MPI45
Jan	0.01	0.04	0.04	0.04
Feb	0.86	0.89	1.70	0.09
Mar	10.92	9.98	9.26	10.70
Apr	46.46	45.23	55.96	34.49
May	81.38	76.44	79.31	73.57
Jun	132.00	124.09	123.22	124.95
Jul	180.31	183.22	181.38	185.06
Aug	276.20	299.83	296.75	302.91
Sep	160.33	142.15	148.32	135.98
Oct	42.65	44.07	46.22	41.92
Nov	1.91	1.73	2.05	1.41
Dec	0.05	0.51	0.10	0.93
Annual rainfall	933.09	928.18	944.31	912.05
Change in rainfall		-4.91	11.22	-21.04
Percentage Change		-0.53	1.20	-2.25

Table 4.5: Future projection (2051 – 2080) of Average rainfall in the Atankwidi basin for RCP 8.5 relative to the baseline (1986 – 2015) in millimeters (mm)

Month	Baseline	Ensemble mean	RCA4_CNRM85	RCA4_MPI85
Jan	0.01	0.06	0.09	0.04
Feb	0.86	1.29	2.09	0.48
Mar	10.92	6.94	7.26	6.61
Apr	46.46	48.05	62.01	34.09
May	81.38	85.96	83.87	88.06
Jun	132.00	136.60	141.94	131.26
Jul	180.31	201.34	193.95	208.72
Aug	276.20	305.09	295.88	314.30
Sep	160.33	169.51	179.58	159.44
Oct	42.65	47.49	39.49	55.50
Nov	1.91	2.01	1.97	2.06
Dec	0.05	0.26	0.41	0.10
Annual rainfall	933.09	1004.60	1008.54	1000.65
Change in rainfall		71.51	75.46	67.56
Percentage Change		7.66	8.09	7.24

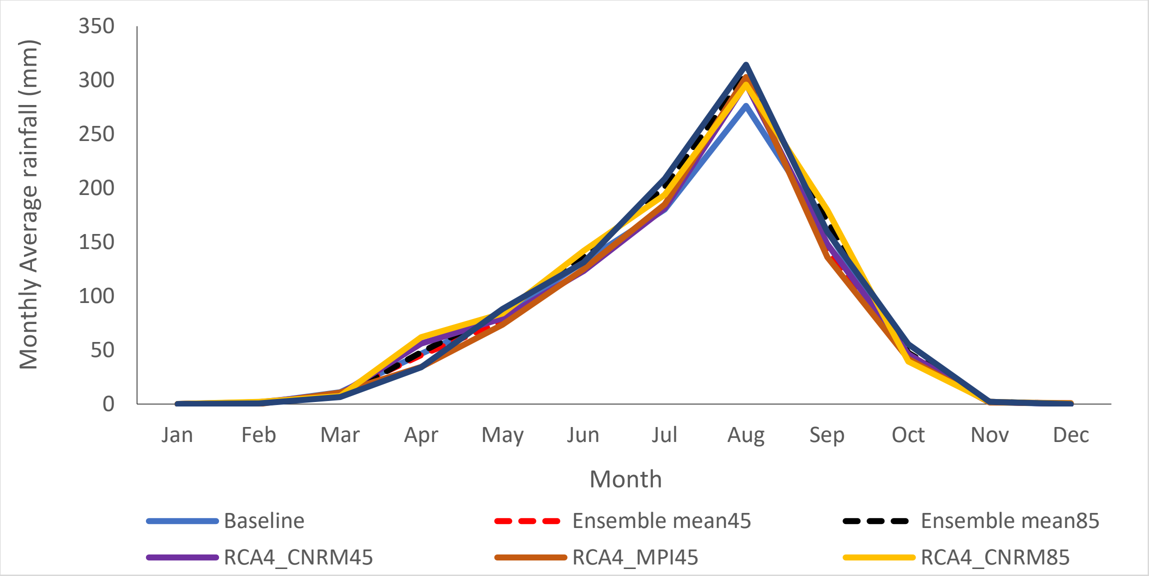


Figure 4.10: Future projection (2051 – 2080) for monthly average rainfall in the Atankwidi basin for RCP 4.5 and RCP 8.5 relative to the baseline (1986 – 2015)

The monthly rainfall distribution over the Atankwidi basin in the figure above is typical of the unimodal pattern of rainfall in the northern part of Ghana. The expected increase in temperature in the future and supported by the findings of Sylla et al., 2016, together with the mean monthly potential evapotranspiration that exceeds the mean monthly rainfall for most of the year in northern Ghana, could affect the rainfall and the river flow regime (Amisigo, 2005). This could affect the recharge of the basin.

4.3.2 Groundwater recharge projection

To estimate the future ground water recharge for the Atankwidi basin, the average recharge depth per year were obtained from the output of a SWAT model from an ongoing CSIR-Water Research Institute research work. The simulated average recharge depth was based on two IPCC emission scenarios, RCP 4.5 and RCP 8.5. The ensemble mean for each of the emission scenarios were used for the projection. The baseline period spans a period from 1986 to 2010 while 2051 to 2080 was considered for the future horizon (Table 4.6).

Table 4.6: Average baseline and future groundwater recharge depth (mm/yr) for the Atankwidi Basin from for RCP 4.5 and RCP 8.5

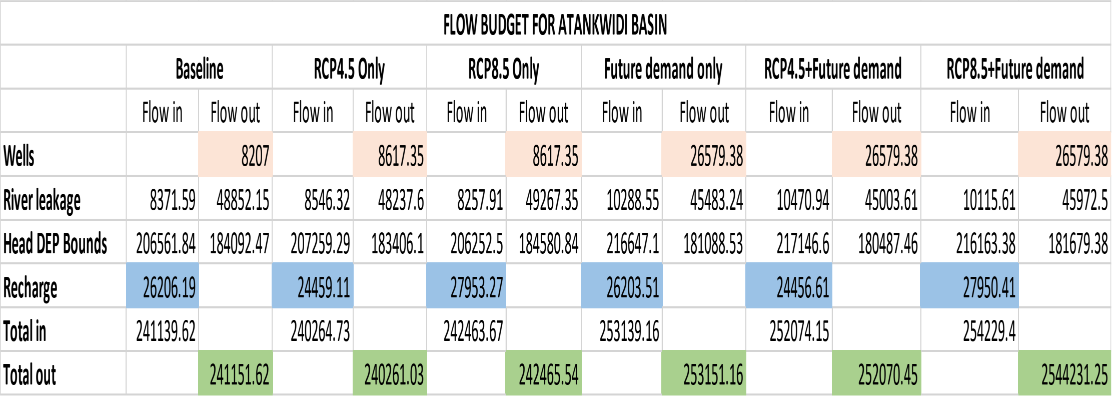
	Baseline (1986-2010)	Future (2051-2080)	Percentage change
RCA4_CNRM45	50.1	50.79	1.38
RCA4_MPI45	59.9	52.39	-12.54
Ensemble	55	51.59	-6.20
	Baseline (1986-2010)	Future (2051-2080)	Percentage change
RCA4_CNRM85	48.7	54.91	12.75
RCA4_MPI85	62.9	64.88	3.15
Ensemble	55.8	59.90	7.34

The medium-low emission scenario indicates a reduction of 6.2 % in recharge for the future. This is an indication that, the change in temperature in the future will impact on the sources of recharge (rainfall, lake and rivers), hence impacting on the recharge. RCP 8.5 indicates that, even though temperature may rise, its impact on the high-end emission scenario will not significantly affect the rainfall, hence the increase in recharge to some extent.

4.3.2.1 Model Scenario 1: Recharge Projection

Climate change impacts on groundwater resources in the river Atankwidi sub Basin aquifer system assessed using RCPs 4.5 and 8.5 scenarios and future demand need for 2080 showed the following results in the table 4.7 below;

Table 4.7: GMS-MODFLOW Flow budget for Atankwidi basin



FLOW BUDGET FOR ATANKWIDI BASIN

	Baseline		RCP4.5 Only		RCP8.5 Only		Future demand only		RCP4.5+Future demand		RCP8.5+Future demand	
	Flow in	Flow out	Flow in	Flow out	Flow in	Flow out	Flow in	Flow out	Flow in	Flow out	Flow in	Flow out
Wells		8207		8617.35		8617.35		26579.38		26579.38		26579.38
River leakage	8371.59	48852.15	8546.32	48237.6	8257.91	49267.35	10288.55	45483.24	10470.94	45003.61	10115.61	45972.5
Head DEP Bounds	206561.84	184092.47	207259.29	183406.1	206252.5	184580.84	216647.1	181088.53	217146.6	180487.46	216163.38	181679.38
Recharge	26206.19		24459.11		27953.27		26203.51		24456.61		27950.41	
Total in	241139.62		240264.73		242463.67		253139.16		252074.15		254229.4	
Total out		241151.62		240261.03		242465.54		253151.16		252070.45		2544231.25

Comparing the projected future recharge by RCP 4.5 (24459.11m^3/d) relative to the baseline recharge of the Atankwidi basin (26206.19m^3/d) shows a reduction of 1747.08 m^3/d in future recharge. This signifies there a drawdown of the water table in the future. Similarly, it will lead to digging or drilling deeper into the aquifer. However, the projected recharge by RCP 8.5 (27953.27 m^3/d) compared to the current recharge shows an increase in recharge of 1747.08 m^3/d. This signifies an up rise in the water table. Figure 4. 11 shows a change in hydraulic heads relative to the baseline (Figure 4.12). This change is much experienced in the North Eastern part of the basin. The hydraulic head in the basin has decreased significantly in area at the region of 214m and increased the region of 198m. These indications imply that the water flows from upstream in the Northern Atankwidi to the south of Atankwidi as the hydraulic contours are increasing downstream. A decrease in hydraulic heads signifies a higher water table, increase in recharge and total water available in the basin.

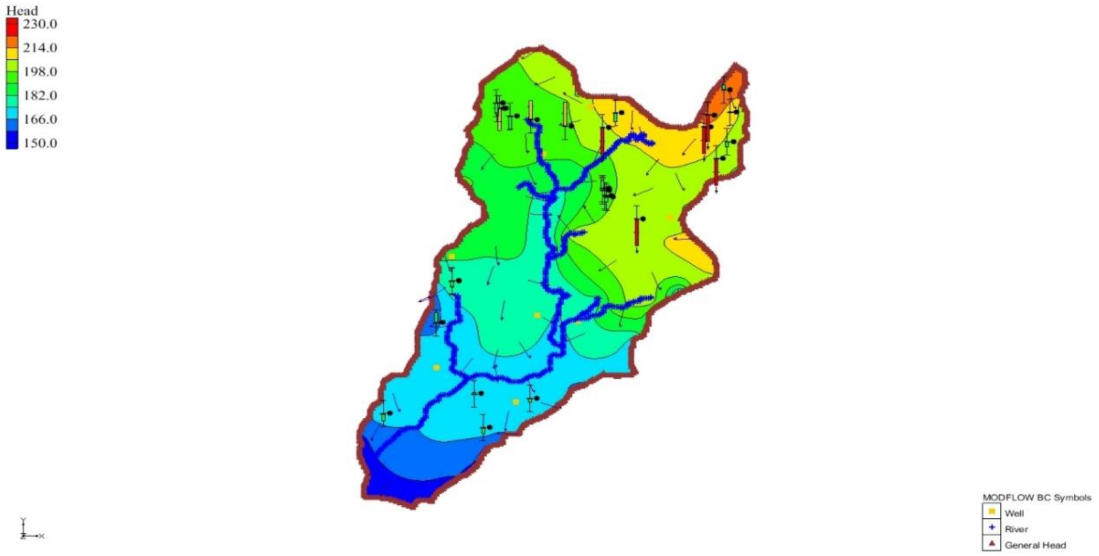


Figure 4.11:Spatial hydraulic head distribution of Atankwidi basin after scenario 1 of RCP 8.5 impact

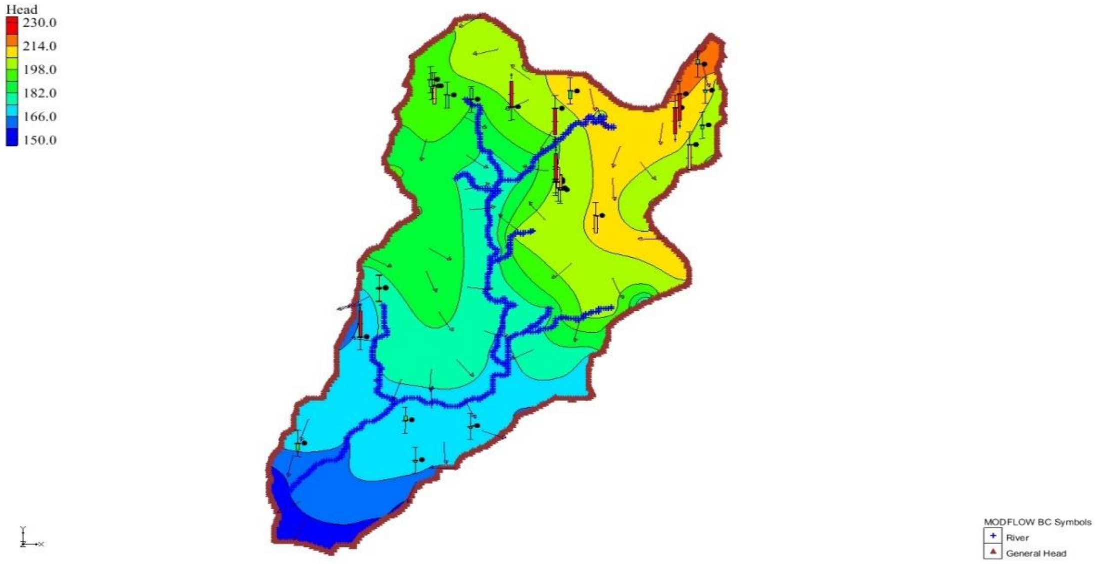


Figure 4.12:Spatial hydraulic head distribution of baseline of Atankwidi basin

4.3.2.2 Model Scenario 2: Demand Projection

Demand increases with increasing population. Hence, there is more abstraction. The continuous draw down adds more stress on the water level if the future recharge declines or remains constant throughout the years or decades. In this scenario recharge was insignificant, and abstraction increased.

Domestic & Industrial demands (2080)

Average per capita requirement for domestic use in 2080 is 21.7m^3/C/y (60% of population – 55L/C/d; 40% of population – 110L/C/d: Agodzo et al., 2003)

Industrial use: assumed to be half of domestic use: 10.85m^3/C/y

Total per capita water requirement for domestic/industrial uses will be 32.5m^3/C/y

Basin population in 2080: 99,007 (growth rate of basin region; 1.1% - GSS, 2012)

Total water requirement for domestic/industrial uses in 2080 will be **10285585m^3**

Irrigated agriculture demand

Basin (2010) irrigation water demand = 3272472m^3

Scenario considered for 2080

Basin population: 45841 (2010 estimated at growth rate of 1.1%) and 99007 (2080)

Increasing irrigation water demand by population growth between 2010 and 2080 = 116%

Irrigation demand = **7,067,857m^3**

Total water demand in 2080 for Atankwidi = 17,353,442m^3 $\cong 47544 m^3/d$

So, the percentage of future water demand (2080) relative to the baseline is 76.5%

Table 4.8: summary of Atankwidi future water demand (2080)

	Baseline	Future Water Demand (FWD)	% of FWD
Population	45841	99007	
	m^3	**m^3**	
Domestic Demand	536,339.7	6,857,056.67	39.5
Industrial Demand	268,169.85	3,428,528.33	19.8
Irrigation Demand	3,272,472	7,067,857	40.7
Total Water Demand	4,083,858	17,353,442	

From table 4. 7 above and based on the projected demand of 76.5% increase in water demand for the year 2080, there would be a decrease by 2.68 m^3/d in the groundwater level if recharge for the Atankwidi basin is insignificant. If the level of demand or abstraction is faster than the level of replenishing or recharge, it leads to stress on the aquifer since there will be more boreholes dug into the aquifer due to increase in water demand.

Model Scenario 3: Impacts on the dynamism between recharge and abstraction

1. RCP 4.5 and Future demand

The combination of scenario 1 (RCP 4.5 only) with a decrease in future recharge (51.1mm/yr) relative to the baseline (54.75mm/yr), and future water demand (FWD) of 76.5% increase to the baseline in figure 4.7 would lead to deficit of 1749.58 m^3/d of the water budget for the Atankwidi basin in the future (2080).

2. RCP 8.5 and Future demand

Coupling RCP 8.5 of future water recharge of 58.4mm/yr as compared to the baseline of 54.75mm/yr and a 76.5% increase in future water demand as shown in figure 4.7 indicates a recharge of 1744.22 m^3/d for the future horizon. Similarly, figure 4.13 below shows the significant change in hydraulic head distribution of the basin relative to the baseline (figure 4.12). The change showed an increase in heads in the entire basin which indicates an increase in elevation heads to tap groundwater or change in static water level to a much lower depth than the current depth of static water level.

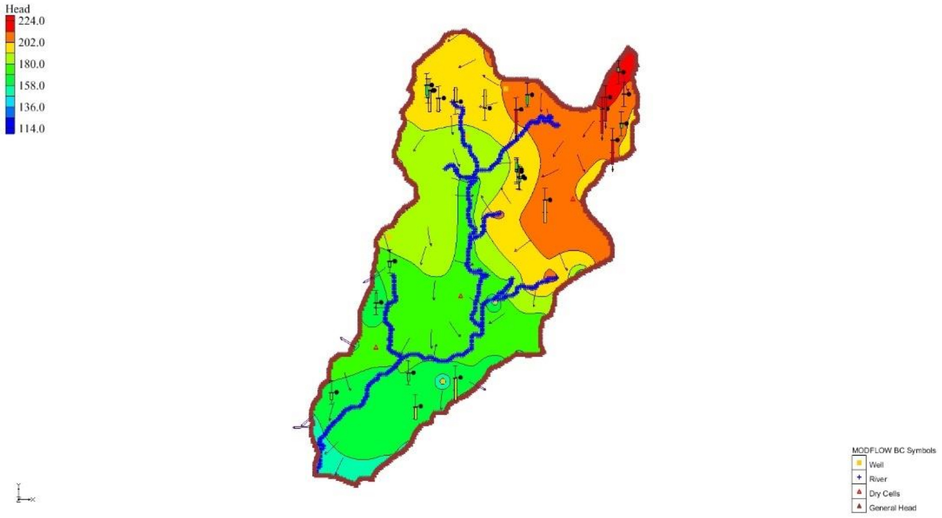


Figure 4.13: Impact of dynamism between climate and demand scenarios on Atankwidi

4.4 Possible obstacles or limitations

As a synthesis of current understanding across of the aquifer systems, there were limitations in the study scope and interpretation.

- Challenges in securing accurate and consistent secondary data. There were gaps in the observed climatic data of the basin area.
- Representation of the observed well for the basin area does not look uniformly distributed because the northern part of the basin falls into Burkina Faso.
- Acquiring of model software for the work was a major constraint to the work. This is due to how costly it was and also not available by the institution.
- Time to complete the entire project. Calibration of model takes a longer time due to arbitrary values used in setting up the model. This is as a result of lack of data for setting up.
- Data for swat model calibration was just for three years. This is due to unavailability and inaccurate data.

- No climate station within or for the Atankwidi basin and so climatic station values for Navrongo was used though it is not within the basin but the nearest to the basin
- Due to the time constraints, only one RCMs was considered with two GCMs.
- Although scientifically proven with evidence of climate change from several studies, the uncertainty surrounding the future is still not clear because most of the climate models are not good. This requires using a lot of climate scenarios derived from GCMs or the use of RCMs, improving of the data via statistical and dynamic downscaling methods before analyzing the impact of climate change on recharge.
- Another limitation is the resolution of the GCMs used. GCMs from CORDEX for my work had significant limitation with regards to my basin area. CORDEX comes with a 50*50 km resolution and using such a resolution on a basin area of 286km^2 restrict the basin to a limited number of grids which affects the results in a way.
- Adding to the above, the future of groundwater quantity under future scenario was not based on the models of climate rather the focus was about the resilient of groundwater to any change in climate scenarios.
- Delta correction approach of bias correction was used to correct the climatic baseline to meet the GMS-MODFLOW model.

5 CHAPTER 5: Conclusion and Recommendation

5.1 Conclusion

- Climate change impacts on groundwater resources in the Atankwidi sub Basin aquifer system was assessed using a set of hydrological models, groundwater model and two GCMs under two RCP scenarios (4.5 and 8.5). Average annual temperature and precipitation were considered as indicators of future climate. It is expected there would be an increase in annual temperature using an ensemble mean of 5.2 ºC and 6.5 ºC for RCP 4.5 and RCP 8.5 respectively end of the 21st century. In the case of precipitation, it is expected that an increase in precipitation using an ensemble mean of -0.53 % and 7.7 % with respect to RCP 4.5 and RCP 8.5 from the baseline. This would cause the basin to be likely warmer and wetter in the future 2080.
- The impact of climate change on groundwater recharge level and storage was examined. it is expected that there would be a decrease in recharge by 6.2% using RCP 4.5 scenarios in the Atankwidi catchment and a slight increase above the baseline region of 7.3% to RCP8.5 in groundwater recharge from 55.8mm/y of the baseline by the end of the 21st century
- Impact of future water demands by virtue of growing population is expected to cause a drawdown of the water table level within the study area. Abstraction increases by 76.5% in 2080 relative to the baseline with irrigation demanding 40.7% of the water compared to domestic 39.5% and industrial 19.8%.
- Scenario 1 showed a drawdown of water table under recharge only due to the decrease in recharge for RCP4.5 to slightly rise above the baseline for RCP8.5.
- Scenario 2 impact on the basin results in more drilling of boreholes which is costly.
- Scenario 3 showed the highest significant impact of drawdown of the water table when recharge is coupled with future demand.

5.2 Recommendations

- Pursue alternative water management to augment the groundwater resource;
  - ✓ Runoff harvesting in small reservoirs
  - ✓ Rainwater harvesting
  - ✓ Roof water harvesting for domestic use
- Adopting a more irrigation efficient method should be adopted as well as type of crop must be considered as irrigation demand has the highest demand of 40.7%

- Education on water-population nexus should be organized to expose the community on water availability/stress linking to future population.
- Further research must be conducted in the Atankwidi basin in order to provide a more robust decision tool for the sustainability of the Atankwidi basin.

All in all, the impact of climate change on groundwater resource is of great concern but knowledge about is relatively limited although the climate change is widely recognized in the world. The impact of climate change may be felt more severely in developing countries who have failed to safeguard and manage their fresh surface water as a result of unregulated mining activities and other anthropogenic factors. Similarly, developing countries that greatly rely on ground water for agriculture and are already in the stressed zone and require alternative irrigation practices or type of crop cultivated. There will be the need for integrated work approach from different disciplines such as socio-economist, agriculture modelers and researchers if the consequences of climate change on future groundwater recharge is made known now.

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Appendix

Figure 0.1:Decisions support systems and processes for groundwater source S.A Pierce et al., 2016

Source	Problem	Scale	GW Simulation	Optimization & larger DSS	Objective function	Decision variables
Fienen et al. (2013)	Forecasting changes in sea level rise and groundwater		SEAWAT model aggregated to Bayesian network	Bayesian network to emulate groundwater response /uncertainty	Propagate uncertainty efficiently for use in forecasts for decision makers	Focus on model performance and calibration; decision model not developed
Molina et al. (2013a)	Evaluating climate change impacts over time	Regional: Serral-Salinas aquifer, Spain	Used Post-process to evaluate groundwater response; MODFLOW model	Scenarios tested with an Object-Oriented Bayesian Network (OOBN)	Comparative analysis across scenarios and time windows; Extensive list of performance measures based on: Agricultural net profits and aquifer storage; Maximizing Total income, employment rates	Intervention actions, such as water rights purchase, land sale, sale of water for irrigation,
Hadded et al. (2013)	Water management generally	Local to Regional: Zeuss Koutine aquifer, Tunisia	MODFLOW	WEAP-MODFLOW Link	Demand satisfaction, cost and drawdown minimization	Limited by salinity levels and flow capacity
Molina et al. (2013b)		Regional: El Salobra aquifer, Spain	Lumped parameter representation of the aquifer within a linked hydro- economic model	Object Oriented Bayesian Network (OOBN) for stochastic modeling	Assess groundwater quality control with uncertainty; Minimize nitrate concentration and recovery times	Fertilizer quotas Fertilizer prices
Le Page et al. (2012)	Water allocation	Regional: Haouz-Mejjate plain, Morroco	MODFLOW	WEAP-MODFLOW Link	Evaluate impacts to regions and identify mitigation options	Principally used to validate modelled aquifer response and sensitivities to parameter change

Assess groundwater quality control with uncertainty	Local to Regional: farm and aquifer for case studies; Upper Guadiana Basin; Altiplano, Spain	Lumped parameter representation of the aquifer within a linked hydro-economic model	General Algebraic Modeling System (GAMS) and Object-Oriented Bayesian Network (OOBN) for stochastic modeling	Maximize gross margin at the farm level as a function of crop prices and yields; the OOBN added response levels in groundwater	Crop surface Irrigation method Soil type
Evaluate feasibility and performance of water management strategies	Regional; Lower Arkansas River Basin	Canal seepage and infiltration to groundwater estimated from a MODFLOW/MT3DMS simulation	Based on River GeoDSS with an Artificial Neural Network (ANN) used to distribute recharge to groundwater	Comparative analysis of estimated performance with a prioritization structure based on performance with Total Storage Water Shortages Compliance with legal compact. Impacts to water quality	Water strategy choices include: Total water diverted Use of storage Weighting of priorities (shown in Objective column)
Ranking alternative water management options with multi-criteria	Local aquifer to regional watershed scale	Mike-SHE Lumped cell structure	Not clearly described; a simplified water transfer model with limited cells	Minimize pumping costs, recharge, and water transport	Not clearly stated, penalty functions are included in the formulation
Quantifying Sustainable Yield	Local to Regional: Central Texas, Barton Springs aquifer	MODFLOW or an aggregated Systems Dynamics Model of the same system	Link to TABU global search algorithm and systems dynamics model of ancillary systems	Six Objectives defined with stakeholders Max water allocation and location of pumping; two formulations for maximizing minimum spring flow; saturated thickness; total storage	Pumping (location and rate) drought policy levels for alarm and critical stages Impervious cover and landuse
Spatially explicit groundwater modeling	Any	MODFLOW	Link to GRASS for geospatial groundwater modeling	Pure simulation capabilities	Not Applicable
Link hydrogeologic model with econometric for agricultural decisions	Regional: Eastern Mancha aquifer, Spain	MODFLOW, possibly 3-D (not clear) steady state	GESMO	Land allocation for crops; Crop yield maximization	Pumping Head levels Electricity costs

Figure 0.2: Observation points for Atankwidi basin

X	Y	Z
721551	1203142	179
722208	1205120	175
722212	1205096	178
728517	1209060	177
728447	1209132	180
728358	1209375	185
728356	1209470	185
726813	1212400	204
725409	1212705	203
724585	1212877	200
724134	1213244	200
724053	1213243	199
724009	1213500	209
729743	1208023	211
725395	1199558	216
723119	1199791	217
723469	1198187	220
733302	1214117	214
732660	1212920	201
732514	1212366	203
733564	1213066	206
733448	1211666	205
733010	1210878	209
728867	1213037	216
728342	1212337	233
719385	1198858	232

Research Thesis Budget for 2018, Albert Elikplim Agbenorhevi (Msc. Water Engineering)

Labour	Units			**Total Cost**	**CFA**	**DZD**	**In US DollarsLab**
Flight (Algeria-Accra-Algeria)		Fly Emirates					**1200**
Algeria to Tlemcen		Taxi				4500	41
Transportation for meeting sessions supervisor		IntraCity Taxi, Accra		400			100
SUB total A							**1341**
Expenses	**Units**	**Name**	**Cost per Units**	**Total Cost**			
Transportation to Bolga & back		Neoplan Station, Accra-Bolga	**140**	560			140
Field Work lodging		EV Royal	144	1040			260
Fuel to field work & office		IntraCity Taxi, Bolga		475			118.75
Field Aide (Allowance)		Mike Tikaah		200			50
Research Equipment							
MIFI	1	MTN	139	139			34.75
GPS Rental and batteries	1	Akrofi Hayford Rentals		130			32.5
Deep meeter Rental	1	Akrofi Hayford Rentals		200			50
Research Materials							
Cost for Monthly Portable Internet Service	4	MTN	300	900			225
Soft skills							
software training		UG Earth Dept.GMS-MODFLOW		400			100
Accommodation for Software Training	1	Dept. Business Acc		300			75
Secondary Data							
Observed data from		Met. Authority		450			112.5
Stationery							
Map of Ghana with stream flows	1	DAV Consult		200			50
Prints out of Lithological data	10	BMS Systems, Accra		115			28.75
Thesis report printing & binding in Tlemcen	4			92	2500		23
Subtotal B							**1300.25**
Total Expenses (A and B)							2641.25
Additional Expenses							
Internship							
Transportation from Ghana to ouagadougou		STC InterCity		242			60.5
Transportation from Ouagadougou to Ghana		STC InterCity		242	28500		60.5
Accommodation		WASCAL GuestHouse		773.5	91000		193.375
Thesis report printing & binding in Ghana	2	BMS Systems, Accra		180			45
Subtotal C							359.375
Total Expenses in USD							3000.625