HYDROLOGICAL MODELING OF ARTIFICIAL RECHARGE OF GROUNDWATER FOR SUSTAINABLE WATER SUPPLY IN DODOMA CITY

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ABSTRACT

The growing human population in Dodoma City has resulted in high demand for water use, which has led to the overexploitation of groundwater in Makutupora aquifer. Therefore, this study was carried out to model artificial recharge to replenish groundwater in the Makutupora aquifer to ensure water supply sustainability in the City. The simulation was done in Modular finite-difference flow model (MODFLOW) with the support of ModelMuse and the calibration was done using 21 piezometers. The Geographical Information System (GIS) technique used in preparing the shapefiles and calculation of groundwater storage capacity. The results indicated that the total groundwater storage in the Makutupora aquifer was about 247.84 Million Cubic Meters (MCM). After simulation of the steady-state reference period, the other four stress periods were simulated, considering the projected population and water demand. The planned injection wells to the model in the first, second, third, and fourth transient state periods resulted in a safe yield of 168 857 m^3/day, 197 760 m^3/day, 360 000 m^3/day, and 600 430 m^3/day, respectively. The recommended artificial recharge source is water from the Kinyasungwe river that flows during rainfall time, generally from November to May. One of the recorded years (2007) indicated a flow of up to 23.646 Million Cubic Meters (MCM). The recommended artificial recharge is possible due to the aquifer storage capacity of 247.84 (MCM). Therefore, information from this study could be used by engineers when constructing artificial engineering structures to replenish the water pumped from the Makutupora aquifer.

DECLARATION

I, Wolfugang Paul Venance, do hereby declare to the Senate of the Nelson Mandela African Institution of Science and Technology that this dissertation is my original work and that it has neither been submitted nor being concurrently submitted for degree award in any other institution.

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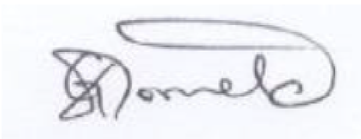

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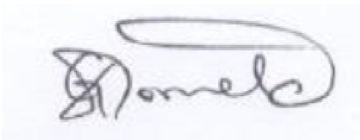

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This work is dedicated to my beloved parents, Venance Kimario and Maria Tesha, for their support and the sacrifices they have always made to support my education from primary school to my master degree. God bless them forever. AMEN.

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LIST OF ABBREVIATIONS AND SYMBOLS

^0C	Degrees of Centigrade
AfDB	African Development Bank
ET_O	Reference Evapotranspiration
FAO	Food and Agriculture Organization
FORTRAN	Formula Translation
GIS	Geographical Information System
GLOW	Global Water for Sustainability Program
I	Interception
JICA	Japan International Cooperation Agency
m.a.s.l	Meter above sea level
MCM	Million Cubic Meters
MODFLOW	Modular Finite Difference Flow Model
MOF	Ministry of Finance
MSc	Masters of Science
NASA	National Aeronautics and Space Administration
NAWAPO	National Water Policy
NM-AIST	Nelson Mandela African Institution of Science and Technology
P	Precipitation
PET	Potential Evapotranspiration
Pr	Infiltration
RF	Rainfall
RMSE	Root Mean Square Error

CHAPTER ONE

INTRODUCTION

1.1 Background of the Problem

Water is an essential commodity to human life and other living things (Brandshaug, 2019). It's the available resource and could be enough, but the problem is its management and distribution to ensure sustainability. Various places, especially those found in arid and semi-arid, where the primary source is groundwater, always experience water shortage (Boyd, 2020). The problem hits more in cities and towns where demand is more significant than supply (Forghani, 2018). The projected population growth of the world to 3 billion by 2050 suggests that the resource's overexploitation can result in water war unless the measures are taken (Vaux, 2011). The improvement of management and supply needs various information like the rate of increase in population, per capita water demand, climate change and variability issues. Always, water demand increases as a result of population growth and the impacts of climate change and variability (Niang *et al*., 2014). In Africa, water security is an issue in almost all dimensions like affordability, accessibility and acceptability, especially to people living in large cities and towns where the population is overgrowing (Foster *et al*., 2018). The climate change issue makes the situation worse, especially to essential resources and services like water.

Urbanization causes a rapid increase in population, which eventually puts pressure on a particular place's resources (Zhang *et al*., 2019). For example, in Tanzania, Dodoma has always faced water deficiencies. The population of Dodoma is increasing quickly between 2020 (689 072) and 2051 (1 972 968) following the implementation of the decision made by the founding President Julius Nyerere in 1973 to relocate the capital from Dar es Salaam to Dodoma. Relocation aims to bring government services closer to the people due to Dodoma's central location (Mukuku *et al*., 2019). The surging increase is due to the government decision to relocate all its major offices from Dar es Salaam to Dodoma. Also, the international organization and other service providers are moving to Dodoma.

The increase in population will increase the demand for water (Mukuku *et al*., 2019). The national census of 1988, 2002 and 2012 had 203 833; 324 347 and 410 956 people, respectively (Ministry of Finance [MOF], 2012). The master plan of the year 1976 projected the population to increase to 350 000 in 2002, yet did not realize the projection's figure due to its failure to implement the plan (Mosha, 2004). The increase in population in 2003 was 320 540 people, less than the projected population. In the years back, the population was increasing slowly, with no enough and adequate developed infrastructure. The current growth is a surge, and hence it needs adequate infrastructure like water supply (ibid). The expected number of people in the year 2021 is 583 613 (Mukuku *et al.*, 2019). Furthermore, the growth rate of 2.5% to 5% has been projected from 2026 to 2051, with a total population ranging from 713 794 to 1 972 968. The expectation of people about the population in 2051 is a rise in four times the current population. The current and estimated population indicates a high-water deficiency. The government is proposing to build homes, offices, and infrastructure. This movement will disrupt the population's natural development to support the cities growth (Mukuku *et al.*, 2019).

Groundwater constitutes the world most considerable portion of the water by 78%. Out of 78%, 36% used for drinking and 42% used for irrigation (Gleeson *et al.*, 2020). In Africa, groundwater is a service to all ecosystems, and it has supported the alleviation of poverty, and hence it helps in the achievement of Sustainable Development Goals (Cuthbert *et al.*, 2019). The groundwater sustainability to support people and ecosystems' livelihood depends much on natural and artificial recharge to replenish the pumped or exploited amount of water (Taylor *et al.*, 2013). The sustainability of groundwater supply to support people's lives has been interfered with in various places due to either population growth or climate change (Kolusu *et al.*, 2019; Seddon, 2018). Also, groundwater quality and quantity have deteriorated in many counties due to overexploitation resulting from the rapid population increase, especially in cities (Venkatramanan *et al.*, 2015). The balance of water demand and supply, especially in semi-arid areas, can be achieved by recovering the aquifer storage (Forghani, 2018). The insufficient surface water resource is always covered by groundwater in many parts of the world (Kisaka, 2018).

Dodoma is located in a semi-arid area, and it receives an annual rainfall of about 550 mm/year (Shemsanga *et al.*, 2018). Furthermore, surface water is also limited in the area, and it suffers from the effects of climate change and variability (Kolusu *et al.*, 2019; Taylor *et al.*, 2013). The groundwater taped from the Makutupora aquifer is the principal primary source for supplying water (Shemsanga *et al.*, 2015). The report of Seureca estimated that the Makutupora produces 72 000 m^3/day. Mukuku *et al.* (2019) contended that the boreholes could produce up to 61 500 m^3/day of water, but the aquifer found supplying between 48 000 m^3/day up to 50

000 m^3/day of water (Ghazavi & Ebrahimi, 2019). An increase in population will lead to increased depletion of aquifers due to groundwater overexploitation for various sectors.

Table 1: Estimated Gross Water Requirement and Total Water Demand from 2021 to 2051

	2021	2026	2036	2046	2051
Total requirement m^3/day	77 586.24	95 460.18	144 373.12	217 897	267 505.69
Gross demand m^3/day	102 957.40	123 029.84	173 247.74	261 476.64	321 006.83

(Mukuku *et al.,* 2019)

Table 2: Projected City Population, Water Demand, Existing Water Capacity and Deficiency 2025 to 2051

	2015	2025	2026	2036	2051
The population of the City	497 934	689 072	1 069 900	713 794	1 972 968
Requirement m^3/day	82 651	137 584	160 730	226 204	418 839
Existing m^3/day	61 500	113 192	113 192	113 192	113 192
Deficit m^3/day	-21 151	-23 992	-47 138	-113 012	-305 247

(Mukuku et al., 2019)

Currently, the primary source of water for the City of Dodoma is the Makutupora aquifer. It is estimated to abstraction exceeds 50 000 m^3/day (Zarate et al., 2020). The projected demand for water from 2021 to 2051 indicated greater than the estimated safe yield due to the population's expected growth (Table 2). The major government challenge is finding the ways and methods that can be used to ensure water sustainability.

Considering the overexploitation of water that various aquifers experience, groundwater modelling is inevitable as it enables water resource scientists and managers to predict the groundwater inflow and outflow in future (Akinwumiju & Olorunfemi, 2019). Modelling of artificial recharge of the aquifer is one of the most water management practices that has already been adopted by some of the developed countries (Austria, Greece, Netherlands, Poland, Hungary, Iran, Israel, Jamaica, South Africa, Belgium, Denmark, Finland, Spain, Switzerland, Australia, and Morocco). In the 1980s, artificial recharge was first introduced in the United State (Zhang et al., 2019). Hydrology models have been used to determine the optimal recharge rates and the amount of water that needs to be abstracted from the groundwater (Mondal et al., 2019). Furthermore, the modelling techniques could specify recharging sites that can best optimize the drawdown (Akinwumiju & Olorunfemi, 2019). Recharge tends to replenish the aquifers, and thus, artificial recharge can support natural recharge (Pathak & Singh, 2014).

Response strategies like adaptation and coping mechanisms are crucial to address water availability in Dodoma City due to the increase in population and climate change that puts pressure on resources like water resources (Seddon, 2018; Zarate et al., 2020). Managed Artificial recharge is the best and most alternative way to increase groundwater amount suffering from over-exploitation due to rapid population growth and possibly climate change and variability (Seddon, 2018). Various numeric approaches are now being used in combination with well-established codes like the Modular Finite Difference Flow model (MODFLOW) and graphical user interfaces like ModelMuse, Groundwater Vistas, and various Geographical Information System (GIS) techniques.

Therefore, this study aimed to estimate recharge in Makutupora groundwater for sustainable water supply in the City of Dodoma. The use of MODFLOW with the support of ModelMuse and various GIS techniques supported the modelling and simulation of the artificial recharge of groundwater in the Makutupora well field.

1.2 Statement of the Problem

The growth of cities and towns causes a rapid increase in population, which eventually puts pressure on a particular City/Town's essential services like pressure on water resource *(*Zhang *et al.,* 2019). The major threat for the rapid increase of people always affects most cities and towns located in arid and semi-arid areas (Cavalcante *et al.,* 2019; Finley & Basu, 2020; Mallick *et al.,* 2019). Recently, the United Republic of Tanzania's government has decided to relocate its major offices from Dar es Salaam to Dodoma City. The move comes with the implementation of the long-term plan that the government announced in 1973. The move has caused and expects to cause water scarcity due to a surge increase in population. The government plans to bring water from either Farkwa Dam or Tanganyika/Victoria Lake or both to meet city need (Mukuku *et al.,* 2019). But getting water from both lakes is a very costly process. There is a threat of the Makutupora natural groundwater aquifer being overtaken in a few years due to more drilled boreholes (Kashaigili *et al.,* 2016). Now, the government is seeking answers/solutions to sufficient water and cost-effective water delivery. Artificial recharge is the best method to support aquifers' natural recharge by replenishing groundwater resources (ibid).

Episodic events and extremely seasonal rainfall have been factors sustaining groundwater (Kolusu *et al.*, 2019). Periods of extreme rainfall cause flash floods in the Makutupora Basin. (Kashaigili *et al.,* 2016). As pumping wells draw groundwater from a larger wellfield area, groundwater level declines gradually (ibid). The wellfield's ability to continue and sustain the recent intensive pumping to meet the demand for safe water following the City's rapid growth is unclear (Grofutures, 2015). Seddon (2019) recommended the Managed artificial recharge with no specific information on how recharge and pumping should be improved. Hence, the Makutupora aquifer requires an urgent expansion in monitoring its infrastructure. Previous studies have studied the Makutupora aquifer by analyzing its hydrogeologic conditions with little attention on recharge mechanism, especially on artificial recharge mechanisms applied in the area (Kashaigili *et al.,* 2003, 2016; Rwebugisa, 2008; Seddon, 2018). Therefore, this study fills in the gap by modelling the effect of artificial recharge and abstraction of groundwater regarding the projected rapid growth of the City population for sustainable water supply.

1.3 The Rationale of the Study

This research helps engineers build various hydraulic structures to support the artificial recharge of the Makutupora aquifer.

1.4 Objectives of the Study

1.4.1 General Objective

The general objective of this research was to develop a mathematical model for hydrological modelling and simulation of artificial recharge and recommend abstraction in the Makutupora aquifer for sustainable water supply in Dodoma City.

1.4.2 Specific Objectives

(i) To develop a mathematical model based on transient flow Equation to simulate natural and artificial recharge given the current and projected abstraction volumes of groundwater in the Makutupora aquifer.

(ii) To determine the increase in the aquifer's safe yield due to the simulated artificial recharge and recommend sustainable groundwater abstraction volumes.

(iii) To simulate and recommend optimum groundwater pumping volumes and pumped water storage.

1.5 Research Questions

This research answered the following questions:

(i) What assumptions and techniques are appropriate for developing the mathematical model based on transient flow Equations for artificial groundwater recharge?

(ii) How much water can the Makutupora aquifer receive from artificial recharge besides natural recharge?

(iii) How much water is available in the Makutupora wellfield catchment area to support artificial recharge?

1.6 Significance of the Study

The study was driven by the government's challenges in ensuring the water supply's sustainability in Dodoma City. This study's findings provide groundwater management skills and could help an engineering design and construct some cost-effective artificial wells that could increase the safe yield and reduce existing and future water shortage in Dodoma. Those skills can be modified and adapted elsewhere in a similar setting, like in Tanzania and other parts of the world. The study's suggested actions and recommendations could reduce water scarcity, especially in rapidly growing Cities/Towns located in semi-arid. The study findings could further help accomplish the National Water Policy (NAWAPO), aiming to reduce poverty and improve people's quality of life in urban areas. Globally, the study helps in the achievement of the sixth sustainable development goal.

1.7 Delineation of the Study

The study focused on the Makutupora aquifer, and the data were limited to this area. Such data includes aquifer parameters, hydrological data, climate data, and various Geographical Information System (GIS) shapefiles.

CHAPTER TWO

LITERATURE REVIEW

2.1 Definition of Key Terminologies

2.1.1 Hydrology

Hydrology is the branch of science that studies water movement, storage and quality control (Balasubramanian & Nagaraju, 2017). It encompasses water cycle, development and management for sustainable water supply (ibid). Marine hydrology and surface hydrology form the hydrology divisions. The study focused on how water moves through porous media such as silt, gravel, rock and sand (ibid).

2.1.2 Model

A model is something you could explain and show in small, easily comprehensible ways to explain something (Devia *et al.,* 2015). In hydrology, it simplifies forecast and interprets various hydrological processes (ibid). Models are divided into three; namely, logical, scientific and physical models. Empirical simulations utilize current data without considering hydrological device, processes and functions. Besides, physical models use state variables that are in space-time functions. In hydrology, an ordinary or partial differential Equation is always used to present water movement processes. Methods of the solution for the Equations are often finite numerical differences. Physical models are best because they are designed to use physical interpretation parameters. Furthermore, the calibration and evaluation of physical models need some meteorological and hydrological data.

2.1.3 Hydrological Modelling

Hydrological modelling is a tool for comparing more complex real-world systems (such as surface water, groundwater, soil, estuary and wetland) that support the prediction and management of surface water and groundwater resources (Marshall, 2014). Advanced modelling has recently allowed for more accurate modelling of rapid hydrological changes (Mondal *et al.,* 2016). Climate change and variability has been pointed out to be among the factors that affect water resources, but groundwater responds more slowly than surface water (Brandshaug, 2019; Izady *et al.,* 2019; Rwebugisa, 2008; Saleem *et al.,* 2018). The additional factor like population rise puts more pressure on water resources. In semi-arid areas where the annual rainfall is low and the evapotranspiration rate is high, groundwater modelling techniques are required for sustainable water supply (ibid).

2.1.4 Natural Recharge and Artificial Recharge of Groundwater

Groundwater accounts for 99% of fresh water that supports people's lives and other living organisms throughout the world (Lall *et al.,* 2020). It occurs naturally or artificially in subsurface soil pore spaces and defined channels such as rock fractures (ibid). Groundwater is said to make up one-third of the world's freshwater (Singh, 2014). Recharge refers to how the surface water infiltrates the aquifers' water table (Yang *et al.*, 2017). Groundwater can help us cope with increased population and climate change, and variability (Kavuri *et al.,* 2011). Water resource managers and professionals always study groundwater to familiarize themselves with the methods used to replenish the aquifers by natural or artificial means (Martínez-Santos & Andreu, 2010). Usually, after precipitation or rainfall, the excess surface water penetrates the aquifers through natural infiltration (Margat & Gun, 2013). The rapid population growth of semi-arid areas like cities has resulted in a decline in the capacity of natural infiltration to support the supply of water that has forced the various Nations and their stakeholders to apply various response measures, including adaptation options (Kavuri *et al.,* 2011; Wasif & Hasan, 2020).

Artificial recharge refers to all kinds of measures to fill in the aquifers' surface runoff (Yang *et al.*, 2017). It is a critical component in knowing the inflow and outflow of a particular aquifer, especially in arid and semi-arid areas where the surface water is limited and the evapotranspiration rate is very high (ibid). Artificial recharge of groundwater has been used for a long time by developed countries as a groundwater management tool for future demand. The use of shallow wells with some additional techniques can be used artificially to recharge groundwater (Zhang *et al.*, 2019). The artificial recharge helps increase groundwater through improved design and construction of engineering structures (Ali *et al.,* 2019).

2.1.5 MODFLOW

The MODFLOW is a modular finite-difference flow model that solves the three-dimensional groundwater flow Equations (Kumar, 2019). It was developed by the United States Geological Survey (ibid). It is a computer code that was created using a Formula Translation (FORTRAN) compiler to solve groundwater flow Equations. It simulates both confined and unconfined aquifer in both steady-state and transient state (Lakshmi & Narayanan, 2015). Furthermore, both natural and artificial recharge for groundwater management can be simulated using the MODFLOW model (ibid).

2.2 The History of Dodoma Concerning Population Growth and Water Supply

The United Republic of Tanzania's government announced its first decision to move its major offices from Dar es Salaam to Dodoma in 1973 to ensure easier accessibility of the government by all Tanzanians (Seddon, 2018). Implementing the constructed master plan did not address all the key issues, including ensuring water security in all dimensions (Callaci, 2016). However, the population was still increasing but at the slowest rate. Still, the lowest rate led to the overexploitation of the surface water in the late 1940s. In the year 1948, the exploitation of the Makutupora aquifer begun. The drilled boreholes had produced a safe yield. Geological Survey of Tanzania did further investigation, and in the year 1964, they had found that the Makutupora is the primary source of water for Dodoma City. Some of the measures have been planned to solve water scarcity: President Jakaya Mrisho Kikwete promised a strategy to build a Dam in the Bahi District (Seddon, 2018). The strategy failed to favor the building of the Farkwa Dam in Chemba. The designed structure would add 120 000 m^3/day to the water supply (ibid). The decision to move has been officially implemented from 2019 after the Late President Dr. John Joseph Pombe Magufuli announcement. The government plans to bring water from either Farkwa Dam or Tanganyika/Victoria Lake or both to meet city need (Mukuku *et al.*, 2019). But getting water from both lakes is a very costly process. Also, there is a threat of the Makutupora natural groundwater aquifer being overtaken in a few years due to more drilled boreholes (Kashaigili *et al.*, 2016).

From 1988 to 1992, the government and the Ministry of Water Energy and Minerals researched the surrounding area and published reports by Shindo (1989, 1990, 1991) to give some of the information that supports the modelling of artificial recharge in the Makutupora aquifer. Furthermore, reports of Japan International Cooperation Agency (JICA) 1998, 2000 and 2002 explain the area's hydrogeologic and hydrological condition. In the study, the researchers estimated that the Chenene project could produce 24 000 m^3/day as a natural resource in the future. The study lacked an established recharging mechanism. Preliminary studies from 1993 yielded secure water flow ranging from 50 000 m^3/day to 70 000 m^3/day of water without a piece of conclusive evidence (Mukuku *et al.*, 2019). Furthermore, water demand from the year 2021 projected to be greater than the estimated safe yield, and hence a need for some mechanisms to increase the safe yield through artificial recharge techniques. This study aims to enhance the recharge of groundwater in the Makutupora aquifer.

2.3 Empirical Studies

Rapid population growth in semi-arid areas has led to groundwater's over-exploitation (Ali *et al.,* 2019). In Tanzania, the major water supply source in Dodoma City is groundwater from shallow and deep aquifers mainly taped from Makutupora wellfield (Shemsanga *et al.*, 2018). Despite the high dependence on Makutupora for safe water to support the surge increase in population, climate change and variability have exacerbated water scarcity. The Makutupora well field provides a sustainable water source to Dodoma (Cuthbert *et al.,* 2019; Kolusu *et al.,* 2019). The long term observation since 1954 indicated that El-Nino events play significant roles in facilitating the recharge of the aquifers surrounding the Makutupora that usually causes huge positive changes of the groundwater storage (Kolusu *et al.*, 2019). Water management through Managed aquifer recharge in Dodoma City is vital to ensure water security because of limited surface water resources and heavy dependence on groundwater (Shemsanga *et al.*, 2018). Population growth has increased the demand for this vital commodity (Rwebugisa, 2008).

The most factor that causes water demand to increase is the higher dependence on intense rainfall to recharge the aquifers, which rarely happens. Climate change and variability automatically affect the recharge rate; hence, artificial recharge is the most recommended response strategy (ibid). One of the most recommended artificial recharges is water infiltration to the ground. It can be achieved by constructing engineering structures like the underground reservoir or pond to collect the surface runoff during the rainy time to replenish the overexploited aquifers (Shemsanga *et al.*, 2018).

The sustainability of the Makutupora wellfield to support the population of Dodoma is unclear (Taylor *et al.,* 2013). The government and people have been at a fear towards water supply sustainability due to receiving major offices, ministries, and embassies to Dodoma City and believing that the water demand will increase much and more than anticipated. Recently, a long-term decline in groundwater storage has been experienced due to increased pumping rate following the movement (Kolusu *et al.*, 2019). Hence, this calls for some strategies to replenish the overexploited aquifers. Artificial groundwater recharge has been a core part of water policy since the 1990s throughout the world (Megdal *et al.*, 2014; Murray *et al.*, 2018). Several projects in Arizona and other US states have successfully managed artificial recharge to meet water sector objectives, specifically on groundwater resources management (Megdal *et al.*, 2014). Countries such as Austria, Greece, Netherlands, Poland, Hungary, Iran, Israel, Jamaica, South Africa, Belgium, Denmark, Finland, Spain, Switzerland, Australia, and Morocco have succeeded to implement artificial recharge programs.

Mathematical models are used to simulate groundwater flow systems and predict aquifer conditions (Jafari *et al.*, 2016). Groundwater is not easily accessible and often receives less attention than surface water resources (Barthel & Banzhaf, 2016). The replenishment of the overexploited aquifer can be simulated using various numerical modelling techniques that provide helpful information for water resource and Engineering Managers (Zuurbier *et al.*, 2017). Models that represent the concept of groundwater flow behaviour are usually expressed in the form of differential Equations in either one, two or three dimensional. The three-dimensional transient flow Equation has been solved using the finite difference methods and coded by the FORTRAN programming language, resulting in powerful software for solving various groundwater flow problems called MODFLOW. The use of the software has enabled various nations to effectively manage groundwater resources (Hashemi *et al.*, 2013).

The partial differential Equation for modelling the three-dimensional groundwater flow problem has been expressed in Equation 1:

$$\frac{\partial}{\partial x}\left(k_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_{zz}\frac{\partial h}{\partial z}\right)=S_s\frac{\partial h}{\partial t}\pm W. \quad (1)$$

Whereby k_{xx}, k_{yy}, and k_{zz} represent the hydraulic conductivity in x, y, z directions. S_s is the specific storage, h is the piezometric head (L), W stands for sinks or sources, and t is time. Usually, the solving of Equation (1) analytically becomes difficult, and it consumes time. Therefore, the best method is to use various finite difference methods to approximate the numerical solution for a given problem (Sundararajan & Sankaran, 2020). In various cases, the finite difference MODFLOW code has been used to analyze and predict future groundwater flow conditions of the aquifers' different types and conditions (Bizhanimanzar *et al.*, 2020; Vázquez-Báez *et al.*, 2019). Various graphical user interfaces like ModelMuse and GIS technique have been used to simplify the simulation and visualization of a given groundwater flow problem use MODFLOW in a particular setting (Kumar, 2019).

Following are a few pointed studies that resulted in positive recommendations regarding modelling groundwater flow specifically to artificial groundwater recharge. Paul (2006) investigated land-use change on groundwater discharge and recharged in East China by using MODFLOW. The study results indicated that urban development reduces the recharge of the studied area due to the destruction of nature. Therefore, from that study, it was concluded that forests effectively conserved the aquifer (ibid). Chenini and Ben-Mammou (2010) carried study to specify artificial recharge locations in the Maknassy basin of the Southern Central part of the Atlas Tunisia using GIS and MODFLOW, and positively they were able to identify suitable sites for implementing the artificial recharge. Wasif and Hasan (2020) modelled and simulated aquifer storage recovery using MODFLOW to increase storage after water scarcity as brought by climate change, urbanization, and an increase in the area's population. Chitsazan and Movahedian (2015) modelled artificial recharge using MODFLOW sand; the results indicated that artificial recharge enhances groundwater recovery effectiveness. Mali and Singh (2016) used MODFLOW to model the groundwater flow and assess the potential for recharge and water table behaviour under varying recharge and pumping conditions. It was found that the sustainability of groundwater in aquifers can be ensured by making water available to the farms (ibid). The latest UN report indicated that in 2018 the global population was 7.1 billion, by which urban comprised 4.2 Million. The population is expected to reach up to 9.7 billion of which 6.6 billion (68%) will live in urban (Sun *et al.*, 2020). Now, the already mentioned studies simulated the artificial recharge, to the specific areas with various hydrogeologic conditions and hence a need to carry out the study in other areas.

Coming to Makutupora, Dodoma, in the years back, Shindo (1991) used MODFLOW to develop groundwater flow under transient state conditions. However, the clear picture of groundwater flow was not indicated because the modelled area was too small. The other study done used MODFLOW to model Makutupora catchment and observed that geologic structures' presence influences groundwater and surface water flow (Rwebugisa, 2008). However, the time was not enough to validate the model and determine recharge rates (ibid). A study by Kashaigili *et al.* (2003) on groundwater management using a mathematical model under MODFLOW code suggested that artificial recharge through infiltration ponds can restore the aquifers. The study did not explain how much recharge is needed and the aquifer's natural recharge to satisfy the people as the City multiplies. Also, Siddiqui (2016) modeled artificial recharge of groundwater using MODFLOW to ensure the sustainability of water for 20 years with regard to the projected population. The results of the study indicated an increase of the daily recharge from 3.6 Million of Gallons per Day to 7.9 Million of Gallons per Day.

Then, Rwebugisa (2008) did research in Makutupora that assessed the recharge of groundwater using MODFLOW. Her recommendations were to monitor the wellfield by introducing boundaries that better reflect the area concerning time to understand inflow and outflow rates. However, the study did not focus on improving the recharge of the site through artificial recharge. Therefore, this study fills in the identified gaps by simulating and determining the recharge rate to the estimated increase in water demand that could be brought by the rise in population, considering the figures projected in the Norplan report of 2019 (Table 2).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Modelling Protocol or Modelling Process

The modelling process has undergone the following steps as described in Fig. 1.

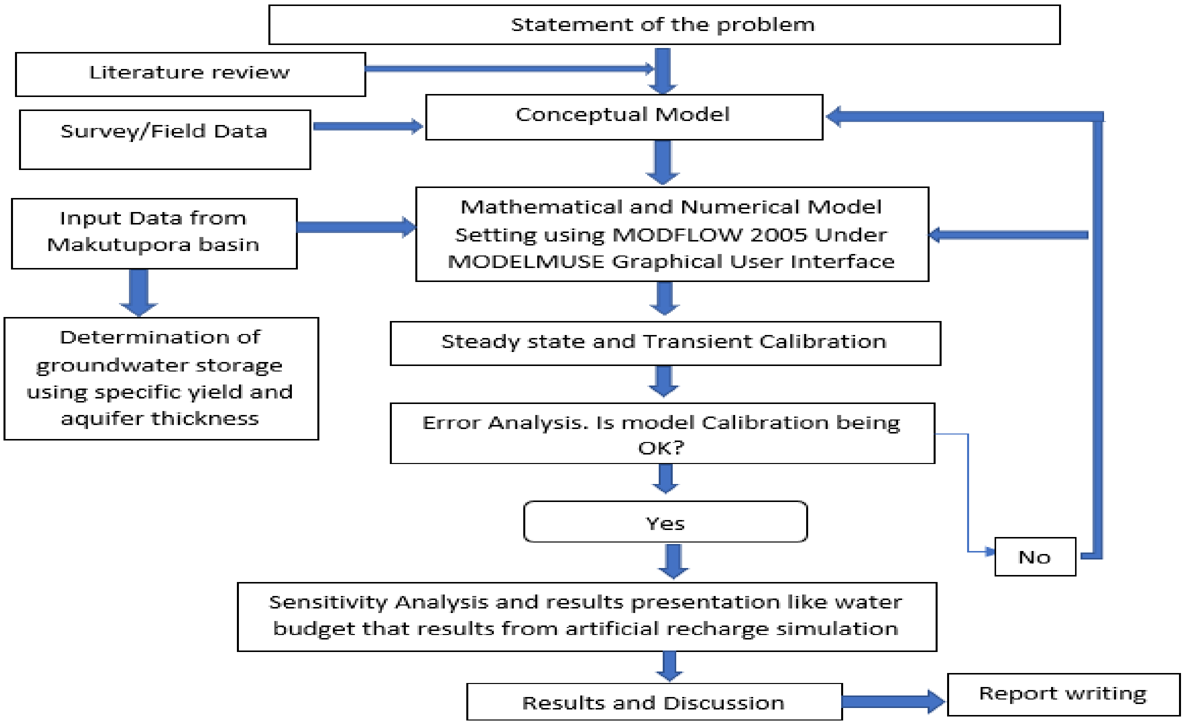

Figure 1: Modelling Protocol (Kisendi, 2016; Rwebugisa, 2008; Timothy, 2015)

Several steps were involved in modelling the artificial recharge of groundwater. Various skills related to hydrogeology were used in the whole process of modelling groundwater, involving understanding the Equations. The first step involved using all knowledge and available data obtained from existing literature, a survey conducted in this study, and field data collected to develop a conceptual model. The available data were also used to establish the groundwater storage of the Makutupora aquifer. The second step involved representing the conceptual model in a mathematical form and construction/setting of the numerical model by applying the analyzed data like recharge rate and evapotranspiration, and other boundaries discovered during the conceptualization process. The third step involved calibration of both steady and transient states that matched the observed and the simulated data. The fourth stage involved the use of the constructed model to predict the flow of groundwater. It also involved the simulation of artificial recharge of groundwater.

3.2 Study Area

The study was undertaken in the Central Semi-Arid part of Tanzania. The specific location for the study is the Makutupora that is found in the Dodoma region. Its location 5^0 36′59" and 6^0 14' 50 " S and 35^0 36' 36"' and $36^0$01' 54"'E. The pumping station is located about 30km North of Dodoma City (Fig. 2).

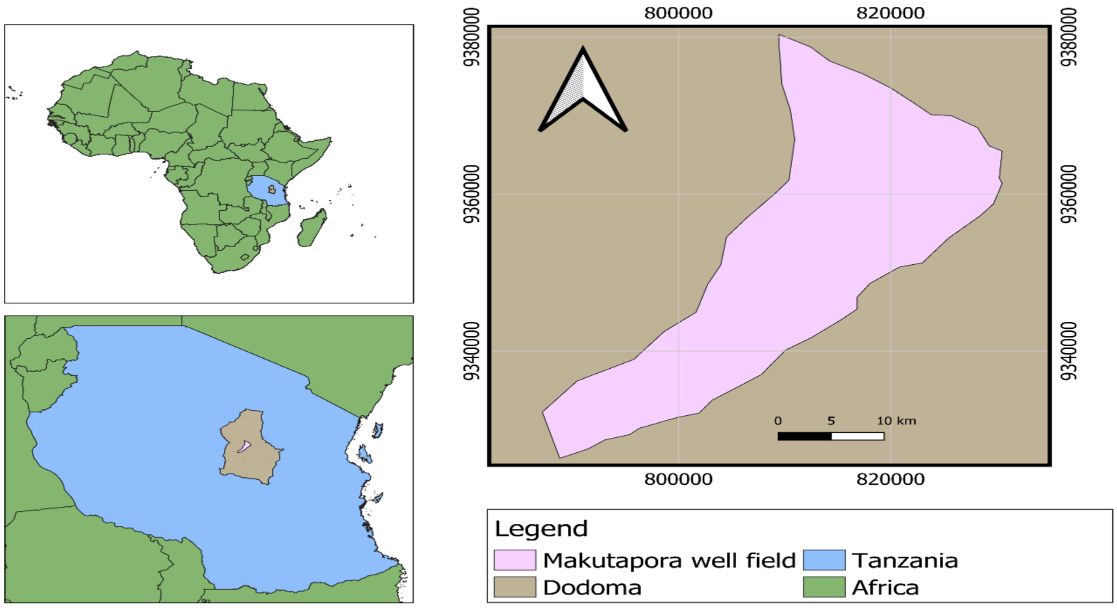

Figure 2: Map to Show the Study Area

3.3 Investigation Survey and Data Collection

The collection of secondary data from the Ministry of water took place from the 13^{th} to the 24^{th} of October, 2020. Furthermore, I did a survey and observed the fundamental nature of Makutupora and its surrounding environment that helped develop the conceptual model. Moreover, the professionals and government officials dealing with the Makutupora basin management participated by providing preliminary information and responding to the survey questions to understand the Makutupora aquifer. Meteorological and hydrological data were taken, processed, and used in MODFLOW with ModelMuse graphical user interface support. Some of the data were not available in Makutupora, like evapotranspiration rate. To overcome the lack of data, calculation of daily evapotranspiration based on downloaded temperature data from NASA’s website and then used to calculate the daily evapotranspiration.

3.4 Data Processing

Modelling requires a lot of varieties of data. The data were collected from the required offices and others obtained from the available literature. In principle, the initial data collected could not be entered in the MODFLOW model directly, and hence the average precipitation, temperature, potential evapotranspiration were calculated and the used in model calibration of the model for better and meaningful results.

3.5 Climate

3.5.1 Precipitation

Evapotranspiration (EPT) and precipitation are key factors that control the hydrological cycle of any geographical location over the whole world (Marshall, 2014). The area surrounding the Makutupora receives an average annual rainfall of 550 mm, and it always rains from November to April (Global Water for Susttainability program [GLOW], 2014; Rwebugisa, 2008). There is less rainfall in the areas near the top of the hills and more in the bottom spots (Rwebugisa, 2008). The site receives bi-modal rainfall whereby *Vuli* rains occur from March to May and *Masika* from October to December (ibid). For this study, the daily rainfall records from 2017/01-2019/12 were used (Fig. 3).

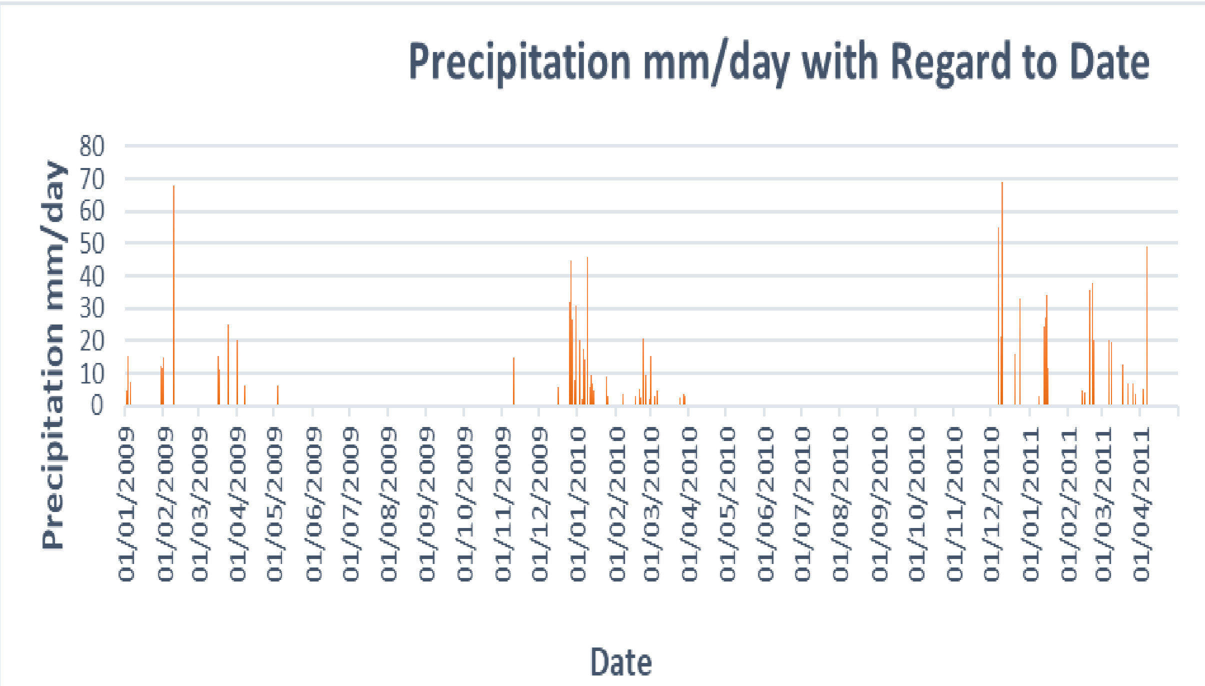

Figure 3: The Daily Precipitation from 2017/01- 2019/12 (Ministry of Water Database Dodoma, 2020)

3.5.2 Temperature

On average, July is the coolest month with the highest temperature of 27.6 ^{0}C, and February is the warmest month, with an average temperature of 33.1 ^{0}C. The collected monthly mean maximum and minimum temperature indicated climate variability that could also exacerbate water scarcity. The issue of climate change and variability affects the recharge process in the Makutupora. The evidence obtained from the study evaluated the recharge mechanism in which El Nino events seem to contribute the highest amount of recharge (Kolusu *et al.*, 2019). Otherwise, the recharge rate in Dodoma is low in normal years, resulting in low groundwater storage; hence, groundwater overexploitation is inevitable. The processed data indicated that the warmest month in 2017 was October with 33.72 ^{0}C and, the coolest month was July with 14.14 ^{0}C. In 2018, the warmest month was November with 33.20 ^{0}C and, the coolest month was July with 13.24 ^{0}C. In the year 2019, the warmest month was September with 32.14 ^{0}C mean maximum temperature and, the coolest month was July with 13.99 ^{0}C mean minimum temperature. The unclear trend of the temperature results in disturbances in the hydrological cycle (Bajracharya *et al.*, 2018). In general, the analysis of the daily maximum and minimum temperature for the study area indicated that the highest temperature is 36.07 ^{0}C and the lowest temperature is 20.82 ^{0}C.

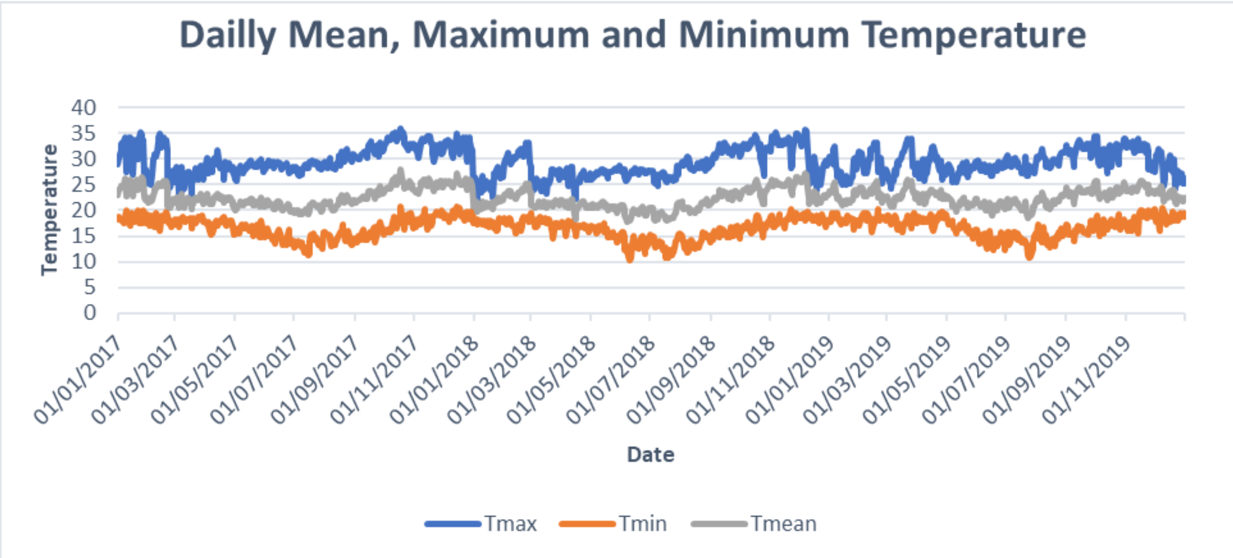

Figure 4: Daily Maximum, Mean and Minimum Temperature from 2017/01-2019/12 (Ministry for water Databases Dodoma, 2020)

3.5.3 Potential Evapotranspiration (PET)

Penman-Monteith and the Hargreaves Equations were used to calculate the potential evapotranspiration rate for the area. This was done due to the lack of direct data from the Makutupora Pan evapotranspiration. The data from the date 01/01/2017 through 31/12/2019 used to prepare reference potential evapotranspiration ET_O. The calculated ET_O was used to calculate Potential Evapotranspiration. After processing the evapotranspiration and mean daily temperature, the results indicated that as the temperature increases, the evapotranspiration rate also increases; that is, the two parameters are proportional (Fig. 5).

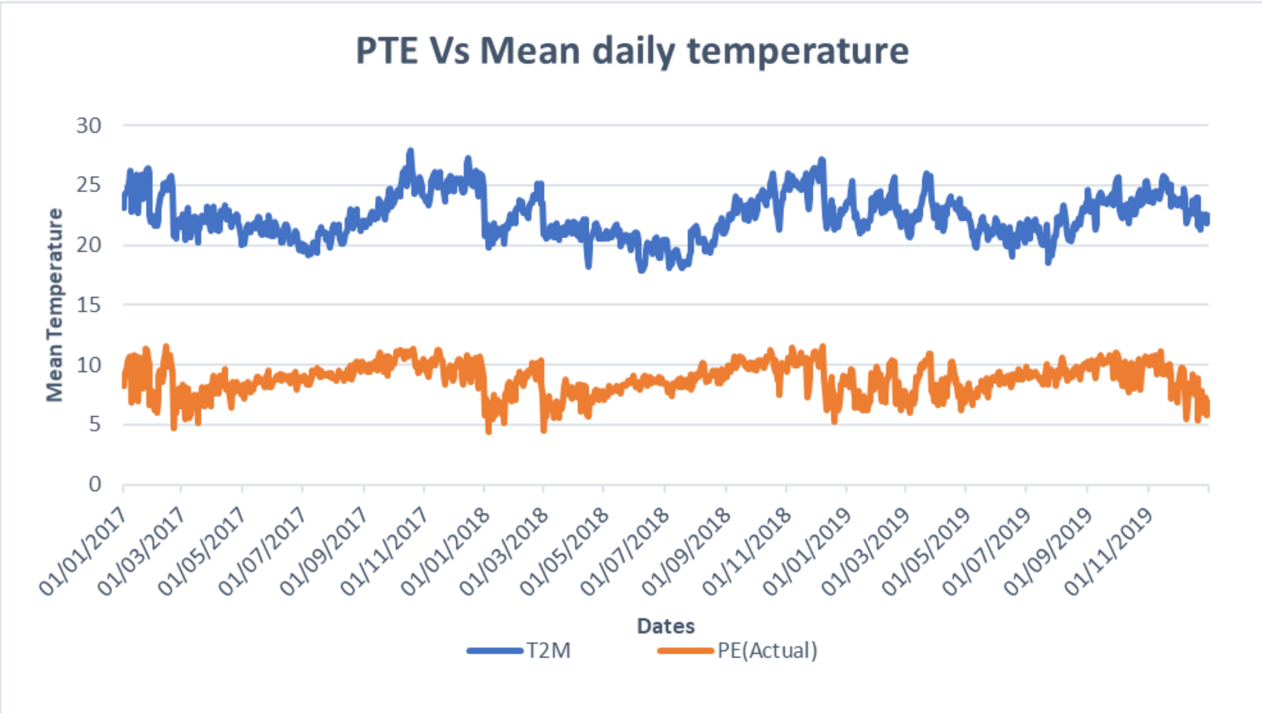

Figure 5: Potential Evapotranspiration Versus Mean Daily Temperature (Ministry of Water Dodoma, 2020)

3.5.4 Calculation Potential Evapotranspiration

Precipitation data from 2017/01-2019/12 was used. The mean minimum and maximum temperature collected were used to calculate the reference evapotranspiration (ET_O). The (ETo) obtained was used to calculate the PET by using FAO original Penman-Monteith Equation and Hargreaves Equation (Paredes *et al.*, 2020).

ET_O from the Penman-Monteith Equation

$$ET_O = \frac{0.48 \times \Delta \times (R_n - G) \times \gamma \times \left(\frac{900}{T+293}\right) \times U_s \times (e_s - e_a)}{\Delta + \gamma \times (1 + 0.34 \times U_s)} \quad (2)$$

The gradient of saturation vapor pressure curve (Δ) is described in Equation 3:

$$\Delta = \frac{4098\left[0.6108exp\left(\frac{17.27T}{T+237.3}\right)\right]}{(T+237.2)^2} \quad (3)$$

Where Δ is the gradient of saturation vapor pressure T (kPa °C^{-1}), T is air temperature (°C), and T is the mean daily air temperature by Equation 4.

$$T_{mean} = \frac{T_{max} + T_{min}}{2} \quad (4)$$

Net radiation (R_n)

$$R_n = R_{ns} - R_{nl} \quad (5)$$

R_{ns} *and* R_{nl} are the incoming and outgoing shortwave radiation, respectively (MJm^{-2} day^{-1}),

$$R_{ns} = (1 - \alpha) \times R_s \quad (6)$$

Where:

α - albedo is 0.23 of the grass reference crop.

R_s- the incoming solar radiation (MJm^{-2} day^{-1}),

$$R_{nl} = \sigma * \left[\frac{T_{max,K^4} + T_{min,K^4}}{2}\right] * \left(0.34 - 0.14 * \sqrt{e_a}\right) * \left(1.35 * \frac{R_s}{R_{so}} - 0.35\right) \quad (7)$$

Where:

σ - Stefan-Boltzmann constant 4.903 x 10-9 (MJm^{-2} day^{-1}),

T_{max}, K - maximum absolute temperature during 24 hours period in kelvin,

T_{min}, K - minimum absolute temperature during 24 hours period in kelvin,

e_a - actual vapor pressure (kPa),

$\frac{R_s}{R_{so}}$- relative shortwave radiation (less or equal to 1.0),

R_s - the calculated incoming solar radiation (MJm^{-2} day^{-1}),

R_{so} - the calculated clear-sky radiation (MJm^{-2} day^{-1}) was calculated by using

$$R_S = (0.75 + 2 * 10^{-5} * Z_e) * R_a \quad (8)$$

Whereby

Z_e is the station elevation above mean sea level (m) and R_a is the extra- terrestrial radiation (MJm^{-2} day^{-1}),

$$e_a = \frac{e_o(Tmin) * \frac{RH_{max}}{100} + e_o(Tmax) * \frac{RH_{min}}{100}}{2} \quad (9)$$

Where:

RH_{min} and RH_{max} - are the daily max and minimum relative humidity (%), and e_o is the saturation vapor pressure (kPa). The calculation of the Potential evapotranspiration based on the following Equations:

$$e_{o(T)} = 0.6108 * \exp\left(\frac{17.27 * T}{T + 237.3}\right) \qquad (10)$$

Saturation vapor pressure (e_s):

$$e_s = \frac{e_o(Tmin) + e_o(Tmax)}{2} \qquad (11)$$

Psychometric constant (γ):

$$\gamma = 0.665 * 10^{-3} * P \qquad (12)$$

Atmospheric pressure (kPa):

$$P = 101.3 * \left(\frac{(293 - 0.0065 * Z_e)}{293}\right)^{5.26} \qquad (13)$$

Average wind speed (u_2) at the height of 2m:

$$u_2 = u_z * \frac{487}{\ln(67.8 * z - 5.42)} \qquad (14)$$

$$PET = ET_O \times K_C \qquad (15)$$

PET is Potential Evapotranspiration

ET_O is reference evapotranspiration

K_C is the crop coefficient

Where $K_C = 0.7$ (The value of K_C Was adopted from Rwebugisa (2008))

***ET_O* from the Hargreaves Equation**

$$ET_O = 0.0023 \times (T_{mean} + 17.8) \times (T_{max} - T_{min})^{0.5} \times Ra \qquad (16)$$

Where T_{min}, T_{max}, and T_{mean} are the are the daily minimum, maximum and mean daily air temperature in ℃, Ra is the extraterrestrial radiation. Julian day (J) and the latitude in radians were used as an input to estimate the incoming solar energy (Equation 17):

$$Ra = \left(\frac{24 \times 60}{\pi}\right) \times (G_{sc} \times d_r) \times \left[\left(\omega_s \times \sin(\varphi) \times \sin(\delta)\right) + \left(\cos(\varphi) \times \cos(\delta) \times \sin(\omega_s)\right)\right] \qquad (17)$$

Where:

G_{sc} is the solar constant which is $0.082 MJm^{-2}day^{-1}$

d_r is the relative distance between the earth and the sun

ω_s is the sunset hour angle

δ is the solar declination

φ is the latitude in radians

$$d_r = 1 + 0.033 cos\frac{2\pi J}{365} \quad (18)$$

Where J is the Julian days

$$\omega_s = arc\ cos[-tan(\varphi) \times tan(\delta)] \quad (19)$$

$$\delta = 0.409 \times sin\left(\frac{2\pi J}{365} - 1.39\right) \quad (20)$$

Where δ is solar declination.

After obtaining the ET_O, the values obtained were converted into PET using the crop coefficient method following Equation (14). The information related to the vegetation distribution was scarce, and hence the Kc value from previously studied was adopted and used in the computations. Therefore, Kc value of 0.7 was assigned to the model (Rwebugisa, 2008). The Summary of the Parameters used to calculate the reference evapotranspiration, and Potential Evapotranspiration is found in Appendix 1.

3.5.5 Water Level Fluctuation for the Piezometers

The available elevation data in meters above mean sea level (m.a.m.s.l) and the general static water level for the chosen boreholes were used to calculate the piezometric level for each borehole by taking the given elevation minus the static water level using Equation (21):

$$\text{Piezometric level} = \text{Elevation (m.a.m.s.l)} - \text{Static water level (s.w.l)} \quad (21)$$

3.6 Groundwater Storage Estimation in Makutupora Aquifer

Estimating groundwater storage in the Makutupora aquifer was done using available borehole data and GIS. The GIS was used to construct the map through georeferencing, where the faults/fractures that stores water were digitized accordingly. The lengths of the faults calculated using a field calculator. The available maps were in image form and had no exact coordinate system and hence were imported in QGIS and then georeferenced accordingly (Fig. 6). The aquifer was divided into four layers: The layers' determination based on the soil type's dominant concentration. The first and third layer were aquitards, and the second and fourth were the aquifers. The estimated aquifer thickness was adopted from the previous literature (Maurice *et al.*, 2018). The specific yield was calculated by averaging the determined values (Johnson, 1967). Specific yield refers to the amount of water available for groundwater pumping from the material containing the water. The specific yield also depends on the depth of the aquifer. Fig. 7 shows the flowchart of groundwater storage estimation.

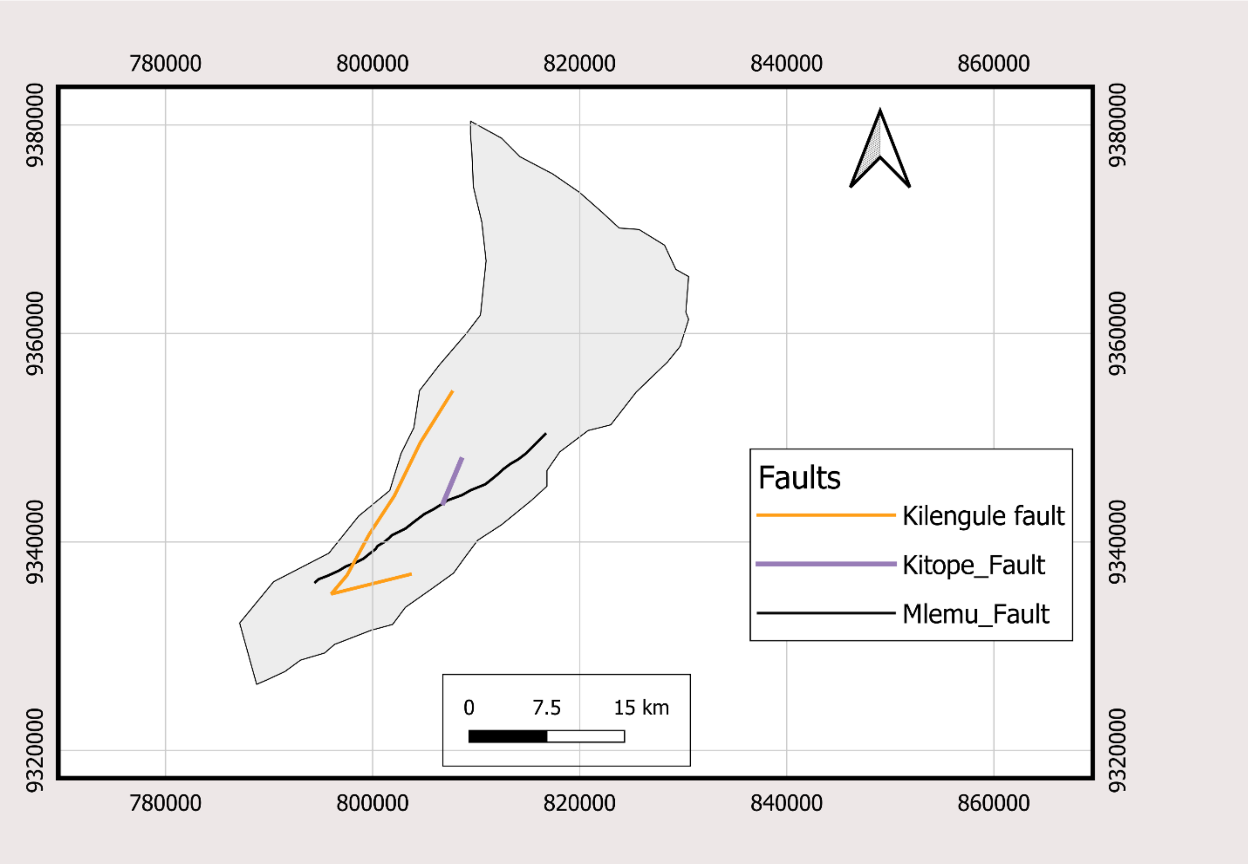

Figure 6: Kilungule, Kitope and Mlemu Faults

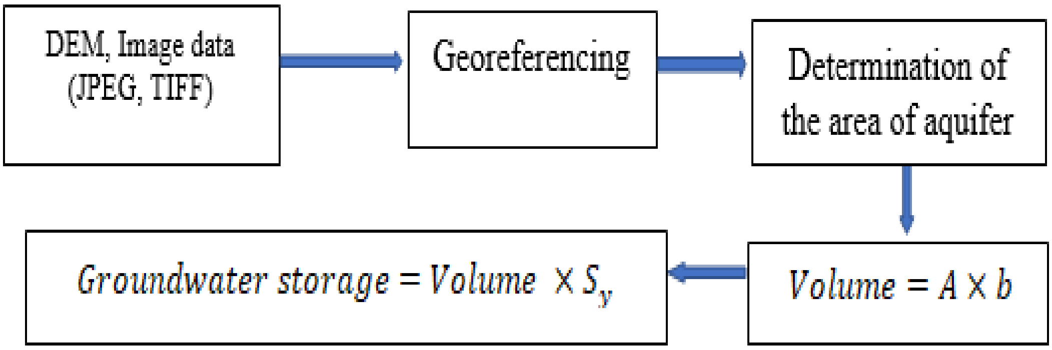

Figure 7: Flowchart Showing Groundwater Storage Estimation

Table 3: Length, Width and Area of the Faults

Fault name	Length	Width	Area (Length X width)
Kilungule fault	30 491.16 m	150 m	4 573 674 m^2
Mlemu fault	26 639.14 m	100 m	2 663 914 m^2
Kitope fault	4472.96 m	90 m	402 566.4 m^2
Total	**61 603.26 m**		**7 640 154.4 m^2**

A map calculator was used to determine the area of the aquifer. Groundwater calculated using the Equation (22):

$$Groundwater\ storage = A \times b\ \times S_y \tag{22}$$

$$Where\ \mathrm{A} = \mathrm{Area}, b\ = \mathrm{Aquifer\ thickness\ \ and}\ S_y = Specific\ yield$$

3.7 The Conceptual Model for Makutupora Well Field

Better water management for the sustainability of a particular site of interest requires a deep understanding of the hydrological system. For the case of groundwater, a conceptual model is necessary before the modelling process (Akinwumiju & Olorunfemi, 2019). The conceptual model refers to the groundwater flow system in a pictorial form (Anderson & Woessner, 1992). The main goal for developing a conceptual model was to use the information obtained from the survey and other sources to create a concrete concept that can simulate the Makutupora well field into meaningful scenarios and applications for sustainable water supply in Dodoma City. Therefore, the combination of knowledge obtained through observation during the personal visit and literature information helped establish the best conceptual model of the Makutupora.

3.7.1 Groundwater Recharge Factors in Makutupora

Climate, Geomorphology, and Geology are among the factors that influence the rate of groundwater recharge (Rwebugisa, 2008). Recharge occurs most extensively in high-topographic regions in most Tanzania places through rainwater infiltration via rock fractures. Groundwater from alluvial sand-grained fans seems to have more infiltration rates. Most of the recharge occurs around the Chenene hills, whereby the part receives about 850 mm of the annual precipitation (Salustian *et al.*, 2017). Water infiltrates through rock fractures and into the site along faults, thus contributing to recharge (ibid).

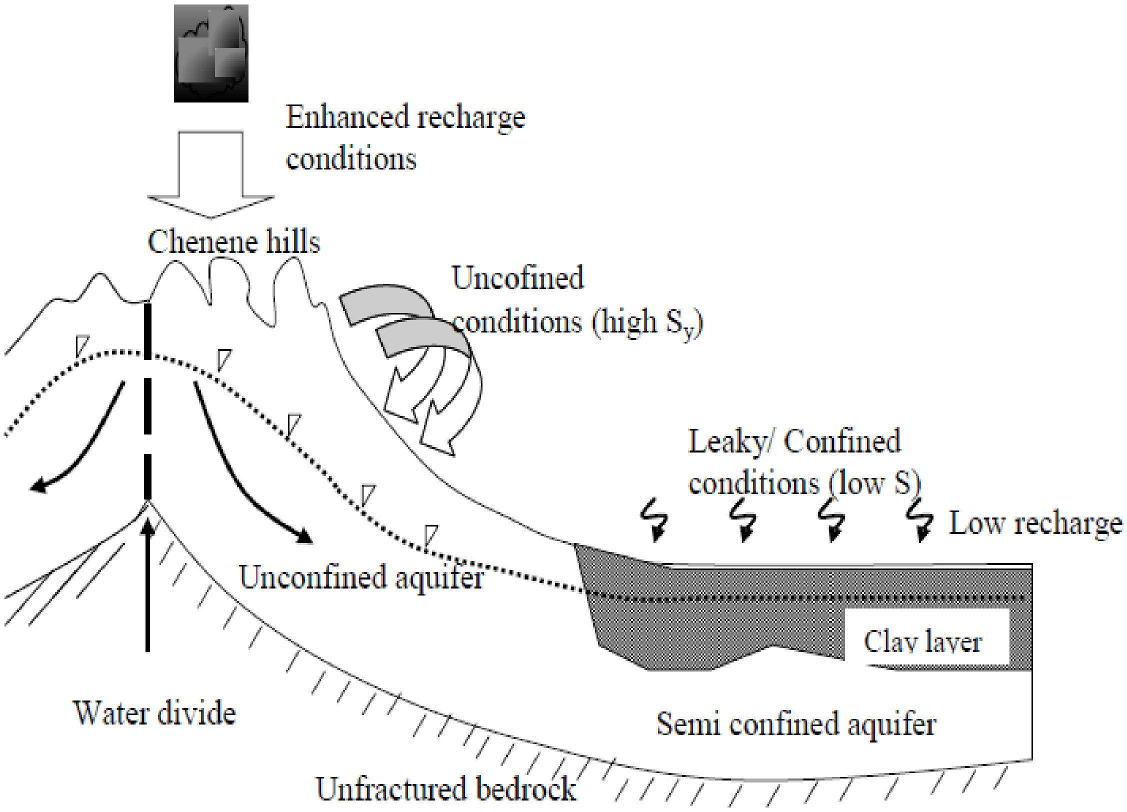

Figure 8: A Conceptual Diagram for the Aquifer Types and Flows in Makutupora (Rwebugisa, 2008)

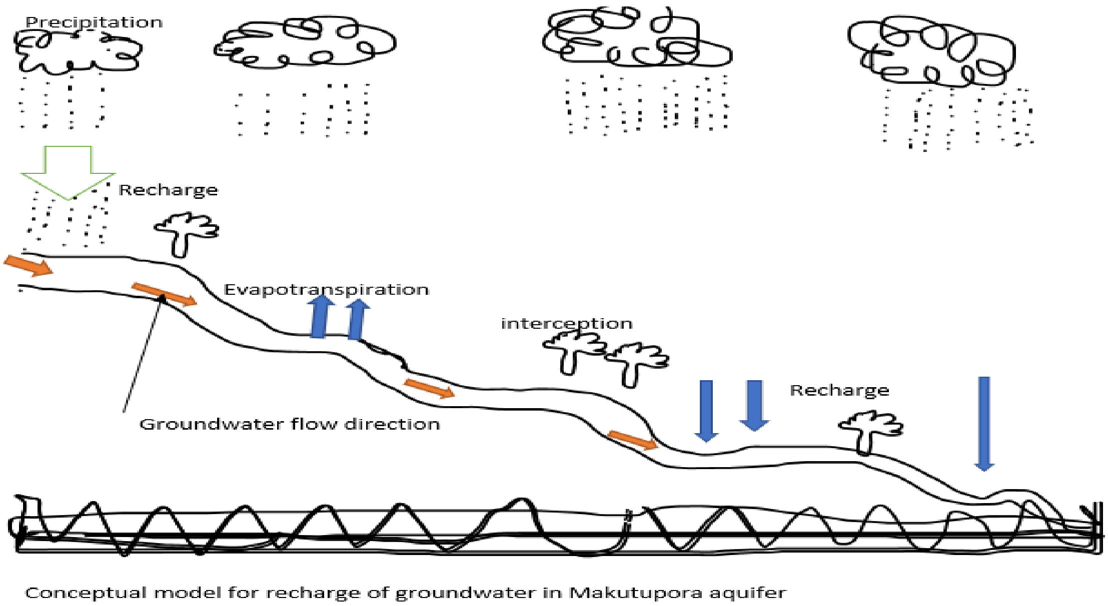

Figure 9: Conceptual Model (Rwebugisa, 2008)

3.7.2 Geomorphology

Geomorphologically, the Makutupora area is described into four major units. Namely: (a) Plateau with thin termite mound and soil cover, (b) Rock hills and inselbergs around Chenene hills, (c) A depressed basin which is filled with clay, (d) Pediment slope consisting of thin soil cover and gentle slope. Generally, the area's geomorphology is surrounded by factors that affect /influence recharge like soil type, faults, topography and vegetation. Therefore, recharging wells were put in the basin basing on those factors.

3.7.3 Hydrostat Graphic Unit

The geological unit of the same hydrogeological properties refers to the hydrostratigraphic unit (Anderson & Woessner, 1992). The study area's hydrostratigraphic unit was set using the lithological profile. Data were collected from the Ministry of Water to identify the hydrostratigraphic unit in the Makutupora aquifer. Various borehole logs drilled indicated that the stratigraphy varies from area to area. The top layer consisted mainly of clay and was considered the topmost layer in the aquitard group. The low permeability for clay soil due to its small pore spaces concludes that this layer's recharge rate is also meagre compared to other soil kinds. The second layer is an aquifer due to silt presence (Holthusen *et al.*, 2018). The third layer was an aquitard, and the fourth layer was an aquifer. In general, the study area was classified into four distinct geologic units. Two aquifers and two aquitards (Fig. 10). Unconfined aquifer dominates the upper part, and confined aquifer dominates the lower.

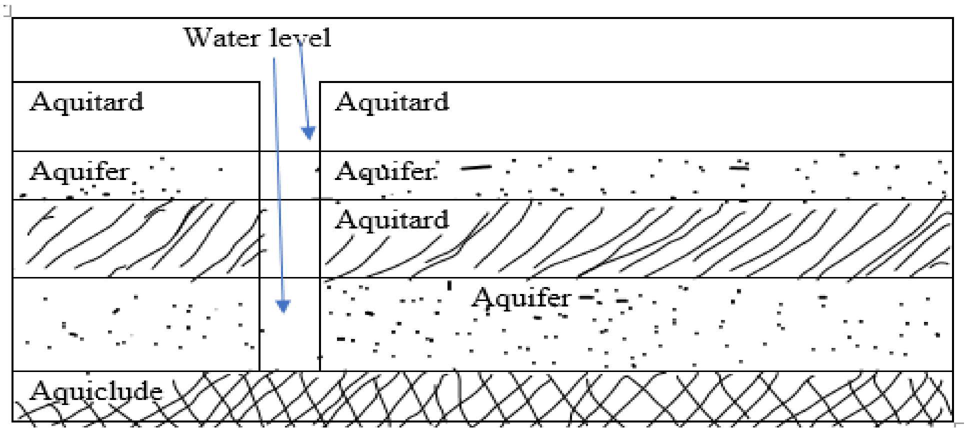

Figure 10: Structured Arrangement of the Aquifers in Makutupora (Lithological Information from Drilled Boreholes, 2020)

An aquifer is a layer of permeable rocks, rock fractures or unconsolidated materials holding groundwater (Sen & Gorelick, 2015). An aquitard is a geological formation that can hold water but cannot allow water to move faster than an aquifer. An aquifer has higher hydraulic conductivity than an aquitard (ibid). Examples of aquitards are the clay, silt and shale, while an aquifer is sand. Calcareous, sandy, highly fractured rocks, gravel, or calcareous, or highly fractured rocks generally make aquifers, while unfractured rocks, poorly sorted sediments and soil with rich clay often form aquitards. Aquiclude acts as a barrier to lower groundwater flow. Hydraulic conductivity is much less than aquifer and aquitard (ibid). Aquitards play an essential role in protecting the aquifer from contamination or pollution from various sources produced by anthropogenic activities (Cherry *et al.*, 2004).

3.7.4 The Aquifer Type in Makutupora

In Makutupora, the upper part is a saturated area due to its nearest to the water table, and hence the aquifer is unconfined in highlands (Rwebugisa, 2008). Rwebugisa (2008) model the area by assuming that an aquifer is stable and in a confined state. The limited number of researches done in the area and the prior information so far suggests it is unconfined and unstable. The distribution of the study area geology is complex, whereby the aquifer and lithological information differ from place to place (Fig. 11).

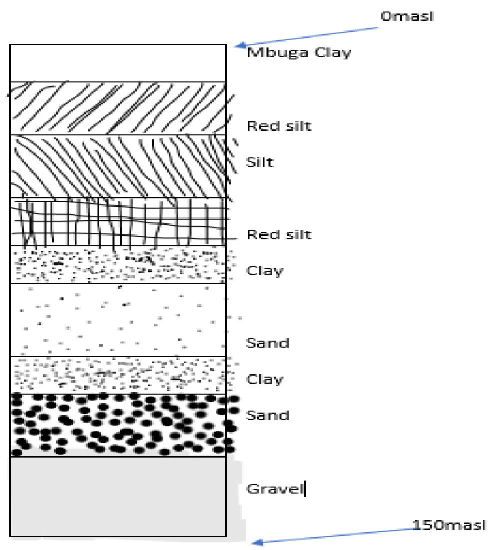

Figure 11: Stratigraphic Units in Makutupora Basin (Rwebugisa, 2008)

3.7.5 Soil Types

The study area comprises three soil types: The most dominant soil types are sand, loam and Clay (Fig. 11). Rwebugisa (2008), as cited in Shindo (1989), contended that there are many varieties of soil, but the Makutupora plateau is dominated by white sand. Loam soil is mainly distributed on rock-basin hillside such as biotite, dolerite and gneiss (ibid). Since the grounds differ so drastically throughout the basin, it would be hard to consider this basin only within one soil property set. Thus, each site would be unique, with its own set of soil properties. The upper area is dominated by sandy soil with porosity ranging from 30% to 50% porous, and recharge occurs mainly in this kind of soil due to big pore spaces.

3.7.6 Geology

Pavelic *et al.* (2012) contended that 75% of Tanzania is composed of the Precambrian basement complex like Archaean and Proterozoic. Dodoma Region is also in Precambrian textures with very dense rocks and difficult to weather (ibid). The fracture zone that is weathered and fractured Precambrian crystalline rock within the aquifer enhance the recharge. In Makutupora, the boreholes draw water from a deep (30m) fractured granite aquifer covering fractured bedrock (ibid).

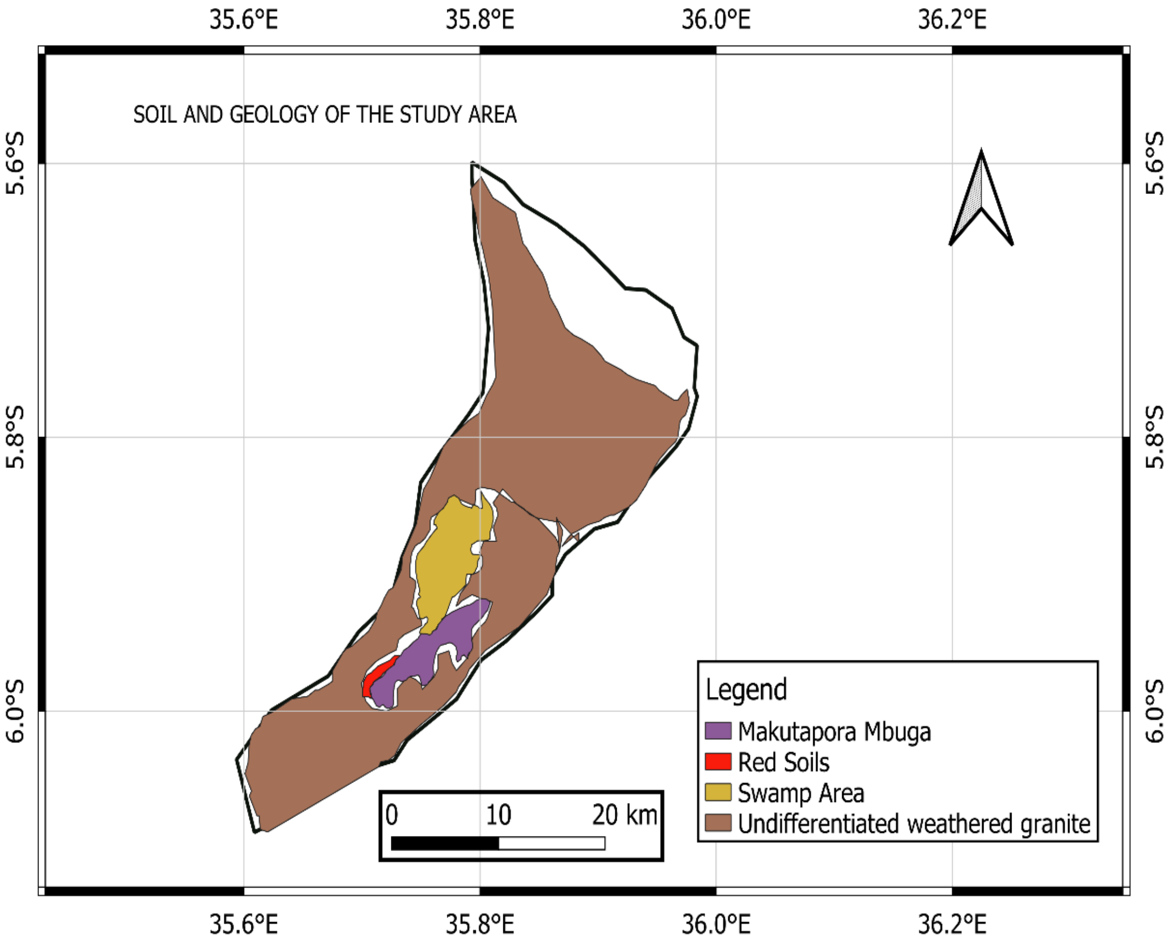

Figure 12: Geological Map of the Area (Soils and Rocks) (Drawn in QGIS 3.14, 2020)

3.7.7 Land cover, Land use and Vegetation Cover

The area has forests, grasslands and bushlands kinds of vegetation cover (Rwebugisa, 2008). The northern part that is surrounded by Chenene hills is covered by Miombo woodland forest. Bushland, shrubs, thicket, acacia trees and grasses cover 60% of the southern upland area. Seasonal swamps are covered by 5% of the lowland, and the remaining 5% is used for subsistence farming. Perennial grasses have been depleted in the northern part during dry seasons, except for woodland forests due to intense domestic grazing (Rwebugisa, 2008). Pastoralism is the dominant activity that is usually practised by the people surrounding the area. The presence of a nearby military base around the well field catchment limits agricultural activities. Changes in land use influences recharge, but there has been little substantial land-use change in recent decades (Taylor *et al.*, 2013). Moreover, the United Republic of Tanzania government protected the area by preserving the places around the drilled boreholes by limiting people to live around the site. Government strategy reduces groundwater pollution (Fig. 13).

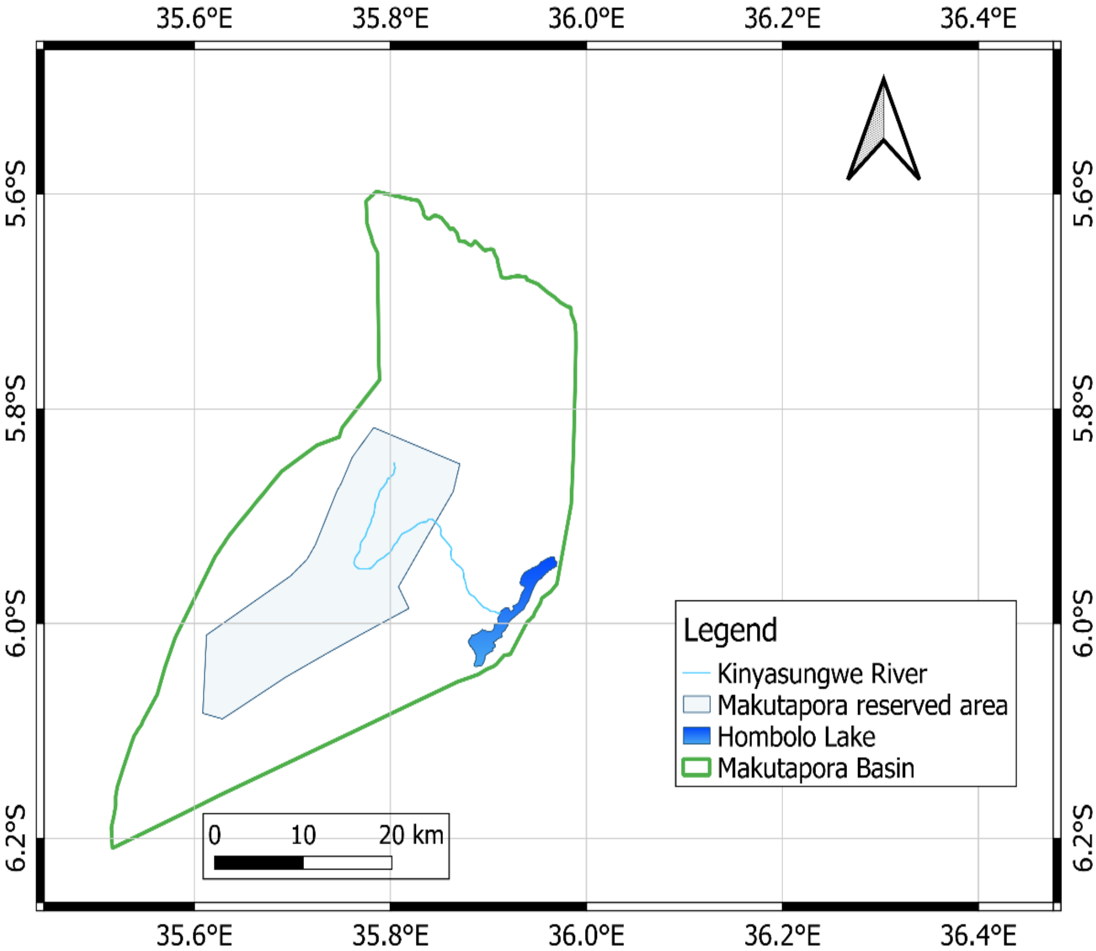

Figure 13: Map to Show the Protected Area in Makutupora Aquifer (Drawn in QGIS 3.14, 2020)

3.7.8 Flow Pattern, Rate and Distribution

The presence of geological features influences groundwater flow in the basin. Regarding surface water, water flows from Chenene hills towards Lake Hombolo. The fault trend that runs North West to North East is very influential to water flow. The fault runs through East Africa along with the Eastern African Rift Valley structures. An ephemeral stream is formed when the rainwater accumulates in the mountainous areas along the Kitope fault, which then runs down towards the Mlemu fault, eventually reaching Hombolo Lake (Fig. 14). The site has various seasonal rivers and streams, including groundwater sources, namely, Nhole stream, Nzuga stream, Mwarabu stream and the Little Kinyasungwe River (Shindo, 1990).

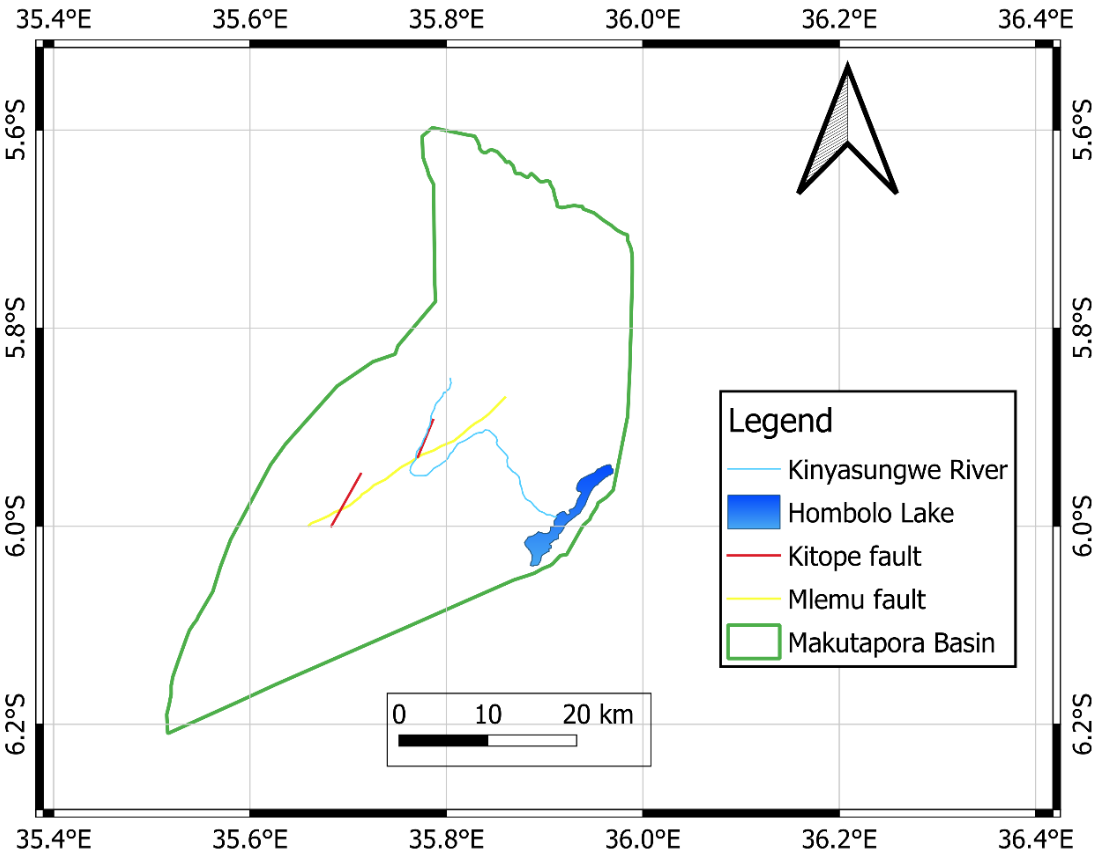

Figure 14: Groundwater Flow Features like Fault with other Features like River Kinyasungwe and Lake Hombolo (Drawn in QGIS 3.14, 2020)

3.7.9 Elevation of the Study Area

In conceptualizing the model, the elevation data from Earth Explorer in the NASA website were also downloaded and visualized in GIS. The data indicated that the elevation data for Dodoma and the surrounding area range from 482 m.a.s.l to 2161 m.a.s.l (Fig. 15). The digital elevation model was also downloaded to represent the target area, and the elevation of the modelled area ranges from 1058 m.a.s.l to 2048 m.a.s.l. (Fig. 16). Furthermore, the study area's contour map was also visualized to help import the MODFLOW code supported by the ModelMuse graphical user interface.

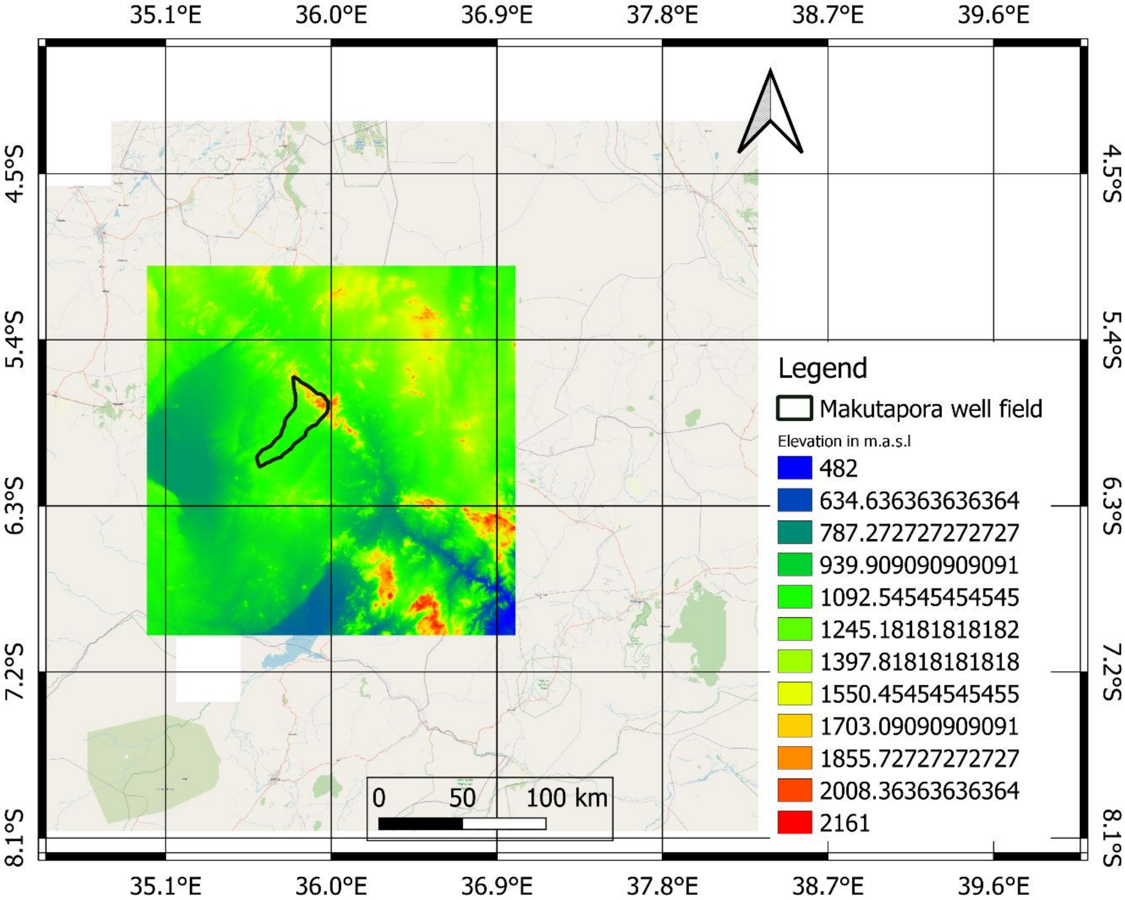

Figure 15: Elevation of the Study Area and its Surrounding Area (Drawn in QGIS 3.14, 2020)

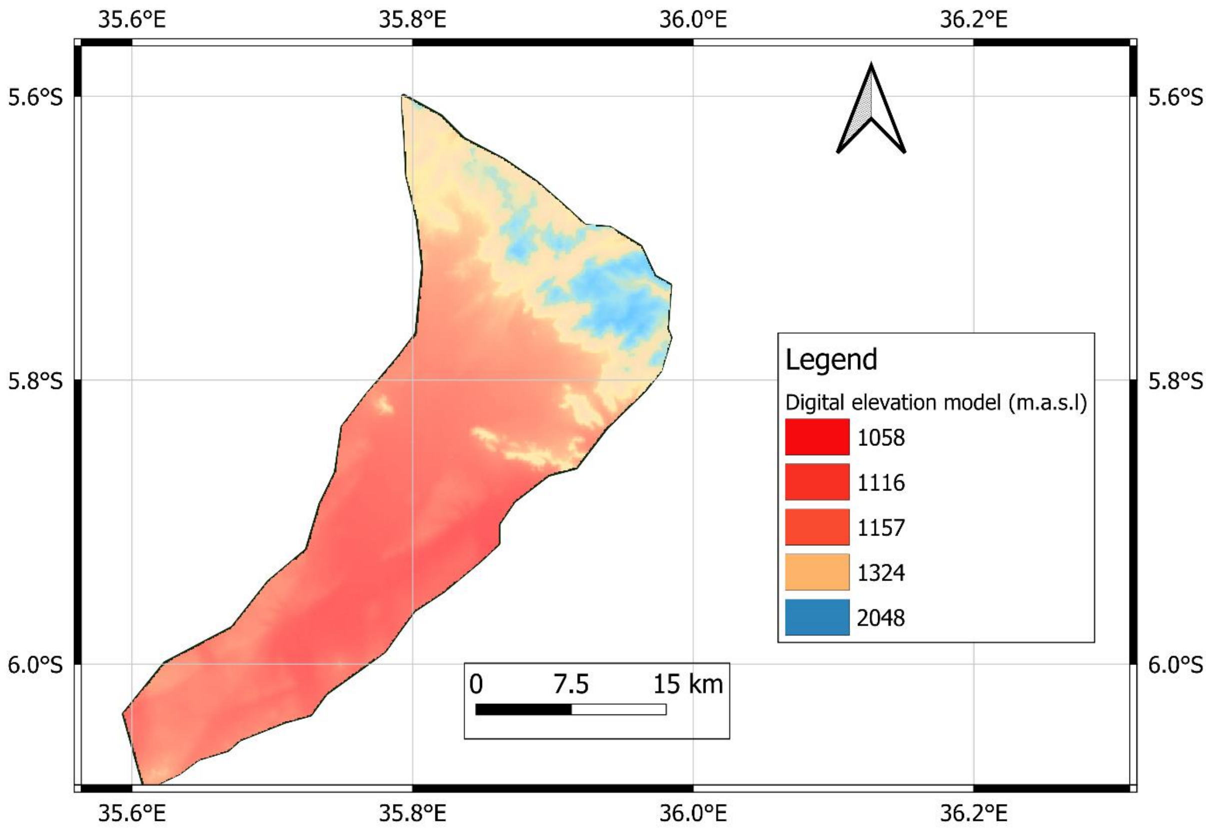

Figure 16: Elevation of the Study Area (Drawn in QGIS 3.14, 2020)

3.7.10 Infiltration Capacity

Infiltration refers to the process by which water enters the soil from rainfall and irrigation. Infiltration capacity refers to how much water pushes into and under the ground through the presence of the fault lines and the underground plant roots (Morbidelli *et al.,* 2018). In Makutupora, water enters the basin from the North-East direction, and Chenene hills and high infiltration capacity occurs around the plateau area. The area comprises two groundwater recharge systems: the zone located around the basin and the groundwater recharge zone in the Chenene hills in the north-flowing into the basin (Taylor *et al.,* 2013).

3.8 Preliminary Groundwater Balance

The hydrological cycle is affected by three major components: evapotranspiration, precipitation, and runoff (Boyd, 2020). After the rainfall, a portion of the water evaporates, some of the water is intercepted by plant leaves, and the rest enters the aquifer through infiltration (Yang *et al.*, 2019). Excess water found in aquifers cannot quickly drain out, but it intrudes into the upper part of the aquifer when evapotranspiration is high (Condon & Maxwell, 2019). The time water is returned to the aquifer is minimized by how water has no way to go out from the aquifer (Zhu *et al.*, 2019). Like the main drainage channels for water, the leading sinks for recharged water are evapotranspiration and abstraction. Groundwater storage is found from the difference between outflow and inflow (Boyd, 2020):

$$I - O = 0 \quad (23)$$

$$\frac{\Delta S}{\Delta t} = I - O \quad (24)$$

Where Δt is the change of time, ΔS stands for a change of storage, O is an outflow, and I stand for groundwater inflow. Equation (24) applies for the transient conditions under a particular stress period, and Equation (23) applies for the steady-state. Transient period means that storage change is not equal to zero in the transitory state as it depends on time. Groundwater (inflow) recharge factors in the study area include: precipitation. Outflow (discharge) includes: evapotranspiration and pumping well. Water storage doesn't change under steady-state conditions because it is not time-dependent, and therefore inflow = outflow.

3.9 Mathematical and Numerical Groundwater Modelling

Numerical modelling of artificial recharge of groundwater has been an essential tool in managing groundwater in various parts of the world (Megdal *et al.*, 2014; Murray *et al.*, 2018). The mathematical formulation and its numerical description used to study groundwater flow in the aquifer are explained in sections 3.9.1 and 3.9.2.

3.9.1 Mathematical Description of Governing Equations

According to Hashemi *et al.* (2013), the governing Equations for a three-dimensional unsteady, transient flow problem with Darcy's law and continuity Equations is expressed by Equation 30, which is the partial differential Equation for physical modelling of the three-dimensional groundwater flow problem. The model is formulated from Darcy's law and continuity Equation, as explained below.

Darcy's law states that, for a given type of sand, the rate of flow of water is proportional to the cross-sectional area A and the piezometric head drop or loss $h_2 - h_1$ and inversely proportional to the difference in the porous media's length (Anderson & Wang, 1995). The groundwater flows from high to low energy potential (Kiptum *et al.*, 2017). The mathematical expression of Darcy's law is as follows in Equation 25:

$$Q \propto A \frac{h_2 - h_1}{l_2 - l_1} \rightarrow q = \frac{Q}{A} = -K \frac{h_2 - h_1}{l_2 - l_1} \quad (25)$$

Where $q = (q_x, q_y, q_z)$ stands for the specific discharge, K is the hydraulic conductivity, and h is the hydraulic head. A minus sign indicates that the flow is in the direction of decreasing head loss. The medium was assumed to be isotropic and that the discharge rate Q is not dependent on time:

$$q = -\mathrm{k}\frac{dh}{dl} \rightarrow q = -k \; grad \; h \quad (26)$$

Where k = (k_x, k_y, k_z) stands for the hydraulic conductivity.

The three-dimensional incompressible continuity Equation is expressed as:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (27)$$

Whereby $u, v \; and \; w$ are the components of velocity in the directions of x, y and z. The velocity components $u, v \; and \; w$ can be replaced with components of $q = q(q_x, q_y, q_z)$. The transient condition is modelled by adding a storage coefficient. The continuity Equation for transient conditions is described by Equation (28):

$$\frac{\partial q_x}{\partial x}(b) + \frac{\partial q_y}{\partial y}(b) + \frac{\partial q_z}{\partial z}(b) = N(x, y, z, t) - S\frac{\partial h}{\partial t} \quad (28)$$

Where N is the sink, b is the thickness of the aquifer, t is time, and S stands for the storage coefficient. Then substitute Darcy's law for q_x, q_y and q_z result in Equation (29) and (30):

$$\left(\frac{\partial}{\partial x}\left(-k_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(-k_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(-k_z \frac{\partial h}{\partial z}\right)\right) = N(x, y, z, t) - S\frac{\partial h}{\partial t} \quad (29)$$

$$\rightarrow \frac{\partial}{\partial x}\left(k_x b \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y b \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z b \frac{\partial h}{\partial z}\right) = S_s \frac{\partial h}{\partial t} - N(x, y, z, t) \quad (30)$$

Where $S_y =$ specific yield

3.9.2 Model Boundaries

Let D represent the study domain, and S be the boundary surface. The initial conditions are used to describe the heads during the transient simulation. The initial condition for Equation (30) is expressed as Equation (31):

$$h = h_0(x, y, z, 0), \; (x, y, z) \in D \quad (31)$$

Where h_0 stands for the value at the initial point. There are three types of boundary conditions applied in solving a groundwater flow Equation:

(i) Prescribed head boundary (Dirichlet boundary/fixed head boundary/specified head boundary/type one boundary):

$$h = h_1(x, y, z, t), \qquad (x, y, z) \in S, \quad t \geq 0 \qquad (32)$$

where h_1 is a known function over the boundary S at time t

(ii) Neumann boundary (Boundary of prescribed flux/fixed flux/specified flux/type two boundary). This is expressed as:

$$\{q\}^T . \{n^0\} = -h_2(x, y, z, t), \qquad (x, y, z) \in S \qquad (33)$$

Where $\{q\}$ is the water flux $[LT^{-1}]$, h_2 is the boundary flux on surface S and is positive for inflow of water about the study domain, and $\{n^0\}$ Is the unit vector normal to the surface S.

(iii) Mixed type of boundary (Cauchy boundary/head-dependent flux/type three boundary):

$$\nabla h(x, y, z, t) + h_0 * a = Constant, \; where \; a \; is \; a \; constant \qquad (34)$$

In application, three boundary condition types apply to the MODFLOW constructed model. For MODFLOW and ModelMuse environments, boundary conditions represent locations where water is flowing in or leaving out the model region due to external factors. The boundary conditions in this model are recharge, rivers (drains), wells, and evapotranspiration. The three boundary conditions are the head-dependent fluxes, specified fluxes and the heads. In specified head boundaries, the head remains constant. The specified flux boundaries in this model are recharge package and well package, whereby the rate at which fluid move out or into the aquifer is specified. The head-dependent fluxes in this model are evapotranspiration, drain, and the general head boundary package. In the specified flux cell, the head changes in response to the flux. Based on the water level and measurements, most of the water enters through Chenene hills along the Mlemu fault zone. The internal model boundaries are the abstraction wells. The general head boundary was set along the Little Kinyasungwe river.

3.9.3 Finite Difference Description

Numerical modelling of Equation (30) is done by the compact finite difference approximation is expressed by Equation 35:

$$\Delta_x(T_x\Delta_x h^{t+\Delta t}) + \Delta_y(T_y\Delta_y h^{t+\Delta t}) + \Delta_z(T_z\Delta_z h^{t+\Delta t}) = \frac{V_b S_s}{\Delta_t}(h^{t+\Delta t} - h^t) - V_b N \qquad (35)$$

Where V_b is the volume of grid block at the location (i, j, k), T is the transmissibility, Δt is the time level increment, t is the current time level, $t + \Delta t$ is the next time step. Figure 17 represents the hypothetical aquifer in three dimensions. The block centred finite difference approach is used to simulate groundwater flow.

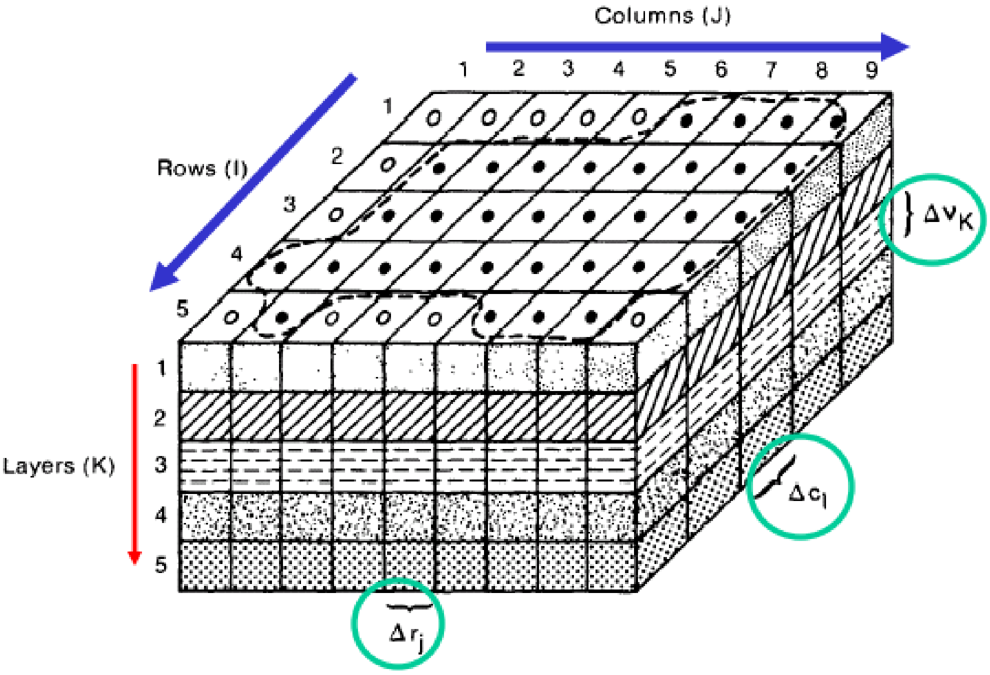

Figure 17: A Discretized Hypothetical Aquifer System in Three Dimensions (Haurbaugh, 2005)

$$\frac{1}{(\Delta x)_{i,j,k}}\left[Kx_{\left(i+\frac{1}{2},j,k\right)}\frac{h^{n+1}_{i+1,j,k}-h^{n+1}_{i,j,k}}{(\Delta x)_{i+\frac{1}{2},j,k}} - Kx_{\left(i-\frac{1}{2},j,k\right)}\frac{h^{n+1}_{i,j,k}-h^{n+1}_{i-1,j,k}}{(\Delta x)_{i-\frac{1}{2},j,k}}\right] + \frac{1}{(\Delta y)_{i,j,k}}\left[Ky_{\left(i,j+\frac{1}{2},k\right)}\frac{h^{n+1}_{i,j+1,k}-h^{n+1}_{i,j,k}}{(\Delta y)_{i,j+\frac{1}{2},k}} - Ky_{\left(i,j-\frac{1}{2},k\right)}\frac{h^{n+1}_{i,j,k}-h^{n+1}_{i,j-1,k}}{(\Delta y)_{i,j-\frac{1}{2},k}}\right] + \frac{1}{(\Delta z)_{i,j,k}}\left[Kz_{\left(i,j,k+\frac{1}{2}\right)}\frac{h^{n+1}_{i,j,k+1}-h^{n+1}_{i,j,k}}{(\Delta z)_{i,j,k+\frac{1}{2}}} - Kz_{\left(i,j,k-\frac{1}{2}\right)}\frac{h^{n+1}_{i,j,k}-h^{n+1}_{i,j,k-1}}{(\Delta z)_{i,j,k-\frac{1}{2}}}\right] = S_s\frac{h^{n+1}_{i,j,k}-h^{n}_{i,j,k}}{\Delta t} - N_{(i,j,k)} \qquad (36)$$

This study used MODFLOW-2005 code for the numerical model and the ModelMuse GUI to implement the numerical model and do simulations for the groundwater flow in the Makutupora aquifer.

3.9.4 Model Assumptions

The following are the major assumptions for the derived Equation 30:

(i) Darcy's law applies to the flow of groundwater

(ii) The porous media is saturated

(iii) The flow is continuous

(iv) The medium is non-homogeneous and anisotropic

3.10 Modular Finite Difference Flow model construction and Discretization

3.10.1 General Concepts

The numerical model illustrates the hydrological system for the environment in nature. Modelling was used to simulates groundwater flow for both steady-state and transient state using MODFLOW code. With time, aquifer storage does not change in steady-state conditions, but there is a change in storage in the aquifer's transient condition. According to Hashemi *et al.* (2013), a three dimensional unsteady, transient flow problem is considered with Darcy's law and continuity Equation.

3.10.2 Selection of the Software

Recent advances in computer software and hardware have made many tasks more manageable. The understanding of groundwater flow is not left behind this advance. The MODFLOW code based on three-dimensional finite-difference approximation has helped predict groundwater flow conditions. To model groundwater flow in the Makutupora aquifer, MODFLOW 2005 were used to simulate groundwater recharge. The code simulated the groundwater flow system in steady-state and transient states.

3.10.3 Forces Driving the Model

There are various driving forces in the model, such as interception, precipitation, infiltration, and potential evapotranspiration. Ministry of water Dodoma-Tanzania database gave climate data from 2017/01-2019/12. Precipitation data were vital for the calculation of the recharge. Figure 3 shows the precipitation whereby the maximum value was 90.5 mm/day and the minimum value was 0 mm/day. The mean rainfall was 1.584502283 mm/day. Also, the PET data were processed, and the minimum value was 4.2 mm/day, and the maximum value was 11.6 mm/day (Fig. 5). The mean evapotranspiration was 8.885701058 mm/day. Infiltration rate and Interception rate are the two terms that cannot be separated from each other.

Some precipitation is absorbed into the aquifers, some are intercepted, and the remainder goes to the atmosphere. Following the earlier explanations, vegetation cover in the area comprises woodlands, the Bushland, thickets, shrubs, a seasonal swamp with grasslands (Rwebugisa, 2008). Land cover is classified into grassland vegetation cover and other vegetation covers (woodlands, Bushland, thickets, shrubs and crops). The interception of grass was 6.9% of the rainfall (Corbett & Crouse, 1968; Kisendi, 2016). The second class of landcover was deciduous forest following its domination in Dodoma. The interception for deciduous ranges from 15% to 25%. The 20% represents the interception of the other vegetation covers. The modelled area covers 785.937 km^2. The vegetation area covers 734.653 km^2 (93%), and the grass area covers 51.284 km^2 (7%). The computed ratio of the grass to other vegetation was 0.07 to 0.93. Then, after determining the area's size and vegetation covers, the interception value was calculated using Equation (36):

$$I = RF * (I_g * Area_g + I_{other} * Area_{Other}) \qquad (36)$$

Where I is the canopy interception (mm d^{-1}), RF is rainfall (mm d^{-1}), I_g and I_{other} are the interception percentage loss for both grass and other vegetation covers. Substituting the values of I_g, $Area_g$, I_{other}, $Area_{Other}$ then Equation (37) becomes Equation (38):

$$I = RF * (0.069 * 0.07 + 0.2 * 0.93) \qquad (37)$$

Then the value of interception used to calculate the infiltration rate using Equation (38):

$$P_r = P - I \qquad (38)$$

Where P_r = infiltration, P = Precipitation and I = interception.

The weighted interception and infiltration of the two were calculated. The minimum, maximum, and average interception were 0 mm/day, 17.270115 mm/day, and 0.302370571 mm/day. The minimum and maximum infiltrations were 0 mm/day and 73.229885 mm/day, respectively.

3.10.4 Head Distribution

The state variables were used in model calibration is the head distribution in the study area. For the steady-state calibration, 20 single time head measurement were used (Table 5). The data for head distribution were obtained from the Ministry of water databases, Dodoma. Figure 18 shows the distribution of the boreholes in the area.

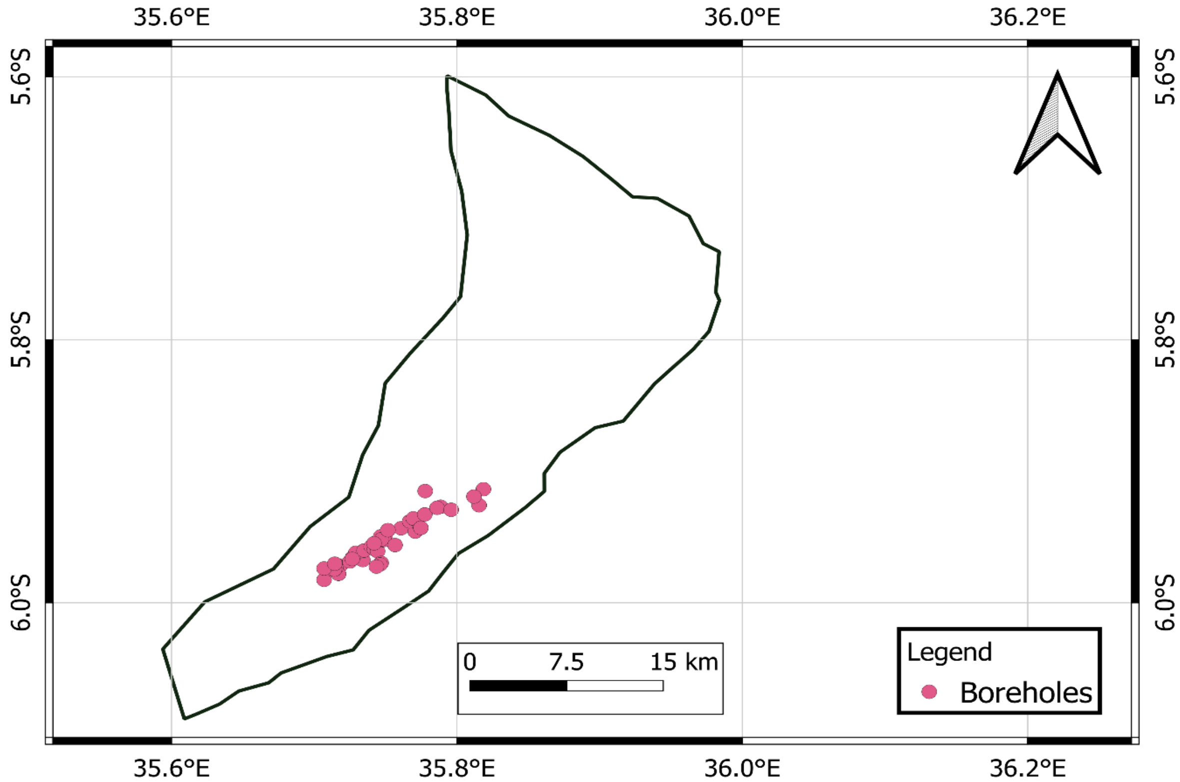

Figure 18: Location and Distribution of the Boreholes in Makutupora Basin (Drawn in QGIS 3.14, 2020)

3.11 Construction of the Modular Finite Difference Flow Model in the ModelMuse

3.11.1 Grids and Active Cell Definition

This study aimed to define the groundwater flow and head for the Makutupora area at the regional scale. Therefore, the grid of 500 m x 500 m was used, whereby the number of rows was 115, and the number of columns was 55, and the total area for the modelled area was 785 937 000 m^2. The four layers were defined in the model regarding the available bore log and lithological profile data having the length elevation of 40, 75, 105 and 150. The MODFLOW model under ModelMuse graphical user interface was used to define the model grids for the active and inactive cells. Figure 19 and Fig. 20 shows the discretized model.

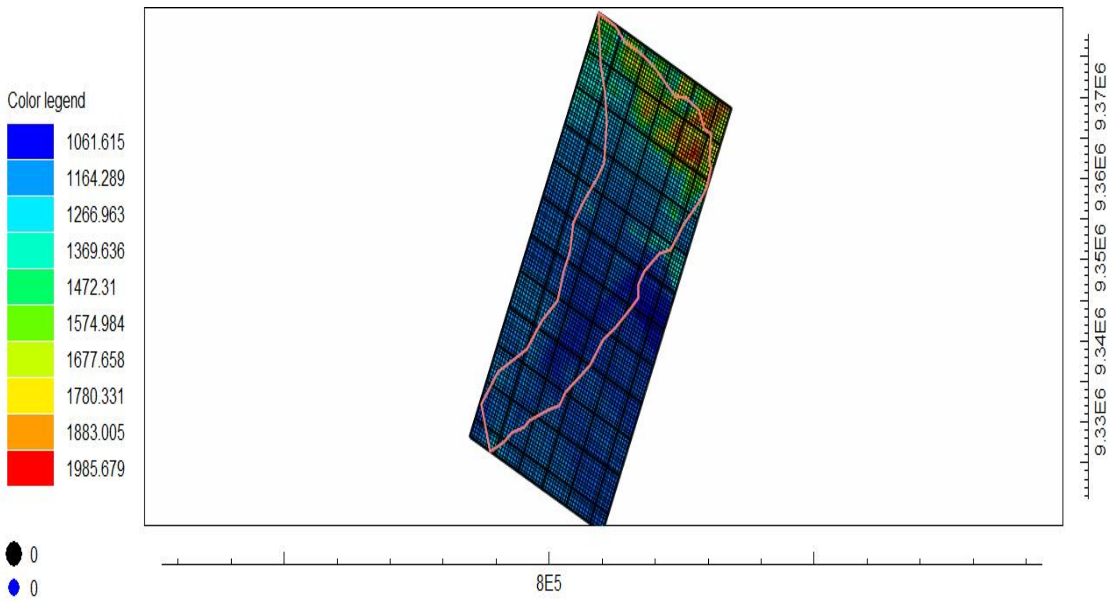

Figure 19: Discretized Model for the Study area with Elevation Data (The MODFLOW Discretized ModelMuse)

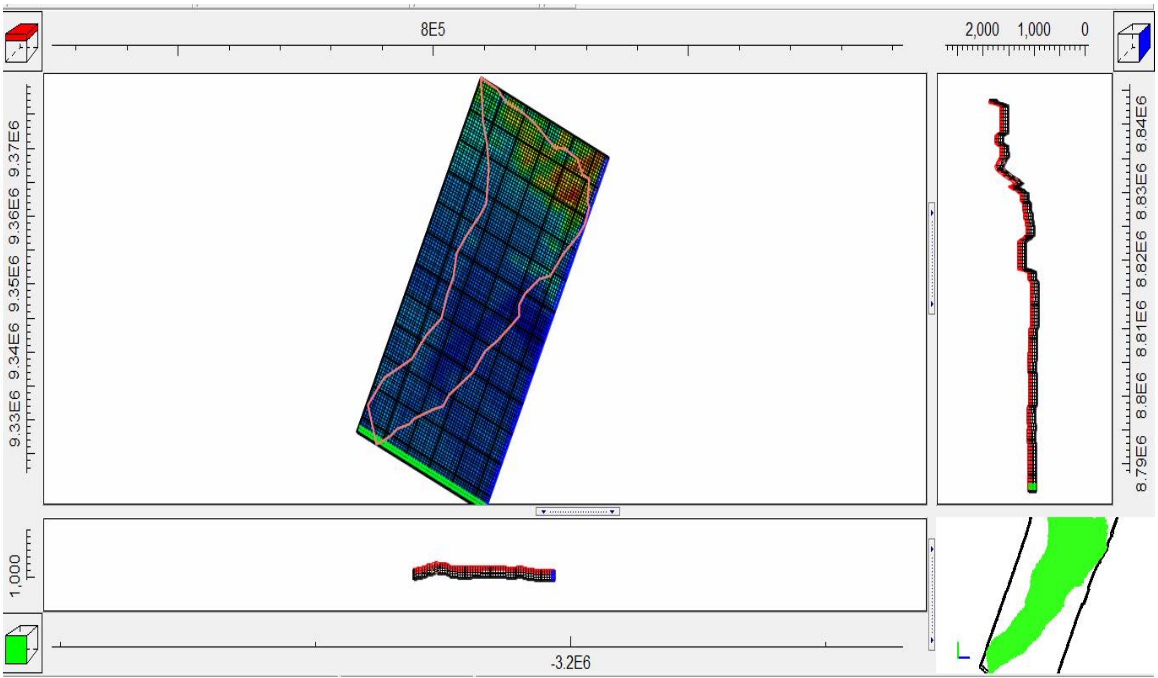

Figure 20: Discretized Model with all Views in MODELMUSE Graphical User Interface

3.11.2 Defining Initial Groundwater Head

The groundwater's initial head was set as the Model top, which contains the digital elevation values. Figure 19 show the highest elevated areas (blue coloured) and the lowest elevated spots (red coloured).

3.11.3 Aquifer Properties Assignment

The pumping test data were not enough to get the average hydraulic conductivity. For that case, the values calibrated by Seddon (2018) were used as the starting point in calibration, taking into consideration the type of the layer. Furthermore, the available lithological profiles enabled us to know the most types of soil that dominate the area and the hydraulic conductivities stated by some kinds of literature were also used. For each of the four layers, hydraulic conductivity was assigned whereby the first top layer is aquitard that comprises clay, silt, and shale, and its horizontal hydraulic conductivity was 1E-7. The second layer was an aquifer with a horizontal hydraulic conductivity of 0.0001. The third layer was also an aquitard with a horizontal hydraulic conductivity of 0.0001. The fourth layer was an aquifer with a horizontal hydraulic conductivity of 1E-6. The vertical hydraulic conductivity for each layer was 1/10th of horizontal *K* for each. The specific yield was obtained for each layer where layer 1, layer 2, layer 3, and layer 4 had specific yields of 5.67, 21, 3 and 23.3, respectively (Table 3). The specific storage was 0.1022, 0.3347, 0.0541 and 0.3758. The data were estimated based on the area's lithology, as indicated in one of the studies (Johnson, 1967).

Table 4: Specific Yield, Specific Storage and Aquifer Layer Thickness

Layer	Lithology	Specific yield (%)	Specific storage	Thickness
Layer1	Clay+ Red silt+ Mbuga	5.67	0.1022	55.5
Layer 2	Sand	21	0.3347	62.75
Layer 3	Silt	3	0.0541	55.5
Layer 4	Gravel	23.3	0.3758	62

3.11.4 Boundary Conditions

The boundary packages that were used in the model are the artificial recharge well package, the pumping well package, the recharge package and the general head package were applied in this model. The well package was introduced as the source (recharging wells) and sink (pumping wells). The determination of the places to insert the wells and the simulated groundwater optimization after the artificial recharge was done by minimizing the drawdown.

3.11.5 Stress Periods

The stress periods were defined based on the projected population rise concerning projected water demand for Dodoma City. The number of stress periods was four, in which the first stress period was the steady-state, and the remainder were the in transient state. The stress periods are 1, 5, 10, 1 and 11 years, from 2019 to 2051. Table 4 shows the stress periods.

Table 5: Stress Periods concerning Duration, State and the Number of Active Wells

No	Duration (Years)	State	Number of active wells
1	1	Steady	0
2	6	Transient	10
3	17	Transient	12
4	18	Transient	20
5	32	Transient	50

3.11.6 Simulation of the Groundwater

Following the groundwater flow modelling protocol in Fig. 1, after model conceptualization, the modelling exercise began by feeding the inputs and calibrating the model after model conceptualization. The calibrated observed and simulated head were then subjected to error analysis to check if the calibrated results are meaningful. After calibration, the artificial wells were introduced in the model to determine the possible increase in the aquifer's safe yield. The injecting wells gave a way to recommend the pumping rate about the rise in the area's population. Furthermore, a sensitivity exercise adjusted the wells and pumped to achieve a maintenance level of consumption, but drawdown was minimized.

3.11.7 Testing of the Model

A total of 20 available boreholes data were used to test the model. Table 5 shows the simulated versus the observed groundwater head. From the model, the difference between the simulated and observed water levels is not very high hence concluded the validity of the model to simulate groundwater. The head observation result from the model indicated that the Root Mean Square Residual (RMSE) for the observed versus simulated head was 5.38. Moreover, Fig. 21 shows the simulated head versus the observed head. Appendix 6: Shows the volumetric Water budget for the steady-state scenario.

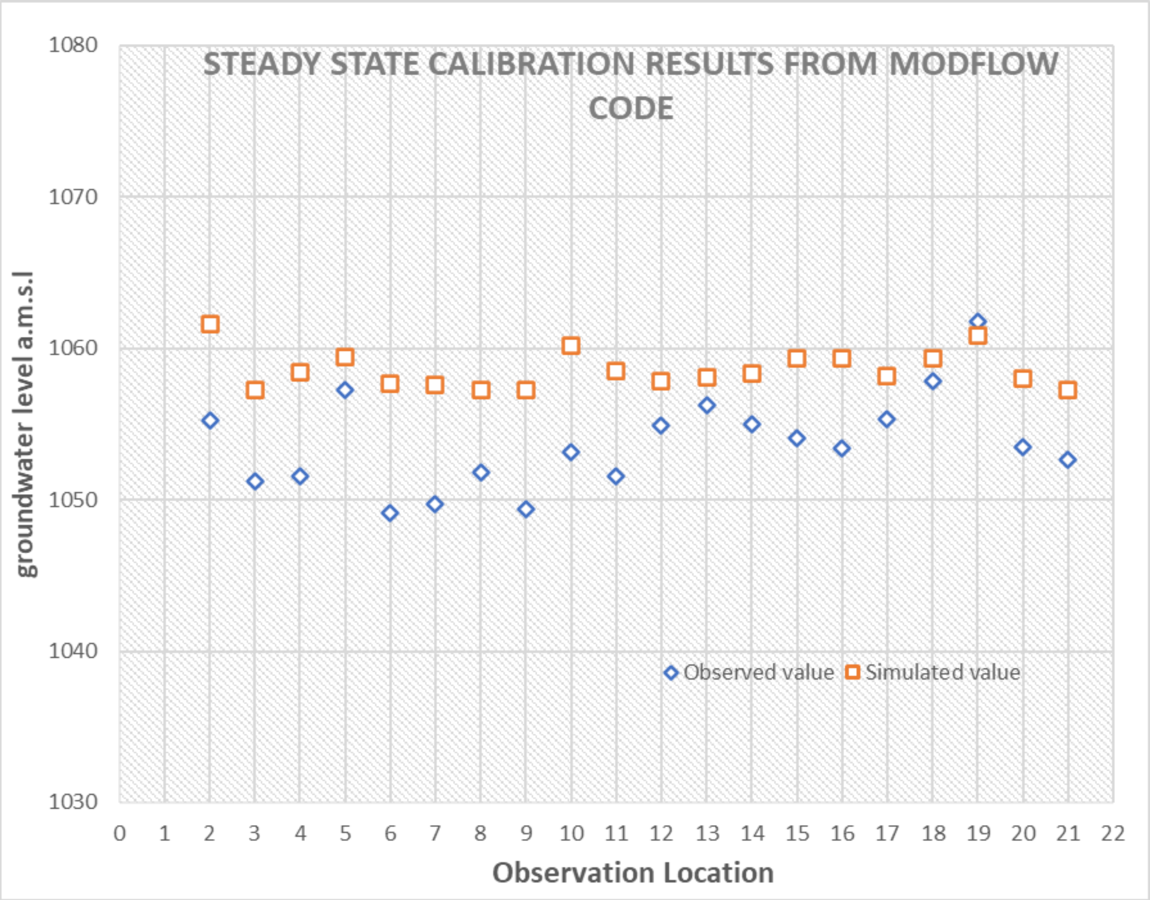

Figure 21: Steady-State Calibrated Results Showing Observed Versus Simulated Values

Table 6: Comparison of the Observed Head Versus Simulated Head for the Calibrated Model

Borehole	Observed	Simulated	Difference
Obs_1	1055.6240234	1059.1162109	-3.4921875000
Obs_2	1055.2299805	1061.5865479	-6.3565673828
Obs_3	1051.1939697	1057.2805176	-6.0865478516
Obs_4	1051.5250244	1058.4381104	-6.9130859375
Obs_5	1057.2690430	1059.4206543	-2.1516113281
Obs_6	1049.0970459	1057.6618652	-8.5648193359
Obs_7	1049.7519531	1057.6212158	-7.8692626953
Obs_8	1051.7840576	1057.2628174	-5.4787597656
Obs_9	1049.4200439	1057.2897949	-7.8697509766
Obs_10	1053.1540527	1060.1611328	-7.0070800781
Obs_11	1051.5329590	1058.4938965	-6.9609375000
Obs_12	1054.9210205	1057.8634033	-2.9423828125
Obs_13	1056.2490234	1058.0837402	-1.8347167969
Obs_14	1055.0219727	1058.3677979	-3.3458251953
Obs_15	1054.0429688	1059.3349609	-5.2919921875
Obs_16	1053.3620605	1059.3349609	-5.9729003906
Obs_17	1055.3070068	1058.1464844	-2.8394775391
Obs_18	1057.8499756	1059.3758545	-1.5258789062
Obs_19	1061.7900391	1060.8487549	0.94128417969
Obs_20	1053.4699707	1058.0278320	-4.5578613281
Obs_21	1052.6080322	1057.2670898	-4.6590576172

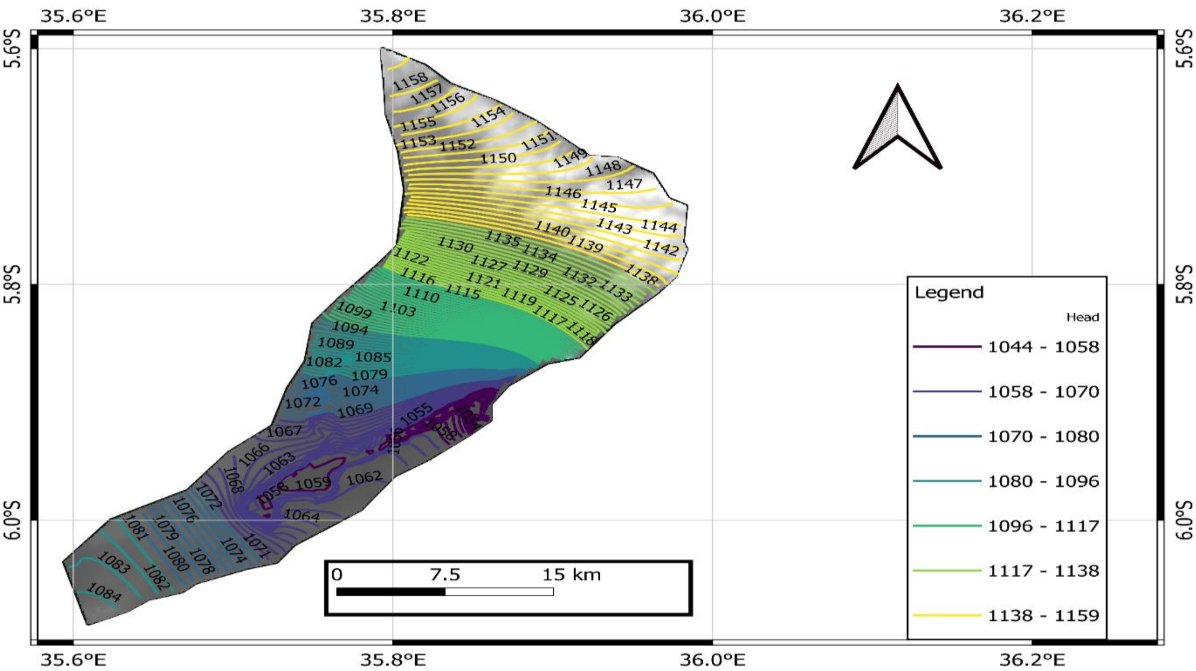

Figure 22: Head Distribution after the Steady-State Simulation

3.11.8 Statistical Tests on Calibration

The calibrated results were tested using various statistical tests like Chi-square and the coefficient of determination RMSE. The RMSE used to test the goodness of the fit of the simulated against the observed parameters. Chi-square test used to determine the distribution difference between the observed and simulated. The following Equation 33 was used to compute the value of RMSE:

$$RMSE = \left(\sum_{i=1}^{n} \frac{(O_i - E_i)^2}{n}\right)^{1/2} \quad (33)$$

The RMSE from the statistical test was 5.51. The value coincides with the value produced by the MODFLOW-ModelMuse graphical user interface, which is 5.38 with a slight deviation. The value of Root mean squared residue ranging from 0 to 20 is accepted. Chi-square results were good as it ranges from 0 to 1. It was computed by using the following Equation 34:

$$\chi 2 = \sum \frac{(O_i - E_i)^2}{E_i} \quad (34)$$

Where $\chi 2$ = Chi-squared, O_i = Observed value, E_i =Expected value and n is the number of observations.

The chi-squared test value is 0.57, which is the same as 57%, indicating that the two values have no much difference. Statistical tests results suggest that the model is reliable for the MODFLOW model so long as the difference between the observed values and the simulated values is not much higher.

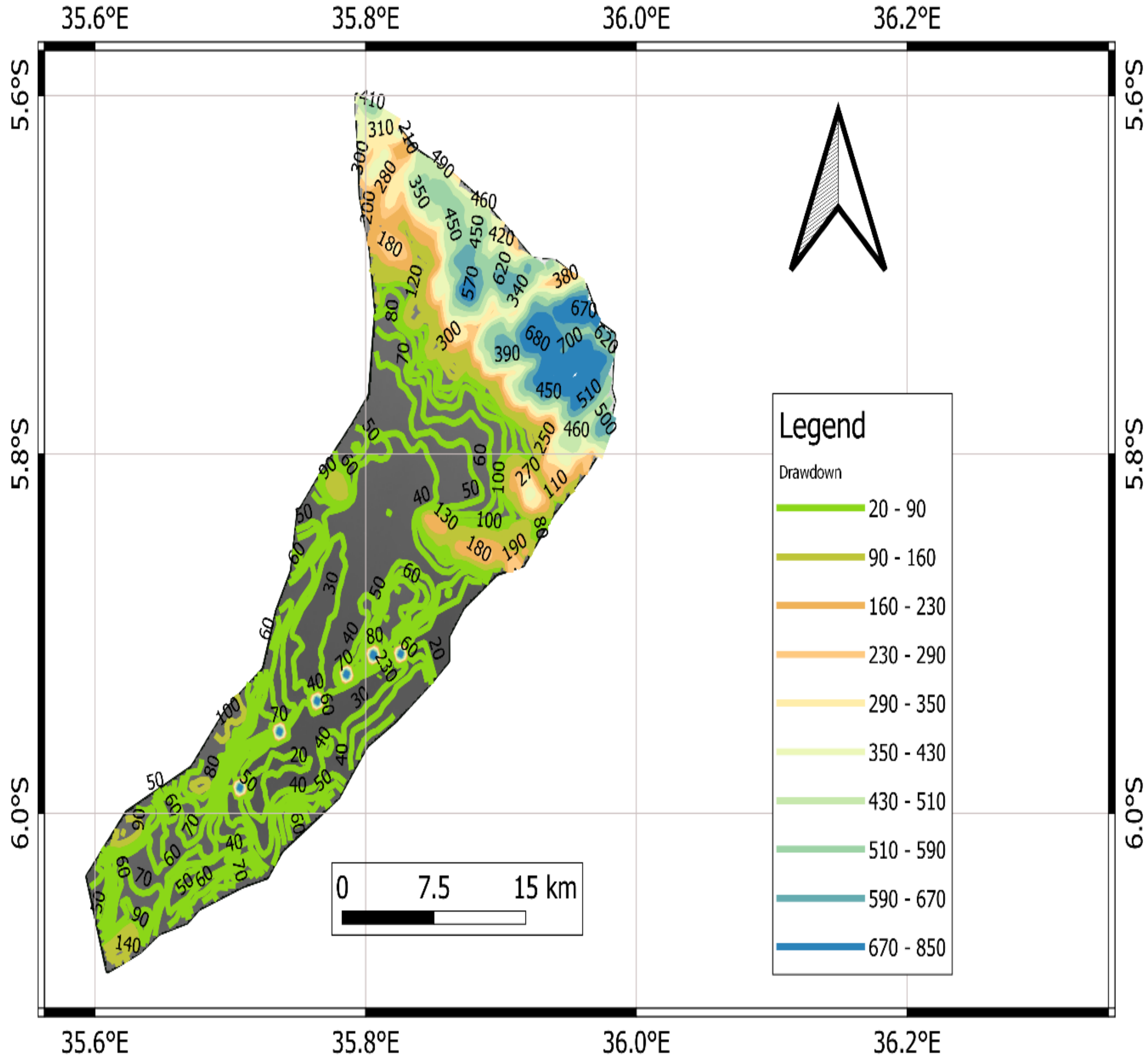

Figure 23: Drawdown Contour Map in the no Artificial Recharge Scenario under Steady State

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Results and Discussion for Processed Data

4.1.1 Evapotranspiration Rate and Temperature

Insufficient data for evapotranspiration forced to use other methods like the Penman-Monteith Equation to estimate the PET values of the area. The results indicated that the average evapotranspiration was 8.885701058 mm/day. After model calibration, the calibrated evapotranspiration was 5.12E-7 mm/day. Initially, the evapotranspiration rate ranges between 5-11 mm/day, as estimated in chapter three earlier. Furthermore, the correlation between mean temperature and calculated evapotranspiration obtained from NASA showed a positive relationship (Fig. 24).

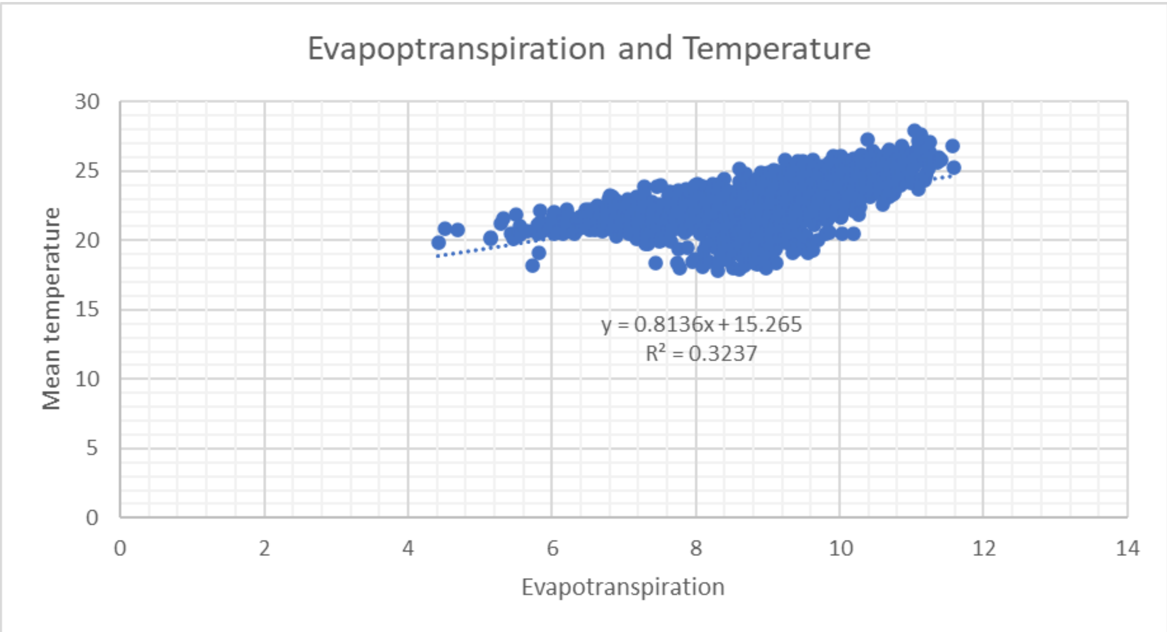

Figure 24: Relationship between Evapotranspiration and Temperature

4.1.2 Infiltration Rate and Percentage of Vegetation Covers

The vegetation covers with their classification enabled to calculate the percentage area covered and finally used to calculate the infiltration rate (Pr) by using Equations (37) to (38), and the summary is presented in Table 6.

Table 7: Statistical Results of the Fraction of Vegetation Cover Type in the Percentage

S/No	Vegetation cover type	Area in km^2	The fraction of vegetation cover in the percentage area
01	Grassland	51.284 km^2	7%
02	Other Vegetations	734.653 km^2	93%
	Total	**785.937 km^2**	**100%**

The area's average infiltration for the chosen period with its dataset showed that the infiltration ranges from 0 mm/day to 73.229 mm/day. The calibrated infiltration used to represent the natural recharge of the area was 1.29909845229579E-9 m^3/day.

4.1.3 Estimated Groundwater Storage in Makutupora Aquifer

The water is always stored in fractures of rock consisting of the Mlemu fault, Kitope fault and Kilungule fault. Using length and width, the total area of the three faults was 7640154.4 m^2. The total groundwater storage capacity was estimated to be 247.8 Million Cubic Meters (MCM). The description of the estimated groundwater storage layer-wise is indicated in Table 7.

Table 8: Estimated Groundwater Storage Capacity of the Makutupora Aquifer

Layer Number	Groundwater storage Capacity	Storage capacity in Million Cubic Meters (MCM)
Layer one	24 042 419.87 m^3	24.04
Layer two	100 678 134.600 m^3	100.68
Layer three	12 720 857.08 m^3	12.72
Layer four	110 369 670.50 m^3	110.40
Total	**247 811 082 m^3**	**247.84**

4.1.4 Calibrated Parameters for the Calibrated Model

The calibration involved adjusting the recharge rate and hydraulic conductivities and systematically to match the observed and simulated head. The adjustment of parameters was done manually, taking into account the estimated range of recharge, evapotranspiration and values of hydraulic conductivity for each layer. Evapotranspiration ranges from 4.2 mm/day to 11.6 mm/day. The recharge rate ranges from 0 mm/day to 73.2 mm/day. The hydraulic conductivities were adjusted by taking the hydrostratigraphic unit into account, and because the hydrostratigraphic unit in the area was complex, the range of hydraulic conductivity ranged from 10^{-8} to 10^{-2} m/day. Table 8 shows the calibrated hydraulic conductivities, recharge rate, evapotranspiration rate, and drain conductance. The hydraulic conductivities of the area differ from one layer to another and influences the area's recharge.

Table 9: Hydraulic Parameters

Parameter	Value	Description
HKL1	1E-7 m/day	Hydraulic conductivity of the first layer
HKL2	0.0001 m/day	Hydraulic conductivity of the second layer
HKL3	0.0001 m/day	Hydraulic conductivity of the third layer
HKL4	1E-6 m/day	Hydraulic conductivity of the fourth layer
GHB	0.1331 m^3/day	The general head boundary conductance
RCH	1.2991979E-9 m^3/day	Recharge rate of groundwater
EVT	5.12E-7 m^3/day	Evapotranspiration rate of groundwater

4.2 Results and Discussion for Groundwater Flow Modeling

4.2.1 Artificial Recharge Simulation (Safe yield of the aquifer due to the simulated artificial recharge)

The artificial simulation of recharge, considered some scenarios. The simulated steady-state flow was the initial point with the hydraulic conductivity's initial calibrated parameters, recharge, evapotranspiration, and drain conductance values. In the first scenario, the model was simulated by involving the estimated parameters with the inclusion of the natural recharge where 50 wells which were pumping the water at the rate of 0.1 m^3/day as planned. The Volumetric water budget for this scenario is shown in Appendix 7. The maximum drawdown under steady-state was 850 (Fig. 23), and the drawdown after small pumping 0.1 m^3/day from the 50 wells reduced to 840 (Fig. 25). Therefore, minimization of drawdown is among the methods of knowing how to pump and at which locations.

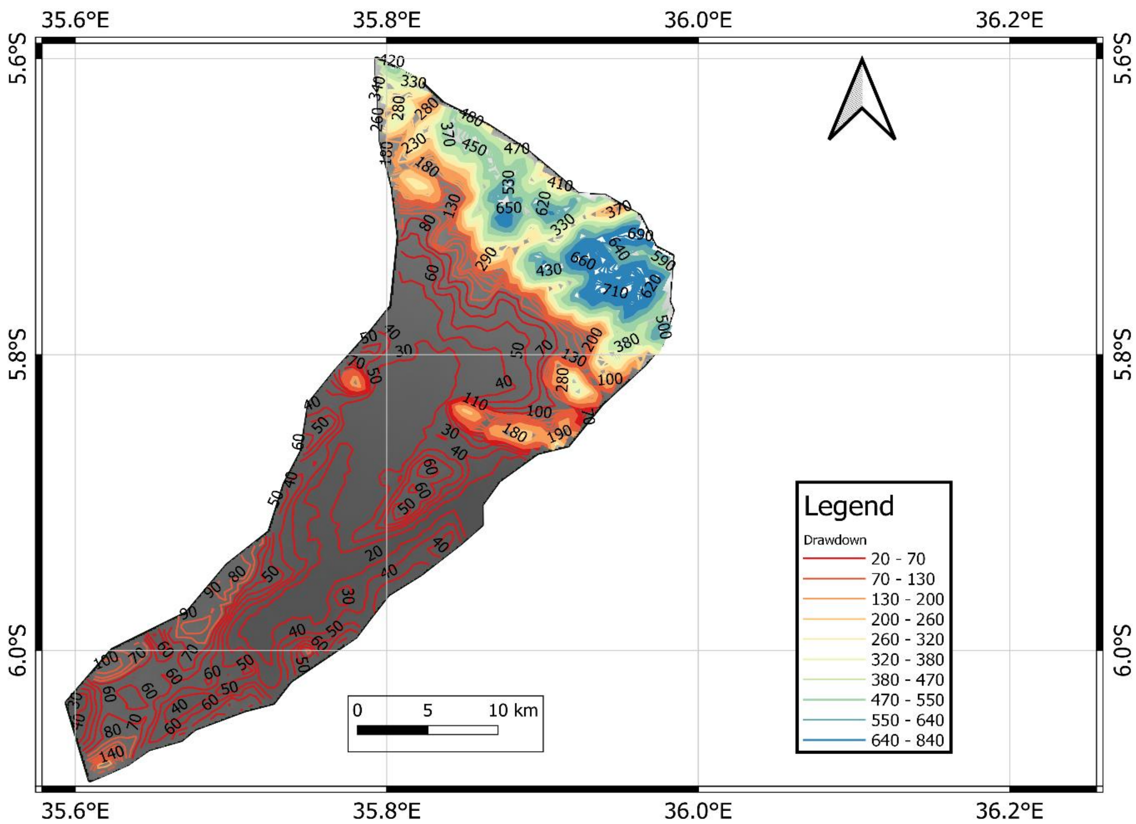

Figure 25: Drawdown Contour Map after Pumping, before Artificial Recharge

Then, a second scenario was done by which a total of 50 injecting wells which were assigned to add the water to the ground by the artificial aquifer recharge methods. In this scenario, it was assumed that no pumping was undertaken to get the exact water quantity recharged to the aquifers (Table 9). The second scenario enabled the increase in the apparent amount of water volume that could have been recharged to the aquifers. The restored water could specify the optimum amount of water to be pumped from the wells for a sustainable water supply. The insertion of 50 wells in the area strategically increased the cumulative volume in recharge. After the simulation, the daily recharge increased from 168 857 m^3/day to 600 430 m^3/day (Table 9). Appendix 2 indicates the volumetric water budget at the end of the last time step in stress period five.

Table 10: Volume Results after Artificial Recharge

No	Duration (Years)	State	Number of active reservoirs	Cumulative Volume recharged	Daily Recharge m^3/day
1	1	Steady	0	0	0
2	6	Transient	6	61 801 828	168 857
3	7	Transient	17	505 474 560	197 760
4	17	Transient	36	2 236 151 296	360 000
5	32	Transient	50	7 013 803 008	600 430

One of the significant identified sources where the water could be drawn for recharge is from the Little Kinyasungwe river flow. The river flows seasonally, especially during the rainy period. The data available from the Ministry of Water in Tanzania indicated a flow of 23.646 Million Cubic Meters (MCM) in 2007. The river discharges its water to the Hombolo dam that has 184 Million Cubic Meters (MCM). The dam is important as it provides water for various uses like fishing, irrigation and domestic water use. Due to the expanded surface area of water created by dams, enormous water volumes are lost to evaporation, much more than would have been lost in the dam's absence. Therefore, a portion of the water flowing in the Kinyasungwe river is recommended for the aquifers' artificial recharge. Also, implementers need to put a lot of efforts into artificially recharge the aquifers in the years that El Niño Southern Oscillation (ENSO) occurs as it contributes a lot of flow due to a huge amount of rainfall.

4.2.2 Recommendation for the Construction of Engineering Structure for Recharging the Aquifer Artificially

The general hydrostratigraphic unit indicated that the topmost layer is dominated by clay soil which goes up to 40m where sandy soil is found (Fig. 11). The sand soil has large pore spaces and hence allows high storage of water in the aquifer. The clay in the top layer with a low infiltration capacity of about 5 mm/hour results in water infiltration to sand for a long time, like 11 months, as calculated (Appendix 7). Therefore, engineers are advised to construct structures with at least a depth of 40 m (40 000 mm). It also helps to reduce the rate of evapotranspiration that could take place quickly as the water is nearer to the surface.

4.2.3 Pumping out the Artificial Recharged of Groundwater

The third scenario involved the simulation of the pumping rate that can be done after artificial recharge. The results indicated that the recharged water could increase the aquifer yield to the extent that the groundwater's abstraction about the projected population meets the demand sustainably. For example, in the year 2051, the estimated existing water would be 113 192 m^3/day. The projected volume of water demanded was expected to be 418 839 m^3/day. The projected demand indicated a deficiency of 305 247 m^3/day. In the second scenario, we saw from table 5 that the injection of artificial wells has increased the recharge rate to 600 430 m^3/day. This study carried out pumping rate simulations against recharge rate after artificial recharge, as illustrated in Fig. 26. The pumping rate assignment indicates that the recharge rate is higher than the pumping rate's speed. For example, in the last stress period, the recharge rate was 0.60 MCM/day while pumping was 0.42 MCM/day (Table 10 and 11). The recharge has been greater than pumping, and hence the responded to safe yield production, and therefore it is sustainable for ensuring water supply to Dodoma City.

Table 11: Planned Pumping Volumes and Rates of the Recharged Volume

Years	State	Wells (out)	Wells (In)	Recharge m^3/day	Pumping rate m^3/day
1	Steady	0	0	0	0
6	Transient	12	6	168 857	137 544
7	Transient	20	17	197 760	160 720
17	Transient	40	36	360 000	226 204
32	Transient	50	50	600 430	418 819

Table 12: Planned Pumping Volumes and Rates of the Recharged Volume (MCM)

Years	State	Wells (out)	Wells (in)	Recharge rate (MCM/Day)	Pumping rate (MCM/Day)
1	Steady	0	0	0	0
6	Transient	12	6	0.16	0.14
7	Transient	20	17	0.19	0.16
17	Transient	40	36	0.36	0.23
32	Transient	50	50	0.60	0.42

Furthermore, artificial recharge simulation in the area is possible due to additional water sources during the rainy season. During the rainy season, the Kinyasungwe river takes a lot of surface water. The river drains the water from the area's upper catchments (Global Water for Sustainable Programme [GLOW], 2014). There is no clear trend of the river flow that can give the actual time of recharge, but as it is a seasonal river, it flows from November to May, and hence that is the time most of the recharge occurs (ibid). Therefore, during this time, the water could be directed towards the constructed engineering structures that can take water to the aquifers to replenish the overexploited aquifer. Other measures of collecting water from other streams surrounding the area can also add more water to the Makutupora aquifer. The pumped water volume graph indicated that the recharge rate is above the pumping rate line whereby, by the year 2051, the recharge rate was 0.6 MCM/day, and the pumping rate was estimated to 0.42 MCM/day (Fig. 26). Therefore, the results indicated that the simulated artificial recharge was in excess, so that the projected scarcity of water demand could be solved by applying artificial recharge techniques.

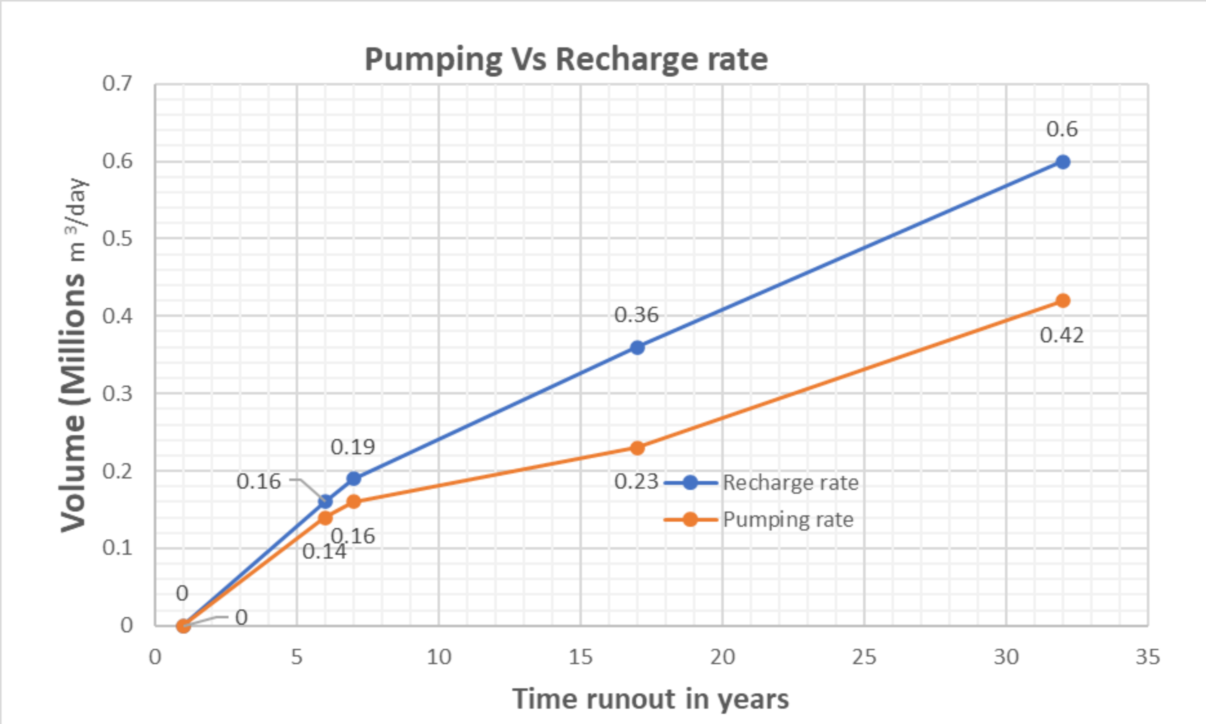

Figure 26: Simulated Pumping Versus Recharge

The aquifer yield increased to the extent that the groundwater's abstraction about the projected population meets the demand sustainably. For example, in the year 2051, the projected amount of water demanded about the population was 418 839 m^3/day. And it was assumed that if there is no recharge out of natural recharge, then the estimated existing water in the year was 113 192 m^3/day. It leads to a deficiency of 305 247 m ^{3}/day. Now the simulated artificial recharge gave the estimated value of 600 430 m^3/day. The implementation of the plan could solve the problem of water scarcity, and good enough, it resulted in a surplus of 181 591 m ^{3}/day (Table 12).

Table 13: City Population Concerning Water Demand, Existing Water, Deficiency, Simulated and Surplus Water

	City Population	Water demand m^3/day	Existing water m^3/day	Deficiency m^3/day	Simulated m^3/day	Surplus m^3/day
2025	689 072	137 584	113 192	-23 992	168857	31273
2026	1 069 900	160 730	113 192	-47 138	197760	37030
2036	713 794	226 204	113 192	-113 012	360000	133796
2051	1 972 968	418 839	113 192	-305 247	600430	181591

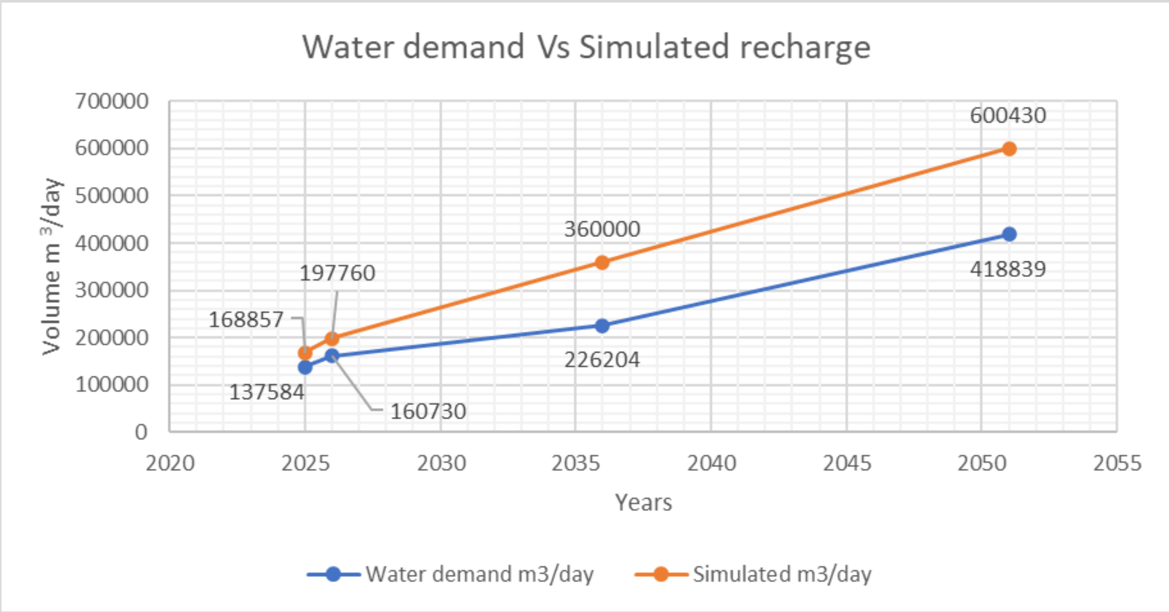

Figure 27: Graph of Water Demand Versus the Simulated Recharge

4.2.4 Pumped Water Storage

Furthermore, the water budget gives out the pumped water storage for all the stress periods, and the results showed a positive increase in the pumped water. Hence an excellent response to the aquifer could also ensure the sustainability of the water supply in Dodoma City and solve the impacts that Climate Change brings to water resources and the achievement of Sustainable Development Goals. Table 13 shows the increase in the pumped water storage due to the simulated artificial recharge. For each stress period, the model pumped water storage was simulated, and the results indicated that under the transient condition, the pumped water storage increased from 37 690 m^3/day to 177 418 m^3/day.

Table 14: Stress Periods concerning Pumped Water Storage

Stress period	1	2	3	4	5
Pumped water storage	0	37 609.4180	39 460.6250	122 370.8203	177 418.3906

4.2.5 Optimum Groundwater Pumping Volumes

The groundwater pumping optimization was done through the wells' arrangement in the system to control the drawdown. The arrangement of both pumping wells and injecting wells resulted in the decline in drawdown from 840 to steady-state whereby as the water was pumped from the aquifer, recharge was taking place (Fig. 28). The pumping and recharging scenario's drawdown map indicated that the drawdown had been lowered to zero in some areas. Other areas showed a negative drawdown. A negative drawdown means that there some of the sites are still receiving the recharge. It also happens because the soil porosity in the area differs from one place to another. Most of the wells for recharging were put nearer to the faults, and the pumping wells placement were set nearer to the areas where most of the recharge occurs. Furthermore, the placement of recharging wells considered the issue of soil type and hence some of the recharging wells were put in the plateau dominated by sandy soil in which its hydraulic conductivity is high facilitate the recharge process. Also, groundwater head distribution at the end of stress period five was simulated (Appendices 3 and 4).

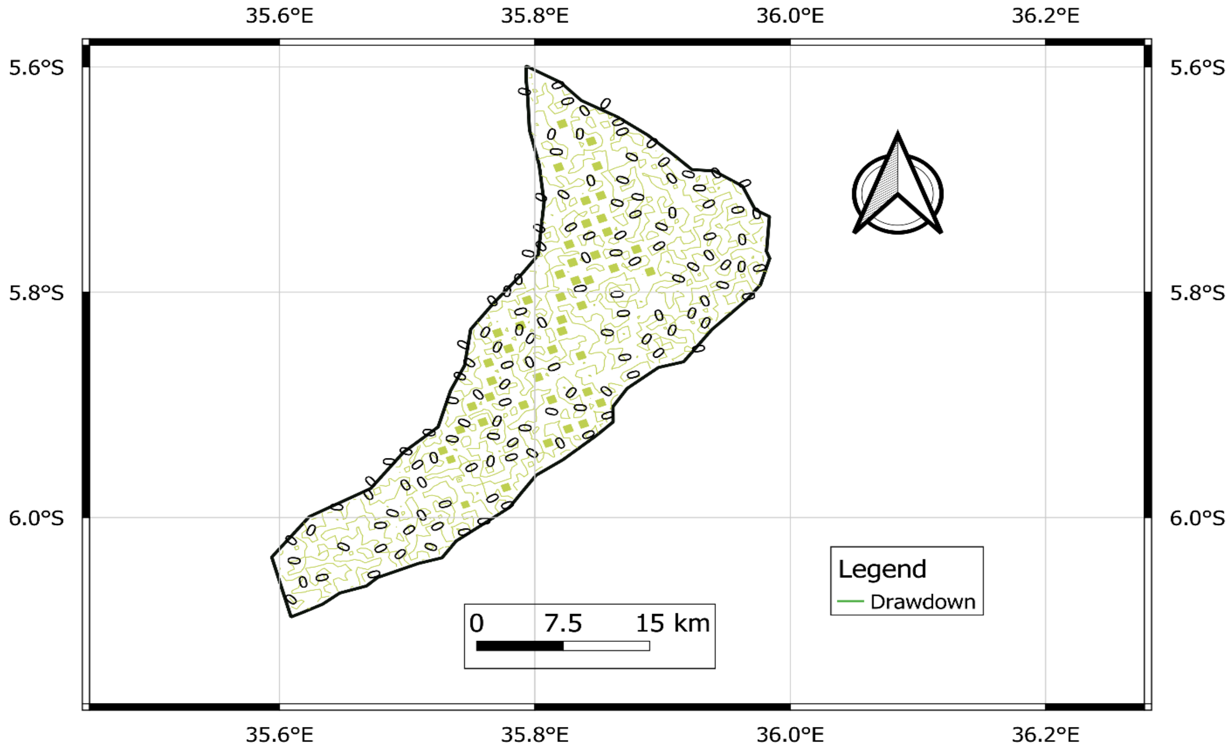

Figure 28: Drawdown Contour Map at the End of Artificial Recharge and Planned Pumping to the Year 2051

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The relocation of Tanzania government offices from Dar es Salaam to Dodoma has led to a surge in population, resulting in overexploitation of water in the Makutupora aquifer. The ability of the well to support the population's sustainability through water supply is likely to be overtaken by the abstraction. The sustainability of groundwater to meet the demand of the Cities that overgrows should be studied. Therefore, this study simulated the power and ability of artificial recharge and natural recharge to increase the aquifers' water for sustainable water supply in Dodoma City and mitigate the shortage. Based on the climate data, the recharge rate and evapotranspiration rate were computed.

The study developed three-dimensional groundwater flow model Equations for simulating the natural and artificial recharge in the Makutupora aquifer. The Makutupora aquifer is the primary source of water for the city. As the City grows, water will not be enough. Some studies have been undertaken, but there is still a paucity of information and knowledge of ensuring water supply sustainability given the projected population. The hydrological modelling was done using the MODFLOW-2005 model to support ModelMuse and GIS for visualization. Results indicated that the aquifer could increase the safe yield if the methods of artificial recharge are applied. The suggested additional water could be taken from the Kinyasungwe river flow and other surrounding rivers.

The groundwater flow simulation results of artificial recharge indicate that artificial recharge mechanisms could enhance the Makutupora aquifer sustainability. The developed model might help the decision-makers to manage the groundwater flow in the Makutupora aquifer. However, data from the area (Makutupora Dodoma) were minimal, especially the evapotranspiration data. Furthermore, the areas stratigraphic units' complexity was a barrier to estimating the hydraulic conductivities. The results indicated a need for about 90% of the flow to replenish the aquifers. Furthermore, the results showed that the simulated recharge is greater than the projected demand to lead to surplus water in the aquifers.

5.2 Recommendations

The recommended artificial recharge is the construction of some wells that can inject the water that flows at the time of rainfall, especially using the Kinyasungwe river. Also, in the wells' construction, consider the areas that could recharge faster. The type of soil also affects the infiltration rate in time, depending on the soil pore spaces. Most of the wells are recommended to be put in areas containing sandy soil and around the fault areas where the rate of recharge is higher, like around the Mlemu fault, Kitope fault, and to the areas with sandy soil properties. Furthermore, the findings of this study recommend the engineers to construct artificial recharge structure that has at least 40 m depth so as the water can reach the aquifer quickly while reducing the rate of evapotranspiration. Therefore, the surface water that drains into Hombolo human-made lake/dam could be taken from the surface to any form of artificial recharge in addition to the portion of natural recharge that occurs through rainfall event in the Makutupora basin area.

5.2.1 Future Study

The study does not conclude the issue of modelling the effect of recharge Makutupora. There have been many challenges encountered, like lack of information such as the evapotranspiration data from the Makutupora station to the extent that the data have been calculated by alternative methods like that of FAO. The future study needs to consider the calculation of the new crop coefficient value rather than adopting 0.7 kc value that was used by Rwebugisa for better results, the geology and aquifer type are also complex to determine due to their differences from one place to another. Also, some of the data, like meteorological data, depend much on climate, and we know climate change and variability is an issue globally. Therefore, there is a need to extend the study by considering some modifications of aquifer parameters, the area's size to be modelled, and the changing of precipitation and evapotranspiration.

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APPENDICES

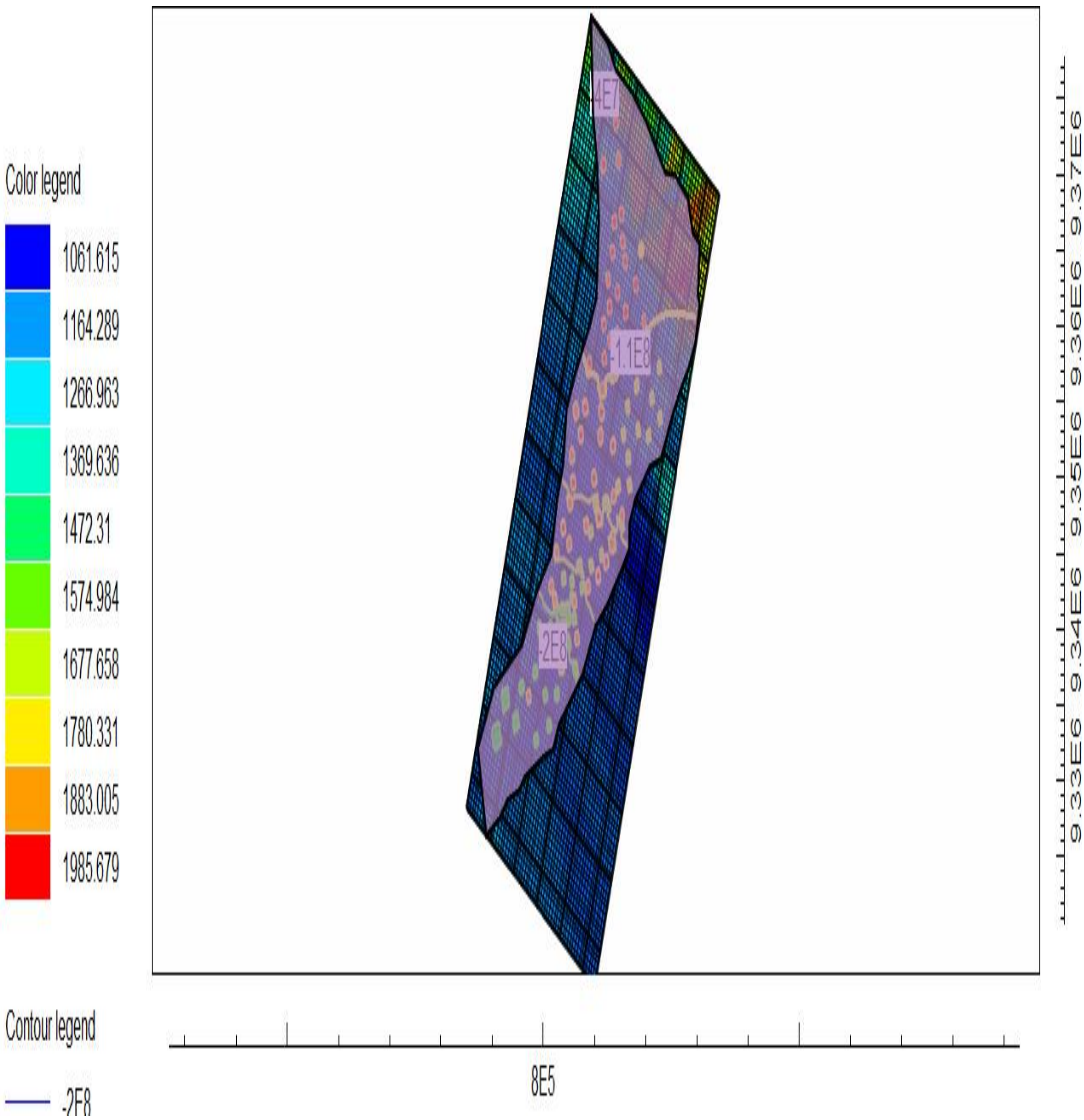
Appendix 1: Summary of the Parameters used to Calculate the Reference Evapotranspiration and Potential Evapotranspiration

Variables	Symbol	Value	Unit
Height	Z	10	m
Elevation of Makutupora	Z_e	1141.42	m
Atmospheric Pressure	P	88.517	atm
Psychometric	γ	5.884296184e-2	
Average temperature max	$T_{max,K}$	302.62525	K
Average temperature min	$T_{min,K}$	289.77975	K
Stefan Boltzmann	σ	5.670 374 419 x 10^{-8}	$MJK^{-4}m^{-2}d^{-1}$
GSc		0.082	$MJm^{-2}d^{-1}$
Latitude= φ		-5.9833	Degree
Albedo of grass	α	0.165	
Crop factor	K_c	0.7	
Mean temperature	T_{mean}	295.5981	K
Average temperature max	$T_{max,C}$	29.47525	C
Average temperature min	$T_{min,C}$	16.62975	C
Mean temperature	T_{mean}	22.4481	C
Average relative humidity max	R_{hmax}	92.22	%
Average relative humidity min	R_{hmax}	37.02	%
Measured wind speed at z m above the ground surface	U_z	4.270256	m s^{-1}
Slope vapour pressure curve	Δ	0.020706372	kPa $°C^{-1}$
Net radiation at the crop surface	R_n	22.34459751	MJ m^{-2} day^{-1}
Net solar or shortwave radiation	R_{ns}	22.3446	MJ m^{-2} day^{-1}
Actual vapour pressure	e_a	1.452284685	kPa
Saturation vapour pressure	e_s	2.522964788	kPa
Net outgoing longwave radiation	R_{nl}	2.4884887742*10^{-6}	MJ m^{-2} day^{-1}
Relative shortwave radiation (limited to £ 1.0),	$\frac{R_s}{R_{so}}$	0.9	
Clear-sky solar radiation	R_{so}	29.13170729	MJ m^{-2} day^{-1}
The incoming solar radiation	R_s	26.76	MJ m^{-2} day^{-1}
Wind speed at 2 m height	U_2	67.63	m s^{-1}

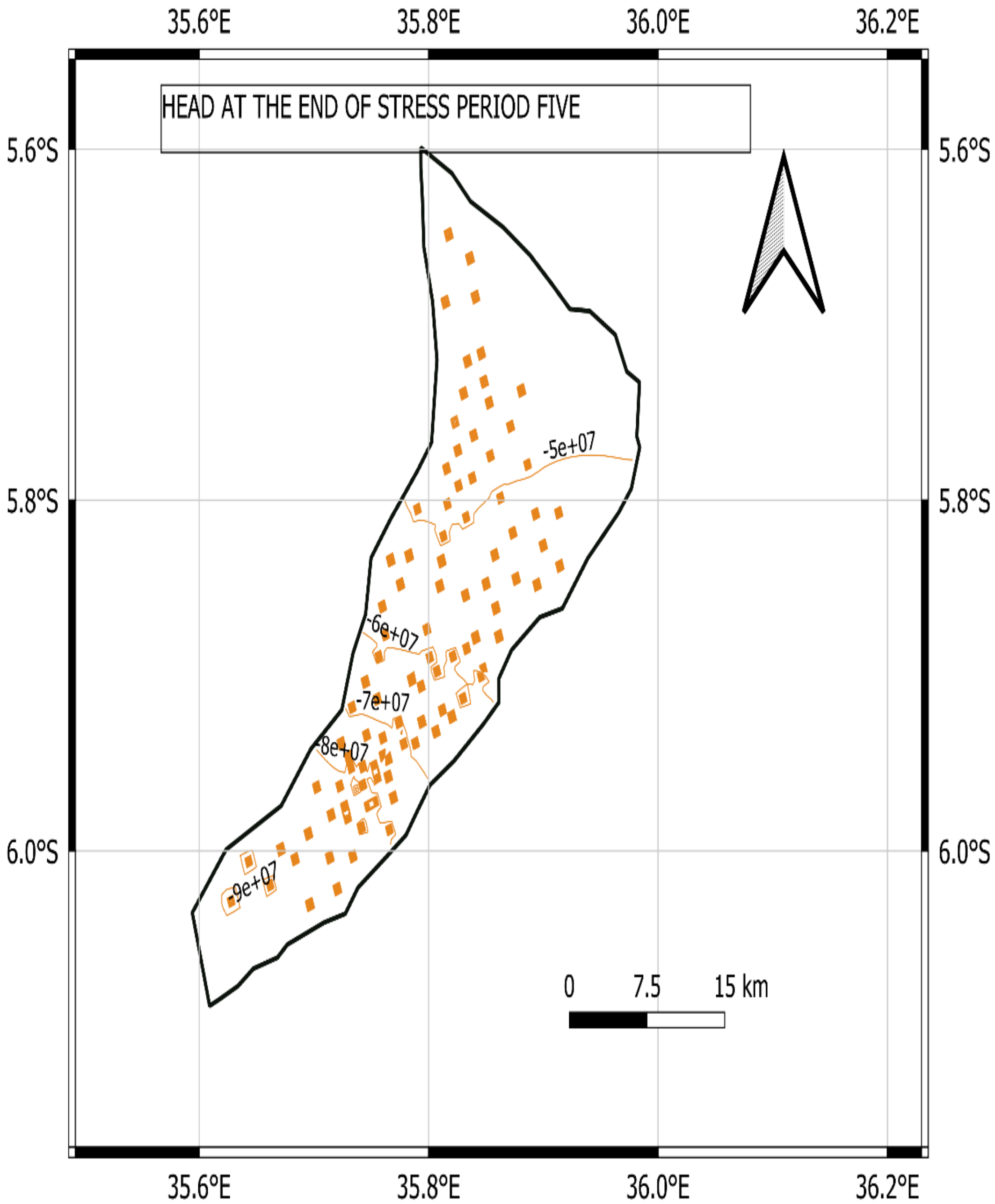
Appendix 2: Volumetric Water Budget at the end of Stress Period 5

```
 VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP    1, STRESS PERIOD   5
 ------------------------------------------------------------------------------

    CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
    ------------------                 ------------------------

          IN:                                      IN:
          ---                                      ---
             STORAGE =      361199.9688               STORAGE =         16.0822
       CONSTANT HEAD =           0.0000         CONSTANT HEAD =          0.0000
               WELLS =  7008600064.0000                 WELLS =     600000.0000
              DRAINS =           0.0000                DRAINS =          0.0000
     HEAD DEP BOUNDS =     4830215.0000       HEAD DEP BOUNDS =        413.5103
            RECHARGE =       11790.7969              RECHARGE =          1.0094
         ET SEGMENTS =           0.0000           ET SEGMENTS =          0.0000

            TOTAL IN =  7013803008.0000              TOTAL IN =     600430.5625

         OUT:                                     OUT:
         ----                                     ----
             STORAGE =  2007679488.0000               STORAGE =     177418.3906
       CONSTANT HEAD =           0.0000         CONSTANT HEAD =          0.0000
               WELLS =  4892224512.0000                 WELLS =     418819.0000
              DRAINS =   113716336.0000                DRAINS =       4178.2241
     HEAD DEP BOUNDS =        3075.5464       HEAD DEP BOUNDS =          0.2726
            RECHARGE =           0.0000              RECHARGE =          0.0000
         ET SEGMENTS =       73263.2344           ET SEGMENTS =          6.2720

           TOTAL OUT =  7013696512.0000             TOTAL OUT =     600422.1250

            IN - OUT =      106496.0000              IN - OUT =          8.4375

 PERCENT DISCREPANCY =             0.00     PERCENT DISCREPANCY =          0.00
```

Appendix 3: Groundwater Head Distribution at the End of the Fifth Stress Period in ModelMuse



Appendix 4: Groundwater Head Distribution at the End of the Fifth Stress Period in GIS



Appendix 5: Volumetric Water Budget under Steady State

```
 VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP    1, STRESS PERIOD   1
 ------------------------------------------------------------------------------

    CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
    ------------------                 ------------------------

          IN:                                      IN:
          ---                                      ---
             STORAGE =           0.0000               STORAGE =           0.0000
       CONSTANT HEAD =           0.0000         CONSTANT HEAD =           0.0000
              DRAINS =           0.0000                DRAINS =           0.0000
     HEAD DEP BOUNDS =       8.3757E-02       HEAD DEP BOUNDS =       2.2884E-04
            RECHARGE =         369.4402              RECHARGE =           1.0094
         ET SEGMENTS =           0.0000           ET SEGMENTS =           0.0000

            TOTAL IN =         369.5240              TOTAL IN =           1.0096

         OUT:                                     OUT:
         ----                                     ----
             STORAGE =           0.0000               STORAGE =           0.0000
       CONSTANT HEAD =           0.0000         CONSTANT HEAD =           0.0000
              DRAINS =         369.5265                DRAINS =           1.0096
     HEAD DEP BOUNDS =           0.0000       HEAD DEP BOUNDS =           0.0000
            RECHARGE =           0.0000              RECHARGE =           0.0000
         ET SEGMENTS =           0.0000           ET SEGMENTS =           0.0000

           TOTAL OUT =         369.5265             TOTAL OUT =           1.0096

            IN - OUT =      -2.5024E-03              IN - OUT =      -6.7949E-06

 PERCENT DISCREPANCY =           -0.00     PERCENT DISCREPANCY =          -0.00
```

Appendix 6: Volumetric Budget with a Pumping Rate of -0.1 from 6 Wells but no Artificial Recharge

```
-
 VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP    1, STRESS PERIOD   1
 ------------------------------------------------------------------------------

    CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
    ------------------                 ------------------------

          IN:                                     IN:
          ---                                     ---
            STORAGE =          0.0000             STORAGE =          0.0000
      CONSTANT HEAD =          0.0000       CONSTANT HEAD =          0.0000
              WELLS =          0.0000               WELLS =          0.0000
             DRAINS =          0.0000              DRAINS =          0.0000
    HEAD DEP BOUNDS =          1.7714     HEAD DEP BOUNDS =      4.8519E-04
           RECHARGE =       3574.6670            RECHARGE =          0.9791
        ET SEGMENTS =          0.0000         ET SEGMENTS =          0.0000

           TOTAL IN =       3576.4385            TOTAL IN =          0.9796

         OUT:                                    OUT:
         ----                                    ----
            STORAGE =          0.0000             STORAGE =          0.0000
      CONSTANT HEAD =          0.0000       CONSTANT HEAD =          0.0000
              WELLS =       2190.6001               WELLS =          0.6000
             DRAINS =       1386.2870              DRAINS =          0.3797
    HEAD DEP BOUNDS =          0.0000     HEAD DEP BOUNDS =          0.0000
           RECHARGE =          0.0000            RECHARGE =          0.0000
        ET SEGMENTS =          0.0000         ET SEGMENTS =          0.0000

          TOTAL OUT =       3576.8872           TOTAL OUT =          0.9797

           IN - OUT =         -0.4487            IN - OUT =     -1.2290E-04

 PERCENT DISCREPANCY =          -0.01     PERCENT DISCREPANCY =          -0.01
```

Appendix 7: Infiltration Rate for Various Types of Soils

Sand type	Infiltration rate (mm/hour)
Sand	Less than 30
Sandy Loam	20-30
Loam	10-20
Clay Loam	5-10
Clay	1-5

Source: (Johnson, 1963)

Calculations of the time it takes water to reach the second layer (Sand)

I hour = 5mm

x = 40,000mm

Therefore 40,000mm will take 8000 hours

$8000\ hours \approx 334\ days$

$334\ days \approx 11 months$

RESEARCH OUTPUTS

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Hydrological Modeling of Artificial Recharge of Groundwater for Sustainable Water Supply in Dodoma City

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Abstract. Groundwater is an important resource that supports the life of people and the surrounding ecosystem in the world. It is the primary source of safe water to semi-arid areas characterized by limited surface water. In Africa, water scarcity has been hitting major cities and towns. In Tanzania, Dodoma has long experienced shortages of water. Owing to the recent transfer of all significant offices from Dar es Salaam to Dodoma, the City's population has drastically increased. The primary source of water in the City is the Makutupora aquifer. The growing human population has resulted in high demand for water use, which has led to the overexploitation of groundwater aquifer. Therefore, this study was carried out using a Modular finite-difference flow model (MODFLOW) to model artificial recharge products to replenish groundwater in the Makutupora aquifer to ensure water supply sustainability in the City. Before simulation of the artificial recharge was done, groundwater storage was estimated using available borehole data and GIS technique. The results indicated that the total groundwater storage in the Makutupora aquifer was about 24.8 BCM (Billion Cubic Meters). The MODFLOW packages used include well package (WEL), General Head Boundary Package (GHB), Evapotranspiration package (EVT), Drain package (DRN), and Recharge Package (RCH). A total of 21 piezometers were used for model calibration. The statistical calibration was also done to validate the model's calibrated parameters. After simulation of the steady-state reference period, the other four stress periods were simulated, considering the projected population and water demand. The planned injection wells to the model in the first, second, third, and fourth transient state periods resulted in a safe yield of 168,857 m^3/day, 197,760 m^3/day, 360,000 m^3/day, and 600,430 m^3/day, respectively. The recommended artificial recharge source is water from the Kinyasungwe River that flows during rainfall time, generally from November to May. One of the recorded years (2007) indicated a flow of up to 23.646 Million Cubic Meters (MCM). The recommended artificial recharge is possible due to the aquifer's storage capacity of 247.84 Million Cubic Meters (MCM). Other flows in small streams within the well field were recommended in creating artificial recharge structures to add more water to the aquifer and natural recharge. Therefore, information from this study could be used by engineers when constructing artificial engineering structures to replenish the water pumped from the Makutupora aquifer.

Keywords: Groundwater, MODFLOW, Artificial Recharge, Makutupora Basin, Groundwater Model, Semi-arid Regions.

AMS Mathematics Subject Classification (2010): 97M10, 93A30

1. Introduction

The world's water crisis is projected to get worse as a result of both climate change and fast population growth [1, 2]. Various places, especially those found in semi-arid areas where the primary water source is groundwater, always experience water shortage [3]. The problem hits more in cities and towns where demand is more significant than supply due to increased population [4–9]. In Africa, water security is an issue in almost all dimensions like affordability, accessibility, and acceptability, especially to people living in large cities and towns where the population is overgrowing [10].

In Tanzania, Dodoma City has always faced water deficiencies. The City's population has increased quickly and will continue to grow between 2020 and 2051 after the government's relocation of all its significant offices from Dar es Salaam to Dodoma. The relocation was made, favoring Dodoma's central location to ensure that the government services are closer to people [11]. The national census of 1988, 2002, and 2012 indicated that Dodoma City had populations of 203 833, 324 347, and 410 956 people, respectively [12]. But recently, the City's population growth is not following the average expected growth and expansions. Still, it is drastic due to government and International Organization offices' movement along with their employees and families and other service providers from Dar es Salaam to Dodoma City (Table 1). This movement has disrupted and will continue disrupting the population's natural development to support the City's growth [11]. The water demand has also increased and will continue rising as the City grows (ibid) (Table1).

Table 1: Projected City population, water demand, existing water capacity, and deficiency 2025 to 2051

	2015	2025	2026	2036	2051
The population of the City	497,934	689,072	1,069,900	1,713,794	1,972,968
Requirement m^3/day	82,651	137,584	160,730	226,204	418,839
Existing m^3/day	61,500	113,192	113,192	113,192	113,192
Deficit m^3/day	-21,151	-23,992	-47,138	-113,012	-305,247

The groundwater taped from the Makutupora aquifer is the principal primary source for supplying water to the City [13]. As pumping wells draw groundwater from a larger wellfield area, groundwater level declines gradually (ibid). Episodic events and highly seasonal rainfall have been among the factors for sustaining groundwater, but this rarely occurs [14]. The wellfield's ability to continue and maintain the recent intensive pumping to meet the demand for safe water following the City's rapid growth is not evident [15]. Researchers contended that the boreholes could produce 61,500 m^3/day. The aquifer was found to supply between 48,000 m^3/day up to 50,000 m^3/day, and hence it is likely to be overexploited [11], [16–18]. Furthermore, the projections regarding population indicated a more significant water demand than the existing capacity resulting in a deficit (Table 1). Response strategies like mitigation, adaptation, and coping mechanisms are crucial to address water availability in Dodoma City due to increased population [18, 19].

The primary government challenge is finding the ways and methods that can be used to ensure water availability sustainability and have that water cost-effectively. The government plans to bring water from either Farkwa Dam or Lake Tanganyika/Victoria to meet the city needs, but this is cost inhibitive [11]. Internationally, some developed countries like Austria, Greece and the Netherlands have already adopted artificial recharge methods to replenish the aquifers [20, 21]. [22] modeled artificial recharge using MODFLOW, and the results indicated that artificial recharge enhances groundwater recovery effectively. [23] used MODFLOW to model the groundwater flow and assess recharge and water table behavior's potential under varying recharge and pumping rates. The results indicated that the prevailing pumping and recharge rates are not sustainable and that there was a need to implement some artificial recharge techniques. [24] modeled the recovery of storage by MODFLOW to simulate the increase in storage after water scarcity as caused by climate change, urbanization, and an increase in the area's population. The results indicated that making water available to the farms ensures the availability of groundwater in aquifers sustainably.

1.1. Previous studies related to groundwater modelling in makutupora basin

Few previous studies on modelling groundwater flow in Makutupora have been undertaken. [23] used MODFLOW to model groundwater flow under transient state conditions in previous years. However, the picture of the groundwater flow was not clear because the modeled area was too small. [23] used MODFLOW to model flow in the Makutupora catchment and observed that the present geologic structures influence the groundwater and surface water flow. However, the time was not enough to validate the model and determine recharge rates (ibid). Furthermore, a study by [25] on groundwater management using a mathematical model under the MODFLOW code suggested that artificial recharge through infiltration ponds can restore the aquifers. The study did not estimate the recharge rate needed and the aquifer's natural recharge to satisfy the people as the City overgrows.

Additionally, [26] carried out research on Makutupora that assessed the recharge of groundwater using MODFLOW. Her recommendations were to monitor the wellfield by introducing boundaries that reflect the area about time for a better understanding of inflow and outflow rates. [16] contended that research was carried out by a team of scientists from the Sokoine University of Agriculture and the Ministry of Water and

Irrigation both in Tanzania and the University College London (UK). The research involved the compilation of a near-continuous 60-year record of groundwater-level observations. The analysis revealed that recharge depends much on heavy seasonal rainfall associated with El Niño Southern Oscillation (ENSO) that occurs episodically. However, the study did not focus on improving the recharge of the site through artificial recharge. [19] carried a study titled "The Climate Controls and Process of Groundwater Recharge in a Semi-Arid Tropical Environment: Evidence from the Makutupora Basin, Tanzania." The study recommended that the managed artificial recharge replenish the groundwater, but the study did not provide specific information to manage recharge and pumping. Therefore, this study fills in the identified gap by simulating and determining the recharge rate with respect to the estimated increase in water demand that could be brought by the increase in population, considering the figures projected in the Norplan report of 2019 (Table 1).

2. Materials and methods

2.1. Description of the study area

The study was undertaken in the Central Semi-Arid part of Tanzania (Figure 1). The specific site for the study is Makutupora Basin, Dodoma region, Tanzania. The pumping station is located about 30km north of Dodoma City (Figure 2). Its location is 5^0 36′59" and 6^0 14' 50 " S and 35^0 36' 36"' and 36^0 01' 54"'E. It covers an area of approximately 785,937,000 m^2. Dodoma receives an annual rainfall of about 550 mm/year, and it always rains from November to May [27]. The yearly evapotranspiration of the area is approximately 2,000 mm.

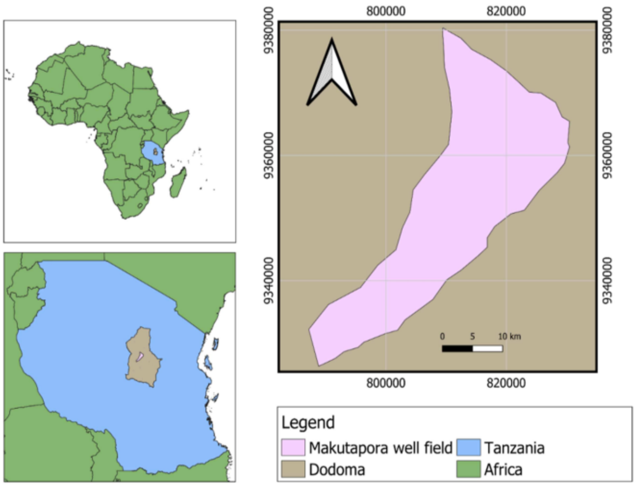

Figure 1: Location Map of the Study area

4

In conceptualizing the model, the elevation data sets from Earth Explorer were downloaded and visualized in the Geographical Information System (GIS). The National Aeronautics and Space Administration (NASA) website provided the information for creating the study area's digital elevation model. The elevation of the modeled area ranges from 1,058 m.a.s.l to 2,048 m.a.s.l (Figure 2).

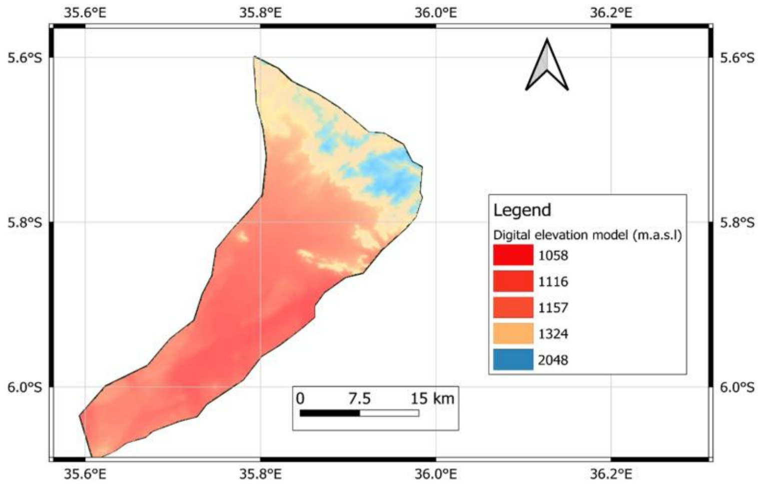

Figure 2: Location Map of the Study Area

2.2. The process of groundwater flow modelling

Several steps were involved in modelling the artificial recharge of groundwater. Various skills related to hydrogeology were used in the whole process of modelling groundwater, involving understanding the equations.

The first step involved using all knowledge and available data obtained from existing literature, a survey conducted in this study, and field data collected in this study to develop a conceptual model. The available data were also used to establish the groundwater storage in the Makutupora aquifer.

The second step involved representing the conceptual model in a mathematical form and construction/setting of the numerical model by applying the analyzed data like recharge rate and evapotranspiration and other boundaries discovered during the conceptualization process.

The third step involved calibration of both steady and transient states that matched the observed and the simulated data. The fourth stage involved the use of the constructed model to predict the flow of groundwater. It also involved the simulation of artificial recharge of groundwater. The modelling process is summarized in Figure 3.

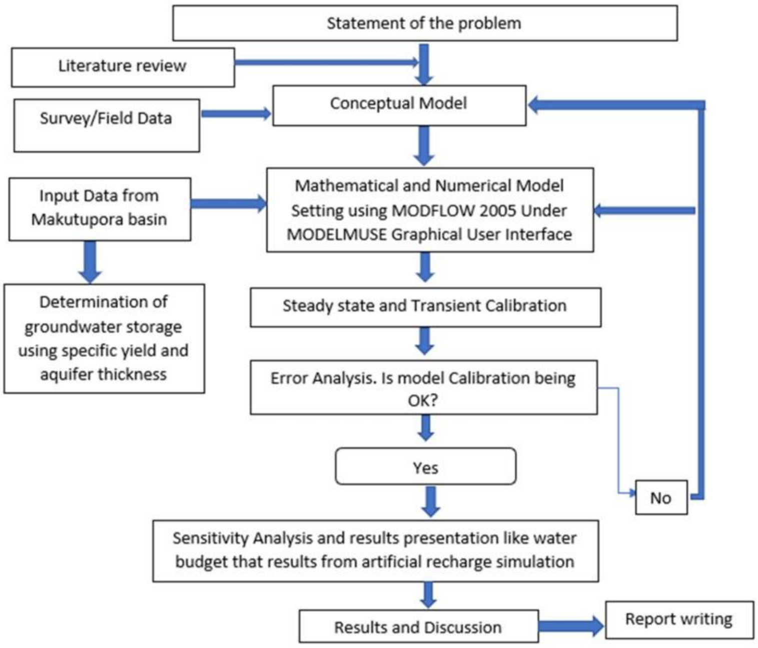

Figure 3: Modelling Protocoll (source: this study, modfied from [26, 28–30])

2.3. Groundwater storage estimation in makutapora aquifer

Estimating groundwater storage in the Makutupora aquifer was done using available borehole data and Geographical Information System (GIS) techniques. The GIS was used to construct the map where the aquifer's surface area and boundary were determined. The available maps were in image form and had no exact coordinate system and hence were imported in QGIS and then georeferenced accordingly. The aquifer was divided into four layers: The layers' determination based on the soil type's dominant concentration. The first and third layer were aquitards, and the second and fourth were the aquifers. The estimated aquifer thickness was adopted from a study by [31]. The specific yield was calculated by averaging the determined values in the study by [32]. Specific yield refers to the amount of water available for groundwater pumping from the material containing the water. The specific yield also depends on the depth of the aquifer. Figure 4 below shows the flowchart of groundwater storage estimation.

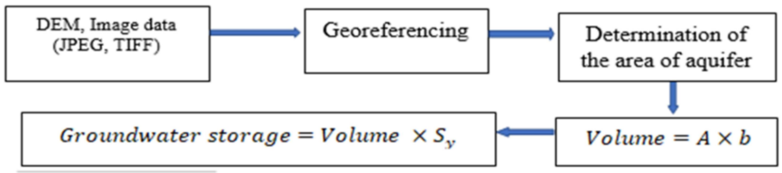

Figure 4: Flowchart showing groundwater storage estimation

A map calculator was used to determine the area of the aquifer. Groundwater calculated using the equation (1) below

$$Groundwater\ storage = A \times b \times S_y \tag{1}$$

Table 2: Estimated values of the Specific yield and aquifer thickness for each layer

Layer Number	Specific yield	Aquifer thickness
Layer One	0.0567 = 5.67 x 10^{-2}	55.50m
Layer two	0.2100 = 2.1 x 10^{-1}	62.75m
Layer three	0.0300 = 3 .0 x 10^{-2}	55.50m
Layer four	0.2330 = 2.33x 10^{-1}	62.00m

Source: [31], [32]

2.4. Meteorological data

The meteorological data that were used in the study area include rainfall, temperature, and evapotranspiration data. The data were obtained from the Ministry of Water, and they cover the date January 2017 to December 2019. The driving forces like interception are used to calculate the infiltration rate of the area. The modeled area covers 785.937 km^2. After classification, the vegetation area covers 734.653 km^2 (93%), and the grass area covers 51.284 km^2 (7%). The computed ratio of the grass to other vegetation is 0.07 to 0.93. Then, after determining the area's size and vegetation covers, the interception value was calculated using equation (2).

$$I = RF * (I_g * Area_g + I_{other} * Area_{Other}) \tag{2}$$

where I is the canopy interception (mm d^{-1}), RF is rainfall (mm d^{-1}), I_g and I_{other} are the interception percentage loss for grass and other vegetation covers, respectively. Substituting the values of I_g, $Area_g, I_{other}$, $Area_{Other}$ equation (2) becomes equation (3).

$$I = RF * (0.069 * 0.07 + 0.2 * 0.93) \tag{3}$$

Then the value of interception used to calculate the infiltration rate using equation (4)

$$P_r = P - I \tag{4}$$

where P_r is the infiltration, P is precipitation, and I is the interception

This study has involved the calculation of the weighted interception and infiltration. The minimum, maximum, and average interception were 0 mm/day, 17.270115 mm/day, and 0.302370571 mm/day. The minimum and maximum infiltration were found to be 0 mm/day and 73.229885 mm/day, respectively. The infiltration rate ranges between 0 mm/day and 73 mm/day inclusive. The daily precipitation ranges between 0 mm/day and 90.5 mm/day, inclusive. On average, the value of rainfall was found to be 1.6 mm/day. Lack of data from the Makutupora potential evapotranspiration pan forced us to use other methods such as the Penman-Monteith method of the Food and Agricultural Organization (FAO). The calculated potential evapotranspiration using the Penman-Monteith method ranges between 4.2 mm/day and 11.6 mm/day. Its mean is 8.9 mm/day.

3. Mathematical and numerical groundwater modeling

Numerical modelling of artificial recharge of groundwater has been an essential tool in managing groundwater in various parts of the world [33], [34]. The mathematical formulation and its numerical description used to study groundwater flow in the aquifer are explained in sections 3.1 and 3.2.

3.1. Mathematical description of governing equations

According to [35], the governing equations for a three-dimensional unsteady, transient flow problem with Darcy's law and continuity equations is expressed by equation (10), which is the partial differential equation for physical modelling of the three-dimensional groundwater flow problem. The model is formulated from Darcy's law and continuity equation, as explained below.

Darcy's law states that, for a given type of sand, the rate of flow of water is proportional to the cross-sectional area A and the piezometric head drop or loss $h_2 - h_1$ and it is inversely proportional to the difference in the porous medium's length [36]. Also, the groundwater flows from high to low energy potential [37]. The mathematical expression of Darcy's law is given by equation (5)

$$Q \propto A\frac{h_2-h_1}{l_2-l_1} \rightarrow q = \frac{Q}{A} = -K\frac{h_2-h_1}{l_2-l_1} \quad (5)$$

where $q = (q_x,\ q_y, q_z)$ stands for the specific discharge, K is the hydraulic conductivity, and h is the hydraulic head. A minus sign indicates that the flow is in the direction of decreasing head loss. The medium was assumed to be isotropic and that the discharge rate Q is not dependent on time.

$$q = -\mathrm{k}\frac{dh}{dl} \rightarrow q = -k\ grad\ h \quad (6)$$

where k = $(k_x,\ k_y, k_z)$ stands for the values of hydraulic conductivity along x, y and z axes

The three-dimensional incompressible continuity equation is expressed by equation 7;

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (7)$$

whereby u, v *and* w are the components of velocity in the directions of x, y and z. The velocity components u, v and w can be replaced with components of $q = q(q_x, q_y, q_z)$. The transient condition is modelled by adding a storage coefficient. The continuity equation for transient conditions is described by equation (8)

$$\frac{\partial q_x}{\partial x}(b) + \frac{\partial q_y}{\partial y}(b) + \frac{\partial q_z}{\partial z}(b) = N(x, y, z, t) - S\frac{\partial h}{\partial t} \quad (8)$$

where N, is the sink or source, b is the thickness of the aquifer, t is time, and S stands for the storage coefficient. Substituting from equation 8 in Darcy's law for q_x, q_y and q_z result in equation (9) and (10)

$$\left(\frac{\partial}{\partial x}\left(-k_x\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(-k_y\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(-k_z\frac{\partial h}{\partial z}\right)\right) = N(x, y, z, t) - S\frac{\partial h}{\partial t} \quad (9)$$

$$\rightarrow \frac{\partial}{\partial x}\left(k_x\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y b\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z\frac{\partial h}{\partial z}\right) = S_s\frac{\partial h}{\partial t} - N(x, y, z, t) \quad (10)$$

where S_s= Specific storage and h = Piezometric head (L),
The equation 9 and 10 solved by finite difference as applied by [38] MHD Arterial Blood Flow and Mass Transfer under the Presence of Stenosis, Body Acceleration and Chemical Reaction: A Case of Magnetic Therapy.

3.2. Numerical equations

Numerical modelling of equation (10) is done by the compact finite difference approximation as expressed by equation (11):

$$\Delta_x\left(T_x\Delta_x h^{t+\Delta t}\right) + \Delta_y\left(T_y\Delta_y h^{t+\Delta t}\right) + \Delta_z\left(T_z\Delta_z h^{t+\Delta t}\right) = \frac{V_b S_s}{\Delta_t}\left(h^{t+\Delta t} - h^t\right) - V_b N \quad (11)$$

where V_b is the volume of grid block at the location (i, j, k), T is the transmissibility, Δt is the time level increment, t is the current time level, $t + \Delta t$ is the next time step. Figure 5 represents the hypothetical aquifer in three dimensions. The block centred finite difference approach is used to simulate groundwater flow.

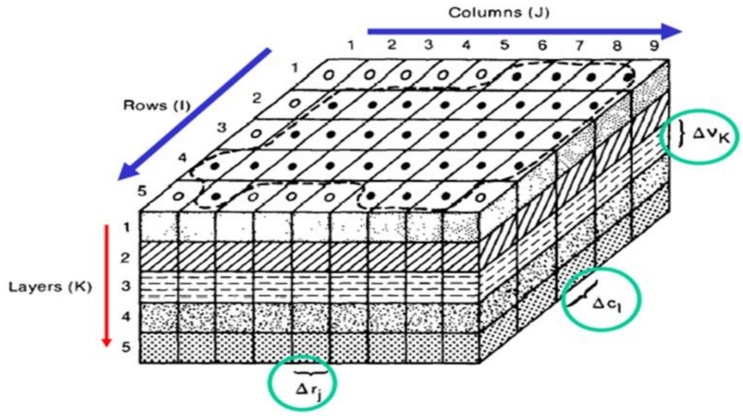

Figure 5: A discretized hypothetical aquifer system in three dimensions (Haurbaugh, 2005).

Equation (10) was discretized using the finite difference quotients of equation (11) form a numerical discrete equation (12):

$$\frac{1}{(\Delta x)_{i,j,k}}\left[Kx_{\left(i+\frac{1}{2},j,k\right)}\frac{h^{n+1}_{i+1,j,k}-h^{n+1}_{i,j,k}}{(\Delta x)_{i+\frac{1}{2},j,k}}-Kx_{\left(i-\frac{1}{2},j,k\right)}\frac{h^{n+1}_{i,j,k}-h^{n+1}_{i-1,j,k}}{(\Delta x)_{i-\frac{1}{2},j,k}}\right]$$
$$+\frac{1}{(\Delta y)_{i,j,k}}\left[Ky_{\left(i,j+\frac{1}{2},k\right)}\frac{h^{n+1}_{i,j+1,k}-h^{n+1}_{i,j,k}}{(\Delta y)_{i,j+\frac{1}{2},k}}-Ky_{\left(i,j-\frac{1}{2},k\right)}\frac{h^{n+1}_{i,j,k}-h^{n+1}_{i,j-1,k}}{(\Delta y)_{i,j-\frac{1}{2},k}}\right]$$
$$+\frac{1}{(\Delta z)_{i,j,k}}\left[Kz_{\left(i,j,k+\frac{1}{2}\right)}\frac{h^{n+1}_{i,j,k+1}-h^{n+1}_{i,j,k}}{(\Delta z)_{i,j,k+\frac{1}{2}}}-Kz_{\left(i,j,k-\frac{1}{2}\right)}\frac{h^{n+1}_{i,j,k}-h^{n+1}_{i,j,k-1}}{(\Delta z)_{i,j,k-\frac{1}{2}}}\right]$$
$$=S_s\frac{h^{n+1}_{i,j,k}-h^{n}_{i,j,k}}{\Delta t}-N_{(i,j,k)} \tag{12}$$

This study used MODFLOW-2005 code for the numerical model and the ModelMuse Graphical User Interface (GUI) to implement the numerical model and do simulations for the groundwater flow in the Makutupora aquifer.

3.2. MODFLOW-2005 model construction and discretization

In this study, numerical modelling of the groundwater flow, including defining boundary conditions, was done through several MODFLOW-2005 packages. ModelMuse (the Graphical user interface (GUI) software) was used for inputting data independently in the MODFLOW-2005 numerical model, generating and editing the numerical model grid, defining and redefining discretization, executing the numerical model, doing simulations and displaying the results of the MODFLOW-2005 numerical model.

The site covering 785,937,000 m^2 was discretized in the grid of 500mx500m comprising 115 rows and 55 columns. Four layers were defined in the model regarding the available bore log and lithological profile data having the length elevation of 40, 75, 105, and 150. The model was run under transient conditions except for the first steady-state stress period. The digital elevation model (DEM) data were downloaded from NASA (ASTER GDEM 2). The Modelmuse GUI was used to define the model grids for the active and inactive cells. Figure 6 shows the discretized model.

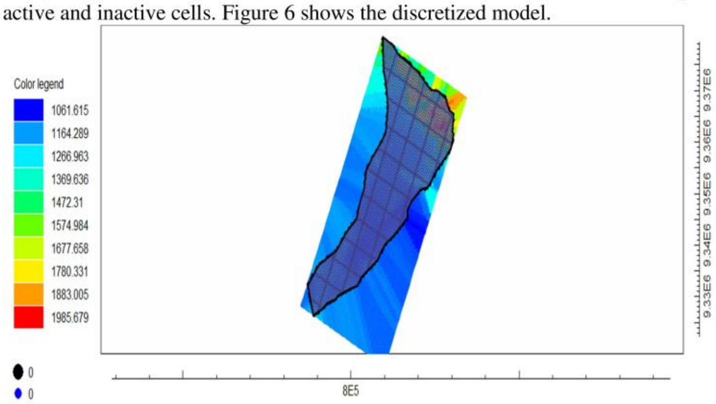

Figure 6: Model grid in Modelmuse GUI with elevation data

3.3. Boundary conditions

The proper assignment of the boundary conditions is vital when constructing a groundwater flow model, especially when establishing the area's hydrological processes. In the case of this study, the following MODFLOW-2005 packages were used to study the area.

- Recharge package (RCH): The recharge package was used as the inflow from the precipitation. The infiltration coefficient used is 68% of the rainfall. It was used as the infiltration in the reference period (which had 1.1 mm/day of rain).

- WEL package (WEL): The WEL package was used to assign the pumping rate and artificial recharging rate to the aquifer. The simulation involved a plan of 50 pumping wells and 50 recharging wells. General head boundary package (GHB): The GHB always defines the general groundwater flow condition. It allows water to move either out or into the system, depending on the elevation. The area's groundwater flow in the system is influenced by faults, especially Kitope and Mlemu Fault. The estimated values of hydraulic conductance used in the simulation were 1.119375E-8 m^2/day, 1.50807233796296E-14 m^2/day, and 1.17994097E-8 m^2/day for both Kitope 1, Kitope 2, and Mlemu Fault, respectively. The boundary head was set as the model top for all faults.

- Evapotranspiration package (EVT). The evapotranspiration package is used to implement the outflow of water from evaporation and transpiration. In the reference period, the evapotranspiration rate of 8mm/day.

- HOB package: The HOB package was used to introduce a hydraulic head in the model, was later used for model calibration.

- Drain (DRN). The Kinyasungwe River that flows within the Makutupora area was assigned as a drain because it drains the water from the upper part of the study area. The stream flows seasonally, and the assigned hydraulic conductivity was 0.1331m ^{2}/day, and the elevation for this was set as Model Top.

3.4. Time discretization

The stress periods were defined based on the projected population rise and the projected water demand for Dodoma City. The number of stress periods was five. The first stress period was the steady-state, and the remainder were in a transient state. The stress periods were in groups of time steps 1, 5, 10, 1, and 15 years, from 2019 to 2051 (Table 3).

Table 3: Flow Conditions and Time Discretization

Stress period	Time Step (Years)	Duration (Years)	State	Calendar period
1	1	1	Steady	2016
2	5	6	Transient	2017-2022
3	1	7	Transient	2023-2024
4	10	17	Transient	2025-2035
5	15	32	Transient	2036-2051

4. Results and discussions

4.1. Estimated groundwater storage in makutupora aquifer

The aquifer has an area of 785 937 000 m^2. The estimated values of specific yield for the aquifer ranges from 3 .0 x 10^{-2} to 0.2330 = 2.33x 10^{-1}. The values of the specific yield and aquifer thickness for each layer is indicated in Table 2. The total groundwater storage was estimated to be 247.84 MCM. The description of the estimation of groundwater storage layer-wise is indicated in Table 4.

Table 4: Estimated groundwater storage capacity of the Makutupora aquifer

Layer Number	Groundwater storage	Groundwater storage in Million Cubic Meters (MCM)
Layer one	24042419.87m^3	24.04
Layer two	100678134.600m^3	100.68
Layer three	12720857.08m^3	12.72
Layer four	110369670.50m^3	110.40
Total	247811082.1m^3	247.84

4.2. Calibrated parameters for the calibrated model

The calibration involved adjusting the recharge rate and hydraulic conductivities and systematically to match the observed and simulated head. Table 5 shows the calibrated hydraulic conductivities, recharge rate, evapotranspiration rate, and drain conductance. The hydraulic conductivities of the area differ from one layer to another and influences the area's recharge.

Table 5: Hydraulic Parameters

Parameter	Value	Description
HKL1	1E-7 m/day	Hydraulic conductivity of the first layer
HKL2	0.0001 m/day	Hydraulic conductivity of the second layer
HKL3	0.0001 m/day	Hydraulic conductivity of the third layer
HKL4	1E-6 m/day	Hydraulic conductivity of the fourth layer
GHB	0.1331 m^3/day	The general head boundary conductance
RCH	1.2991979E-9 m^3/day	Recharge rate of groundwater
EVT	5.12E-7 m^3/day	Evapotranspiration rate of groundwater

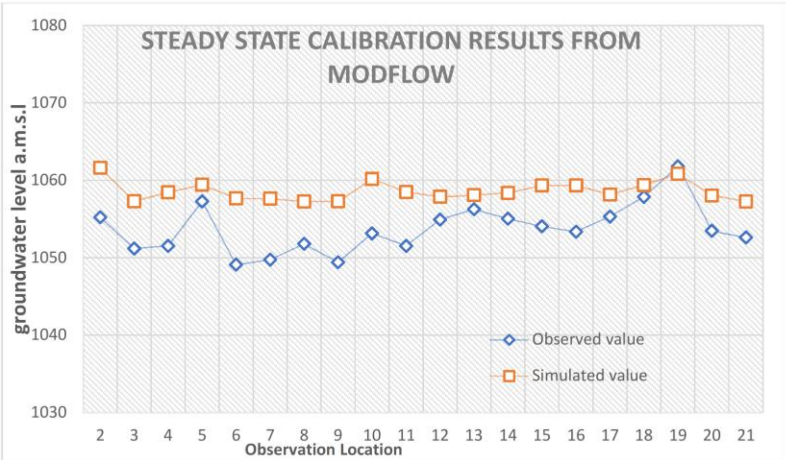

Figure 7: Steady-State Calibrated values from the MODFLOW.

Various statistical tests like Chi-square and the coefficient of determination were used to validate the calibrated results. Equation (5) was used to compute the value of Root Mean Squared Error (RMSE).

$$RMSE = \left(\sum_{i=1}^{n} \frac{(O_i - E_i)^2}{n}\right)^{1/2} \quad (11)$$

The RMSE from the statistical test was 5.51. The value coincides with the value produced by the MODFLOW 2005 and Modelmuse graphical user interface, which is 5.38 with a slight deviation. Using equation (6), we computed the value of Chi-square, where the. Chi-square results were good as they range between 0 and 1.

$$\chi 2 = \sum \frac{(O_i - E_i)^2}{E_i} \quad (12)$$

where $\chi 2$ = Chi-squared, E_i =Expected value O_i = Observed value, and n is the total number of observed values.

The chi-squared test value is 0.57, which is the same as 57%, indicating that the two values are not much different. The statistical findings suggest that the model works as long as the variance between the actual and predicted values does not vary greatly.

4.3. Scenarios simulated

4.3.1. First scenario

The simulated steady-state flow was the initial point with the hydraulic conductivity's initial calibrated parameters, recharge, evapotranspiration, and drain conductance values. The model was first set by considering the effect of natural recharge that usually occurs through infiltration after precipitation. After that, a pumping rate of 0.1 m^3 /day for about ten years indicated a decline in groundwater level. Hence, other strategies to replenish the aquifers from the extra water that flows out of the system during the rainy season are vital. The plan to fill the aquifer was simulated after introducing the artificial injecting artificial wells that could artificially increase the groundwater storage. This model attempts to simulate artificial wells' introduction to replenish the overexploited groundwater in Makutupora, given the surge increase in Dodoma City population.

4.3.2. Second scenario

Then, a second scenario was done by which a total of 50 injecting wells were assigned to add the water to the ground by the artificial aquifer recharge methods. In this scenario, it was assumed that no pumping was undertaken in the area (Table 6). The second scenario enabled the increase in the apparent amount of water volume that could have been recharged to the aquifers. The restored water could specify the optimum amount of water to be pumped from the wells for a sustainable water supply. The insertion of 50 wells in the area strategically increased the cumulative volume in recharge. After the simulation, the daily recharge increased from 168,857 m^3/day to 600,430 m^3/day. Table 6 shows the results of the implementation of artificial recharge. We simulated this following the cumulative recharged volume and the rate of the daily recharge.

Table 6: Volume Results After Artificial Recharge

No	Duration (Years)	State	Number of active reservoirs	Cumulative volume recharged m^3/year	Daily Recharge m^3/day
1	1	Steady	0	0	0
2	6	Transient	6	61 801 828	168 857
3	7	Transient	10	505 474 560	197 760
4	17	Transient	20	2 236 151 296	360 000
5	32	Transient	50	7 013 803 008	600 430

One of the significant identified sources where the water could be drawn for recharge is from the Little Kinyasungwe river flow. The river flows seasonally, especially during the rainy period. The data available from the Ministry of Water in Tanzania indicated a flow of 23.646 Million Cubic Meters (MCM) in 2007. The river discharges its water to the Hombolo dam that has 184 Million Cubic Meters (MCM). The dam is important as it provides water for various uses like fishing, irrigation and domestic water use. Due to the expanded surface area of water created by dams, enormous water volumes are lost to evaporation, much more than would have been lost in the dam's absence. Therefore, a portion of the water flowing in the Kinyasungwe river is recommended for the aquifers' artificial recharge. Also, implementers need to put a lot of efforts into artificially recharge the aquifers in the years that El Niño Southern Oscillation (ENSO) occurs as it contributes a lot of flow due to a huge amount of rainfall.

4.3.3. Third scenario

The third scenario involved the simulation of the pumping rate that can be done after artificial recharge. The results indicated that the recharged water could increase the aquifer yield to the extent that the groundwater's abstraction about the projected population meets the demand sustainably. For example, in the year 2051, the estimated existing water would be 113,192 m^3/day. The projected amount of water demanded was expected to be 418,839 m^3/day. The projected demand indicated a deficiency of 305,247 m^3/day. In the second scenario, we see from Table 5 that the injection of artificial wells has increased the recharge rate to 600,430 m^3/day. So, the simulated artificial recharge has given the estimated value of 600,430 m^3/day. This study carried out pumping rate simulations against recharge rate after artificial recharge, as illustrated in Figure 5. The pumping rate assignment indicates that the recharge rate is higher than the pumping rate's speed. For example, in the last stress period, the recharge rate was 0.6 million cubic meters per day while pumping was 0.42 million cubic meters per day.

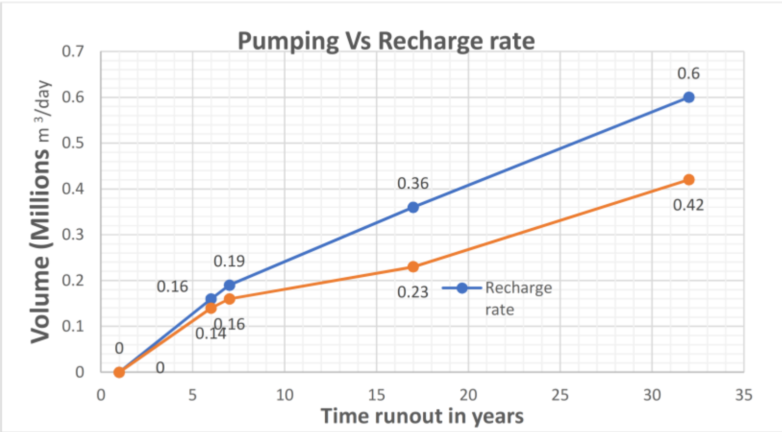

Figure 8: Recharge rate Versus the Pumping rate

Table 7 indicates the projected population as the City grows, the existing water, and the water demand. The deficiency is also shown. The values enabled the water simulation to be pumped from the aquifer after artificial recharge be carried out. The simulation results showed water surplus, which suggests that artificial wells are essential to replenish the aquifer depleted after increasing the population and other factors like climate change and variability. For example, Table 7 shows that in 2025, the projected water demand is 137,584 m^3/day, while the simulated amount is 168,857 m^3/day, resulting in a surplus of 31,273 m^3/day.

Table 7: City Population concerning Water Demand, Existing Water, Deficiency, Simulated and Surplus

	City Population	**Water demand** m^3/day	**Existing water** m^3/day	**Deficiency** m^3/day	**Simulated** m^3/day	**Surplus** m^3/day
2025	689 072	137 584	113 192	-23 992	168 857	31 273
2026	1 069 900	160 730	113 192	-47 138	197 760	37 030
2036	1 713 794	226 204	113 192	-113 012	360 000	133 796
2051	1 972 968	418 839	113 192	-305 247	600 430	181 591

4.4. Water budget of the groundwater at the end of the last stress period

Table 8 indicates the water budget at the end of the last stress period. The results show that artificial recharge mechanisms enhance aquifer sustainability. About 99.9% of the inflow is estimated to come from artificial wells. The aquifer's effective planning could support water production of up to 69.75% of the outflow from the planned 50 pumping wells. The rate of natural recharge alone is not enough to help keep the replenishment of the aquifer. The aquifer's sustainability is disturbed as the rate of natural recharge is meagre.

Table 8: Water Budget after Pumping the Water From 50 Pumping Wells

	Input		**Output**	
	m^3/day	**%**	m^3/day	**%**
Storage	16.0882	0.0027	177,418	29.5
Wells	600,000	99.9	418,819	69.75
Drains	0	0	4,178.2241	0.0796
Head Dependent Bounds	413.5103	0.07	0.2726	0.0000454
Recharge	1.0094	0.00017	0	0
Evapotranspiration	0	0	6.272	0.00104
Total	600,430.5625	100	600,422.1250	100

5. Conclusion

The relocation of government offices from Dar es Salaam to Dodoma has led to a surge in population, resulting in overexploitation of water in the Makutupora aquifer. The ability of the well to support the population's sustainability through water supply is likely to be overtaken by the abstraction. The sustainability of groundwater to meet the demand of the Cities that overgrows should be studied. Therefore, this study simulated the power and ability of artificial recharge and natural recharge to increase the aquifers' water for suitable water supply in Dodoma City and mitigate the shortage. Based on the climate data, the recharge rate and evapotranspiration rate were computed.

The groundwater flow model which was used is MODFLOW-2005 with the support of Modelmuse Graphical User Interface. The packages used for the model are RCH, WEL, EVT, DRN, HOB, and GHB packages. Both the steady-state and transient flow models were calibrated by systematically adjusting the parameters. The steady-state model was used as a reference for the transient, and it had a Root Mean Square Residue of 5.3.

The groundwater flow simulation results of artificial recharge indicate that artificial recharge mechanisms could enhance the Makutupora aquifer sustainability. The developed model might help the decision-makers to manage the groundwater flow in the Makutupora aquifer. However, data from the area (Makutupora Dodoma) were minimal, especially the evapotranspiration data. Furthermore, the areas stratigraphic units' complexity was a barrier to estimating the hydraulic conductivities. The results indicated a need for about 90% of the flow to replenish the aquifers.

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Poster Presentation

Hydrological Modelling of Artificial Recharge of Groundwater for Sustainable Water Supply in Dodoma City

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1. Introduction

- The world's water crisis is projected to get worse as a result of both climate change and fast population growth (Brandshaug, 2019).
- Groundwater is an important resource that supports the life of people and the surrounding ecosystem the world (Gleeson *et al.*, 2020: Shemsanga *et al.*, 2018)
- In Tanzania, Dodoma has always experienced water shortages due to transfer of all the major offices from Dar es Salaam to Dodoma
- The primary source of water is Makutapora aquifer which is likely to be overtaken by abstraction volume
- Hence, the aquifer needs an urgent monitoring and infrastructure to increase the recharge through artificial recharge techniques that uses the mathematical and hydrological modeling techniques

Table 1: Projected City Population, Water Demand, Existing Water Capacity and Deficiency 2025 to 2051

	2015	2025	2026	2036	2051
City population	497 934	689 072	1 069 900	713 794	1 972 968
Requirement m^3/d	82 651	137 584	160 730	226 204	418 839
Existing m^3/d	61 500	113 192	113 192	113 192	113 192
Deficit m^3/d	-21 151	-23 992	-47 138	-113 012	-305 247

2. Materials and Methods

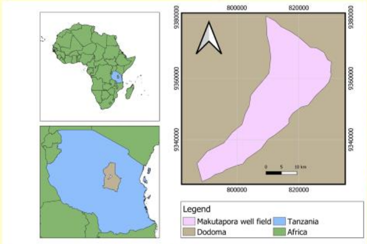

Figure 1: Study area

- Darcys law and continuity equations are used to form groundwater flow equation . Equation (1) express the groundwater flow equation
- $\frac{\partial}{\partial x}\left(k_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_{zz}\frac{\partial h}{\partial z}\right)=S_s\frac{\partial h}{\partial t}\pm W$
- The Modular Finite Difference flow modeType equation here.l (MODFLOW) that was developed by USGS using FORTRAN compiler solves the equation (1)
- The MODFLOW was used in modelling the artificial recharge of groundwater

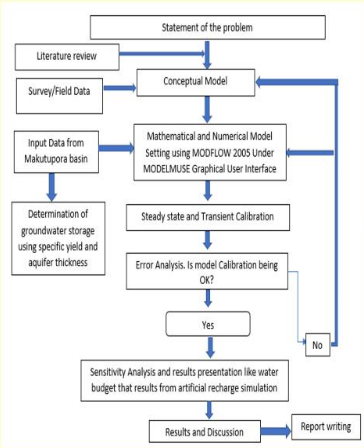

Figure 2: Groundwater Modeling Protocol

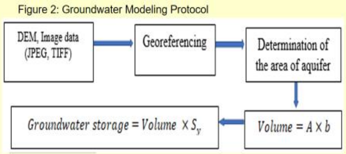

Figure 3: Flowchart of the groundwater storage estimation

Table 2: Estimated Length, Width and Area of the Faults

Fault name	Length	Width	Area (Length X width)
Kilungule fault	30 491.16m	150m	4 573 674m^2
Mlemu fault	26 639.14m	100m	2 663 914 m^2
Kitope fault	4472.96m	90m	402 566.4 m^2
Total	61 603.26m		7 640 154.4 m^2

Table 3: Comparison of the Observed Head Versus Simulated Head for the Calibrated Model

Borehole	Observed	Simulated	Difference
Obs_1	1055.6240234	1059.1162109	-3.4921875000
Obs_2	1055.2299805	1061.5865479	-6.3565673828
Obs_3	1051.1939697	1057.2805176	-6.0865478516
Obs_4	1051.5250244	1058.4381104	-6.9130859375
Obs_5	1057.2690430	1059.4206543	-2.1516113281
Obs_6	1049.0970459	1057.6618652	-8.5648193359
Obs_7	1049.7519531	1057.6212158	-7.8692626953
Obs_8	1051.7840576	1057.2628174	-5.4787597656
Obs_9	1049.4200439	1057.2897949	-7.8697509766
Obs_10	1053.1540527	1060.1611328	-7.0070800781
Obs_11	1051.5329590	1058.4938965	-6.9609375000
Obs_12	1054.9210205	1057.8634033	-2.9423828125
Obs_13	1056.2490234	1058.0837402	-1.8347167969
Obs_14	1055.0219727	1058.3677979	-3.3458251953
Obs_15	1054.0429688	1059.3349609	-5.2919921875
Obs_16	1053.3620605	1059.3349609	-5.9729003906
Obs_17	1055.3070068	1058.1464844	-2.8394775391
Obs_18	1057.8499756	1059.3758545	-1.5258789062
Obs_19	1061.7900391	1060.8487549	0.94128417969
Obs_20	1053.4699707	1058.0278320	-4.5578613281
Obs_21	1052.6080322	1057.2670898	-4.6590576172

The validity of the results in table 2 were supported by statistical test, in which Chi-square test resulted to a value of 0.57 , hence the model is valid because Chi-squared value ranges from 0-1

3. Results

Table 4: Estimated Groundwater Storage Capacity of the Makutupora Aquifer

Layer Number	Groundwater storage Capacity	Storage capacity in Million Cubic Meters (MCM)
Layer one	24 042 419.87m^3	24.04
Layer two	100 678 134.600m^3	100.68
Layer three	12 720 857.08m^3	12.72
Layer four	110 369 670.50m^3	110.40
Total	247 811 082m^3	247.84

Table 5: Hydraulic Parameters

Parameter	Value	Description
HKL1	1E-7 m/day	Hydraulic conductivity of the first layer
HKL2	0.0001 m/day	Hydraulic conductivity of the second layer
HKL3	0.0001 m/day	Hydraulic conductivity of the third layer
HKL4	1E-6 m/day	Hydraulic conductivity of the fourth layer
GHB	0.1331 m^3/day	The general head boundary conductance
RCH	1.2991979E-9 m^3/day	Recharge rate of groundwater
EVT	5.12E-7 m^3/day	Evapotranspiration rate of groundwater

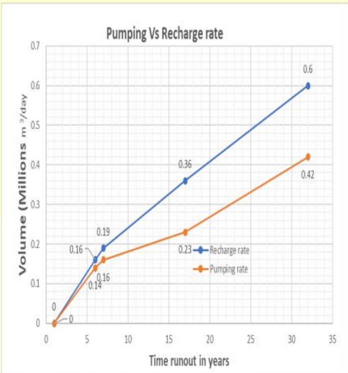

Figure 4: Simulated Pumping Versus Recharge

Table 6: City Population with regard to Water Demand, Existing Water, Deficiency, Simulated and Surplus water

	City Population	Water demand m^3/day	Existing water m^3/day	Deficiency m^3/day	Simulated m^3/day	Surplus m^3/day
2025	689 072	137 584	113 192	-23 992	168857	31273
2026	1 069 900	160 730	113 192	-47 138	197760	37030
2036	713 794	226 204	113 192	-113 012	360000	133796
2051	1 972 968	418 839	113 192	-305 247	600430	181591

4. Conclusion

- The relocation of Tanzania government offices from Dar es Salaam to Dodoma has led to a surge increase in population, resulting in overexploitation of water in the Makutupora aquifer.
- Now the simulated artificial recharge resulted to increase of recharge from 168 857 m^3/day to 600 430 m^3/day.
- The estimated storage capacity was 247.8 Million Cubic Meters (MCM), hence, able to receive the recharge.
- The general hydrostratigraphic unit indicated that the topmost layer is dominated by clay soil which goes up to 40m where sandy soil is found.
- The clay in the top layer with a low infiltration capacity of about 5mm/hour results in water infiltration to sand for a long time, like 11 months.

5. Recommendations

- The recommended artificial recharge is the construction of some wells that can inject the water that flows at the time of rainfall, especially using the Kinyasungwe river.
- Therefore, engineers are advised to construct structures with at least a depth of 40m so as the water can reach the aquifer quickly
- The future study needs to consider the calculation of the new crop coefficient value rather than adopting 0.7 value value that was used by Rwebugisa for better results. Also the geology and aquifer type were also complex to determine due to their differences from one place to another. Hence, a need of further studies
- Furthermore, due to time limit, the study did not consider the costs of artificial recharge like cost benefit analysis. Hence, a need of further study in Makutapora

6. Funding

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