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Effect of Recharge and Abstraction on Groundwater Levels

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Abstract

Groundwater constitutes 99% of all liquid freshwater globally that is available for human use. Groundwater levels in the Nairobi aquifer system (NAS) have been declining over time because of excessive abstraction fueled by increased water demand. This has increased the cost of pumping and drilling boreholes, which is unsustainable. The objective of this study is to determine the effect of recharge and abstraction on groundwater levels using a more realistic approach by estimating recharge using the SWAT model while considering climatic data, soil type, land use/cover, and topography. Recharge obtained from SWAT was applied in MODFLOW to model the groundwater system. Results showed that the average annual recharge was 73 mm, which is about 9.7% of the precipitation. Groundwater levels decreased with an increase in abstraction and a decrease in recharge and vice versa. Groundwater levels will decrease by 76 m by the year 2063 if the abstraction rate is kept constant and the recharge is maintained, and will decrease by 14m by the year 2030 if the trend of abstraction rate continues to increase while recharge is kept constant. The abstraction rate should be regulated according to available recharge and recharge enhanced to avoid possible depletion of groundwater.

Keywords: Recharge; Abstraction; Groundwater; Groundwater Levels; SWAT; MODFLOW.

1. Introduction

Groundwater constitutes 99% of all liquid freshwater globally that is available for human use [1], but rates of groundwater turnover vary widely among and within aquifers [2]. Human development of groundwater resources, including large-scale deployment of irrigation systems, has often led to water imbalances or 'mining' of groundwater, causing a drastic lowering of groundwater levels and associated storage [3]. Groundwater depletion causes negative impacts such as loss or reduction of baseflow; loss of wetland and riparian vegetation; changes in channel morphology; reduced supply of safe drinking and irrigating water; and increased costs of drilling and pumping for long depths [4]. The status of groundwater in the aquifer can be reflected by monitoring groundwater levels [5].

Groundwater is influenced by natural and non-natural factors [6], such as land use/cover, rainfall, recharge, geology, soil type, evaporation, and abstraction [7]. With the increased demand for water fuelled by an increase in the population, an increase in abstraction rates has been witnessed, causing a decline in groundwater levels [8, 9]. An increase in

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urbanization increases the area under built and pavement areas, which reduces recharge and consequently causes a decline in groundwater levels [6]. Rainfall is a major component of recharge and it correlates positively with groundwater levels [10, 7]. The Nairobi Aquifer System (NAS) is a strategic aquifer in which water levels are in a declining state [11]. The aquifer is facing high pressure due to a rapid increase in water demand within the Nairobi Metropolitan area that overlies it as a result of population and economic growth [12]. Most of the rivers within the aquifer area are polluted and thus cannot serve as water supply sources. Therefore, a large percentage of water comes from the Tana basin through inter-basin water transfers and 25% from groundwater, leading to overdependence on the aquifer [13]. As a result of groundwater over-abstraction and a possible reduction in recharge due to reduced rainfall resulting from climate change and increased paved areas [12, 14], groundwater levels have been declining over the years by between 6.6 to 13m per decade as observed in most monitoring boreholes within the aquifer [11, 15, and 16]. This groundwater level decline has increased the cost of drilling boreholes because water is struck at a deeper depth and has increased pumping costs with increased pumping head. This also increases the risk of groundwater depletion, which may lead to water shortages and land subsidence due to groundwater mining if management measures are not put in place [17, 18].

Various studies to determine the effect of groundwater recharge and abstraction on groundwater levels have been conducted. The fluctuation of groundwater levels and recharge patterns were studied in Northern Ghana where recharge was estimated using the Water Table Fluctuation Method (WTF). The results showed that groundwater levels increased in response to increased precipitation. Aguilera et al. and Wilopo et al. studied the impact of precipitation and land use on groundwater levels using trend analysis in Indonesia [5, 7]. Results showed that groundwater levels increased with an increase in precipitation and decreased with an increase in built areas. These results agreed well with another study done by Prajapati et al. in the Kathmandu valley, Nepal [10]. A similar study in Bangkok, Thailand by Ghimire et al. showed that as recharge decreased with an increase in urbanization, causing groundwater levels to decline while recharge remained high in low urbanized areas [6]. According to a study by Lam et al. in Vietnam, a decrease in rainfall decreased recharge and groundwater levels [9]. A study in the Vietnamese Mekong Delta by Duy et al. found that an increase in abstraction rates led to a decline in groundwater levels [8].

Limited studies to determine the effect of groundwater recharge and abstraction on groundwater levels have been conducted on the Nairobi Aquifer System. Oiro et al. studied the depletion of groundwater resources under rapid urbanization in Africa with a case study of NAS using MODFLOW and a recharge value of 5% of precipitation was adopted in this study [15]. However, recharge being a crucial factor that influences groundwater levels, the existing studies have not focused on a more realistic approach of estimating recharge considering climatic factors, topography, soil type, and land use/cover type to give a more accurate value.

This study seeks to fill this gap by using the SWAT model to estimate recharge and coupling it loosely with the MODFLOW model to determine the effect of groundwater recharge and abstraction on groundwater levels. The SWAT model has been used to estimate groundwater recharge in various places, such as BJC Australia, where it provided an alternative to point scale modeling and spatial recharge distribution [19]; India in the lower Chenab canal [20]; Ghana in the Volta river basin, annual recharge was estimated to be 8% of the annual rainfall [21]; central Kuwait [19, 22] and Australia [23]. The model has proved to be reliable and handy in the estimation of groundwater recharge.

2. Materials and Methods

2.1. Study Area

NAS covers an area of approximately 6,500 m^2, and underlies much of the Nairobi metropolitan area. It is a complex multi-layered volcanic/volcano-classic aquifer system, recharged along the eastern edge of the Rift Valley with groundwater moving toward the east. The principal aquifer unit, the Upper Athi series, is entirely confined, and with depths ranging from 120 to 300 m below ground level. Aquifer transmissivity ranges from 0.1 to 160 m^2/d, hydraulic conductivities from 0.01 to 1.3 m/d and storage coefficients from 1.2×10^{-4} to 4.2×10^{-1} [24].

NAS lies within the Athi catchment area of Kenya which is one of Kenya's five river basins [25]. It encompasses the counties of Nairobi, Kiambu, Kajiado, and Machakos (Figure 1). It extends from 0°37‘ 58"‘ to 1°59‘ 23"S and from 36°34‘ 27"‘ to 37°28‘ 17"‘E [16] with an altitude ranging from1400m to 2600 m above mean sea level (a.s.l.).

NAS area experiences a subtropical highland climate with June and July as the coldest months sometimes with temperatures as low as 10°C. The area experiences a bimodal rainfall pattern, with the highest rainfall occurring in March-May and November-December, with a mean annual rainfall of 1050 mm. Annual average humidity ranges from 60 to 84%, with higher percentages occurring during seasons of heavy rainfall. Flooding occurs during the wet season, particularly within residential areas and lowland plains [16]. Research methodology is summarized in a flowchart in Figure 2.

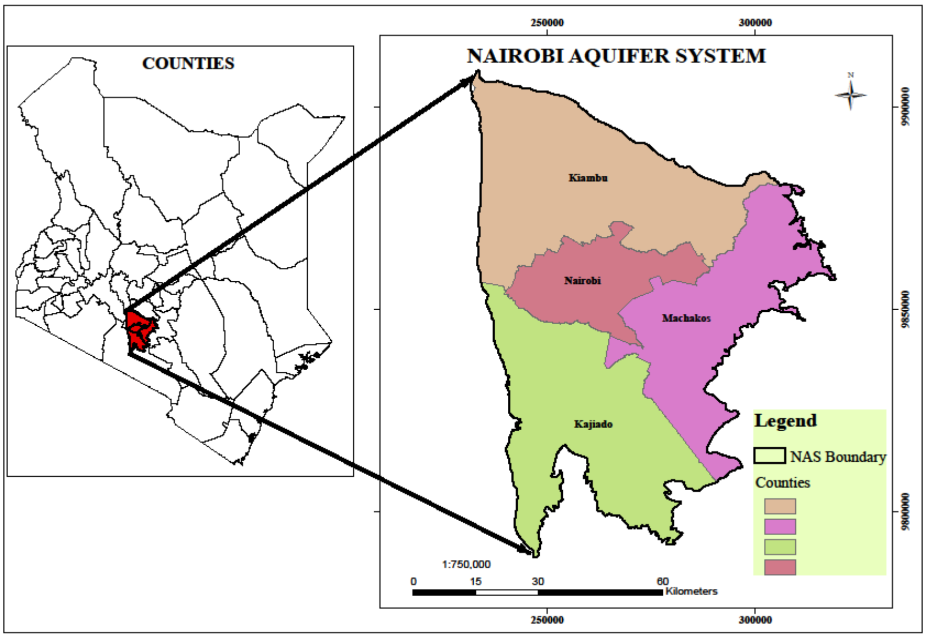

Figure 1. Map of Nairobi Aquifer System (NAS)

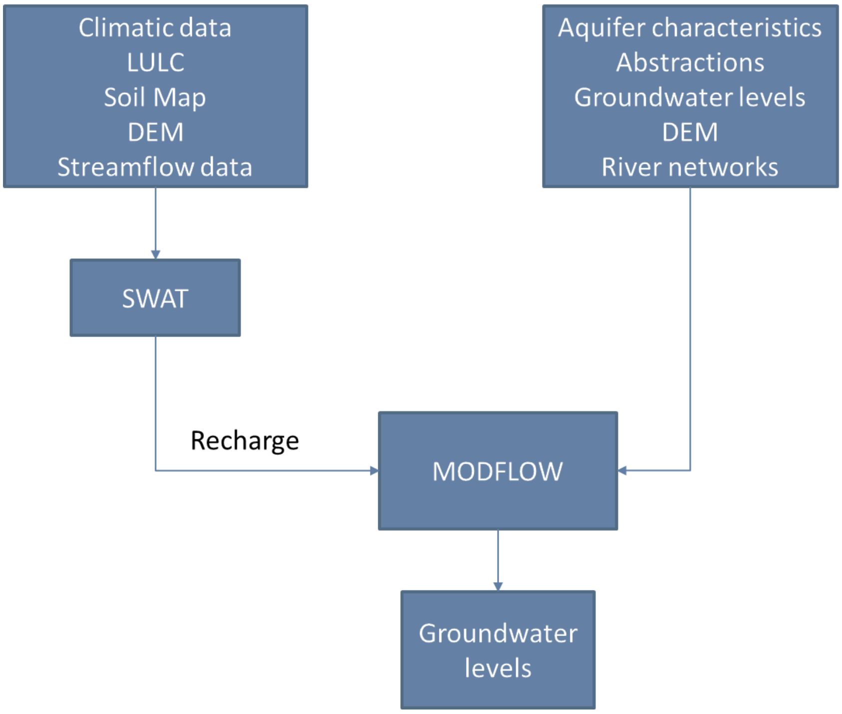

Figure 2. Research Methodology Flowchart

2.2. Model Set-up

Soil Water Assessment Tool (SWAT) model (version 2012) was used in this study. SWAT is a hydrologic, semi-distributed, comprehensive, and physically-based model able to model surface and sub-surface flow of water and operates on the water balance equation as its principle equation. The model was developed by the United States Department of Agriculture–Agricultural Research Service (USDA–ARS) for predicting the impact of land management practices on water, sediment, and agricultural chemical yields [26]. The equation states that water stored in the system is equal to the difference between inflow and outflow (Equation 1).

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}\right) \quad (1)$$

where SW_t is the final soil water content (mm water), SWo is the initial soil water content on the day i (mm water), t is the time (days), R_{day} is the amount of precipitation on the day i (mm water), Q_{surf} is the amount of surface runoff the on day i (mm water), Ea is the amount of evapotranspiration on day i (mm water), W_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm water), and Q_{gw} is the amount of return flow on day i (mm water) [26].

The water balance equation in SWAT based on the hydrologic cycle was used to estimate recharge which was to be used by the recharge and River packages of MODFLOW [27]. The set-up involved input data preparation in SWAT acceptable format as shown in Table 1; the watershed was delineated into 37 sub-basins and 233 HRUS using a filter of 10% for both land-use and soils; sensitivity analysis; calibration; validation and results visualization The main outlet was identified as Athi Munyu River station 3DA02 with coordinates -1.093860°S and 37.194940°E whose discharge was used for calibration and validation.

Table 1. SWAT Input Data

S/No.	Data	Characteristics	Source
1.	Digital Elevation Model (DEM)	30 m resolution	*https://search.asf.alaska.edu/#/?dataset=ALOS*
2.	Land use / Land cover map	2012	*https://opendata.rcmrd.org/datasets/kenya-sentinel2-lulc-2016*
3.	Soils map	2004	KEN-SOTER
4.	River network	Shape file	Water Resources Authority
5.	Discharge output point	Shape file	Prepared from Water Resources Authority data
6.	Climate	Satellite (1988-2020)	Climate Hazards Group Infra-Red Precipitation with Station data (CHIRPS)
7.	River discharge	Observed (1981-2019)	Water Resources Authority

Land use/Cover map for the year 2012 was downloaded as shown in Figure 3

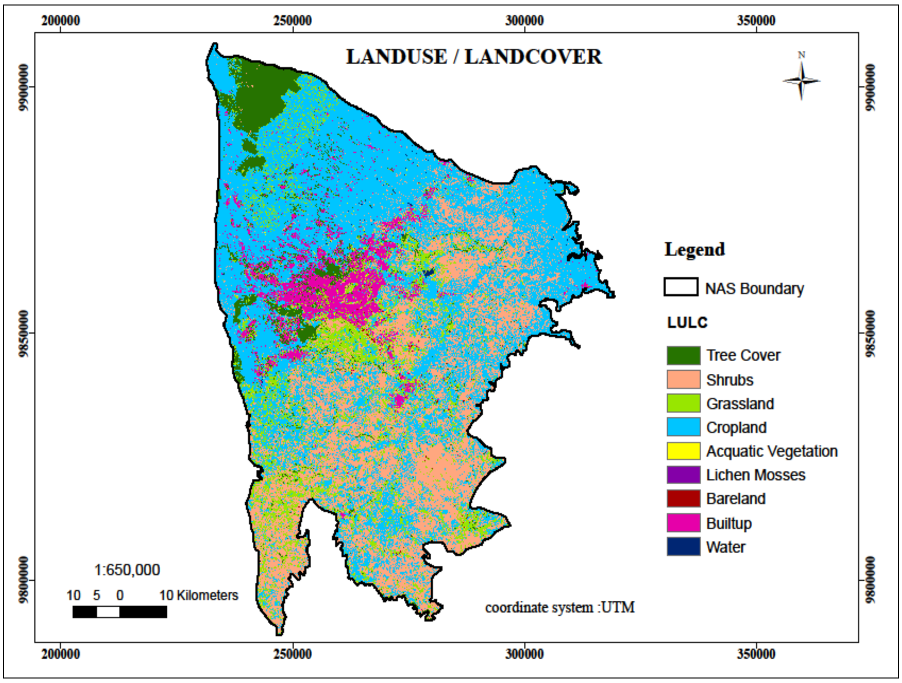

Figure 3. Land use/cover map for NAS

The land use classes were converted to SWAT a code which was later defined in the land-use look-up table shown in Table 2. The predominant land use in NAS is agriculture (47.24 %) followed by shrubland at 26.96%. Barren and swampy lands form small portions of the land at 0.20 and 0.11% respectively. Built up area comprises of 6.78% which is a significant portion in terms of groundwater recharge as it impedes groundwater recharge.

Table 2. Land-use/Cover Classes and Percentage Coverage in NAS

Value	Actual Land Use/Cover classes	Swat land Use/Cover Classes	Swat Code	% Watershed Area
1	Forest	Mixed forest	FRST	6.92
2	Shrub land	Shrub land	RNGB	26.96
4	Agricultural land	Agriculture land	AGRR	47.24
5	Swampy land	Wetland	WETF	0.11
6	Woodland	Range	RNGE	11.67
7	Barren land	Strip mines	SWRN	0.20
8	Built-up areas	Urban High Density	URHD	6.78
10	Water	Open water	WATR	0.13

A Digital Elevation Model (DEM) of 30 m resolution was downloaded as shown in Figure 4.

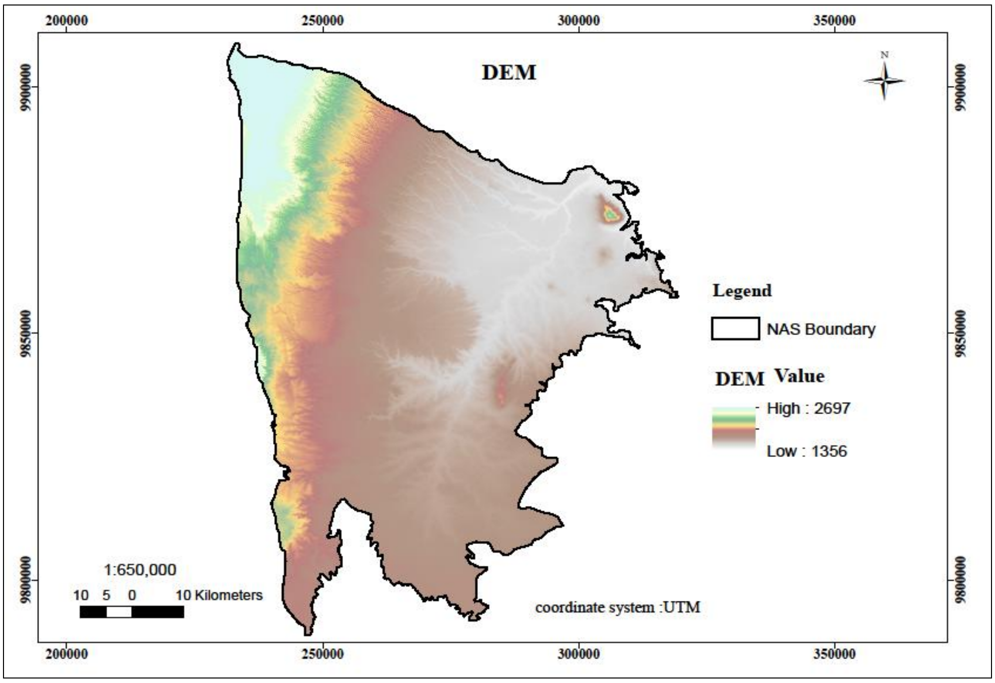

Figure 4. Digital Elevation Model (DEM)

Soil map was obtained from the soil and Terrain database for Kenya (KENSOTER) of classification International Soil Reference and Information Centre (ISRIC) showing classes as per Figure 5. The data contains soil physical and chemical properties such as depth of horizon, soil texture bulk density, organic carbon, water-holding capacity, number of soil layers among others [28]. The data was used to generate the soils look-up Table and the user soil Table for model development.

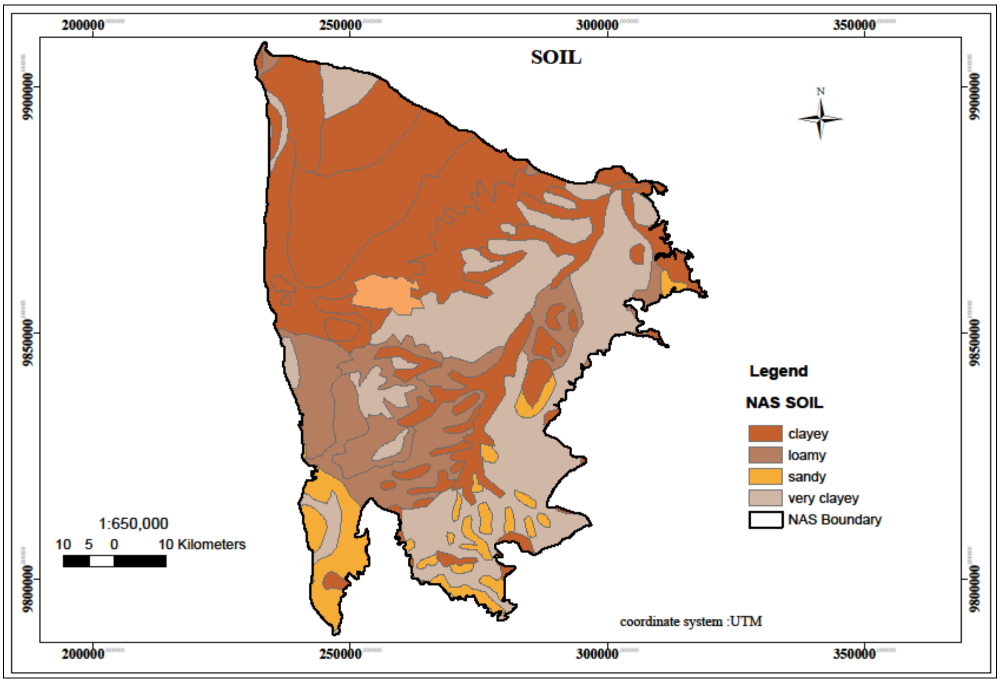

Figure 5. Soil map for NAS

The study utilized Climate Hazards Group Infra-Red Precipitation with Station data (CHIRPS) datasets as an alternative to conventionally available climate datasets. This was because there was limited availability of precipitation data and that available had substantial gaps. From the CHIRPS website daily, tiff files were downloaded for the years 1988 to 2020. Using a script in Rand R-studio software, daily precipitation data for a total of 23 stations selected to ensure spatial distribution within the study area is achieved was generated as shown in Figure 6.

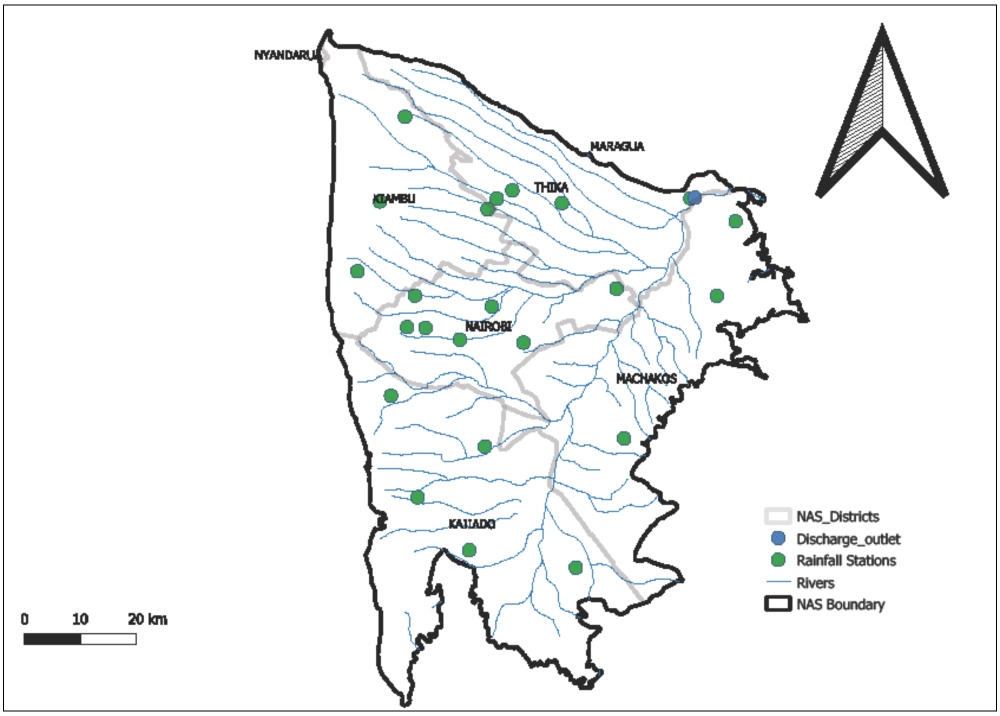

Figure 6. Rainfall stations

Groundwater model was constructed using MODFLOW (Model muse) which is a numerical fully- distributed three dimensional groundwater model which uses a block-centered approach and a modular structure consisting of a main program and a series of subroutines that are grouped into packages. It uses finite-difference method to solve a partial differential equation of the three-dimensional groundwater flow. Equation 2 is the governing equation solved by MODFLOW [29].

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \tag{2}$$

where, K_{xx}, K_{yy}, K_{zz} are hydraulic conductivity in the x, y and z direction; W is volumetric source/sink, S_s is specific storage.

A grid size of 2050 m was chosen to divide the study area into grids. Aquifer thickness of 400 m below the ground level was modeled since this is the maximum depth of most boreholes within the study area [15] and the aquifer was assumed to be a single layer. The boundary and Digital Elevation Model (DEM) shapefiles were imported into the software. Aquifer characteristics such as hydraulic conductivity, specific storage and specific yield were obtained from [17]. A no flow boundary condition was taken around the study area because the area falls on a regional divide except on the north-eastern side where the boundary condition was specified head towards the outflow of the river. The drain boundary conditions were defined in all river networks to assist in establishing whether the rivers are gaining from or losing to groundwater. Recharge boundary condition was defined to be uniform over the study area and was taken to be 73.05mm/year as obtained from the SWAT model. Wells boundary condition was also defined by importing a total of 9196 boreholes obtained from WRA as shown in Figure 7. Observation head boundary condition was defined using Observation head package on a sample size of 100 observed boreholes determined using Yamane's formula as shown in Equation 3.

$$n=\frac{N}{1+N(e^2)}$$

$$n=\frac{9196}{1+9196(0.1^2)} \tag{3}$$

where; n is 98.9 which was approximated to 100 boreholes, where; n = Sample size, e = error limit (0.1), N = population size, [30].

Abstraction rates was calculated using the number of borehole per year data for the years 1988-2020 obtained from WRA and the standard yield applied for in the groundwater abstraction permit application by borehole owners taken as 20 m^3/day [15]. For scenario analysis the abstraction rate was projected using the rate of increase of borehole numbers.

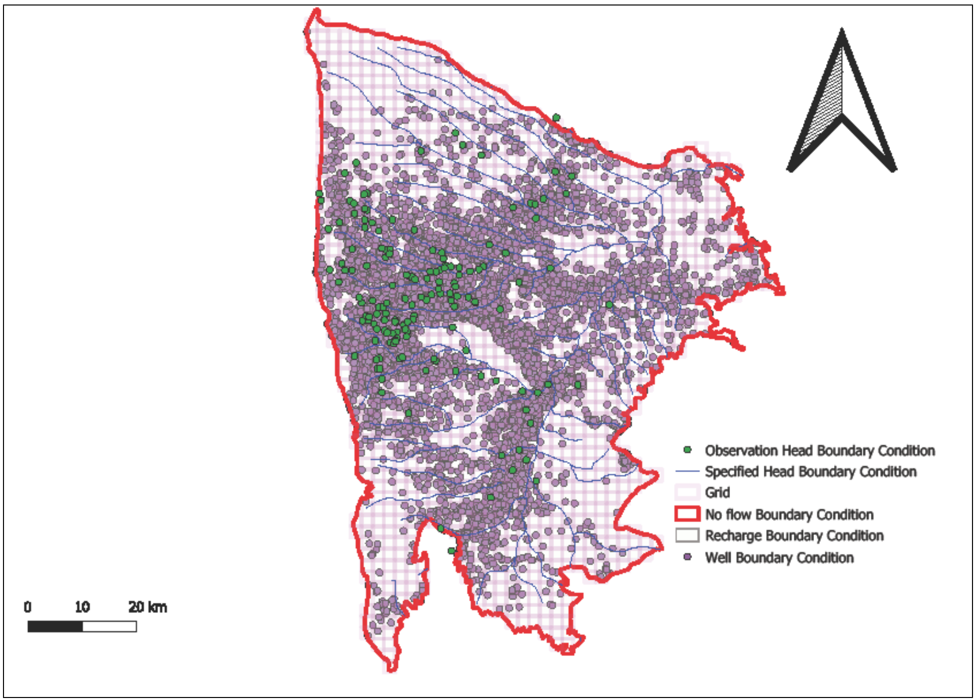

Figure 7. MODFLOW Solution with boundary conditions

2.3. Model Calibration and Validation

Sensitivity analysis was done in SWAT cup software using the sequential uncertainty fitting algorithm (SUFI-2). The algorithm accounts for different uncertainties that may arise from model conceptualization, parameters, and observed data [31]. Data for the period 2005-2011 was used for calibration while that for 2013-2016 was used for validation. Selected SWAT parameters that influence recharge and runoff in the order of their sensitivity were calibrated shown in Table 3.

Table 3. Calibrated SWAT parameters

S/No	Input Parameter	Description of Parameter	Min & Max Range
1.	GW_DELAY.gw	Groundwater delay (days)	0 - 500
2.	RCHARG_DP.gw	Deep aquifer percolation fraction	0 - 1
3.	SOL_AWC.sol	Available water capacity of the soil layer(mm H_2O /mm soil)	0 - 1
4.	ESCO.bsn	Plant uptake compensation factor	0 - 1
5.	GW_REVAP.gw	Groundwater "revap" coefficient	0.02 -0.2
6	ALPHA_BF.gw	Base flow alpha factor (days)	0 - 1
7.	GW_QMN.gw	Threshold depth of water in the shallow aquifer required for return in mm	0-5000
8.	CN2.mgt	SCS runoff curve number	35 - 98
9.	REVAP_MN.gw	Threshold depth of water in the shallow aquifer for "revap" to occur (mm)	0 - 500
10	SURLAG.bsn	Surface runoff lag time (days)	0.05 - 24

Streamflow data was divided into three sets; 2003 to 2004 was used as a warm-up, 2005-2011 was used for calibration and 2013-2016 was used for validation. The periods were selected based on available data quality. Monthly discharge data was formatted into swat-cup format; swat model was input into swat-cup and 200 simulations were run, the new parameters were obtained were then input back in the next iteration until the best objective function of NSE and R^2 was obtained. MODFLOW Calibration and validation were done using 60 and 40% of the observed groundwater levels data respectively. Manual calibration was done by adjusting hydraulic conductivity between the 0.010368 m/day and 1.296 m/day given by Foster et al. [24] to obtain a perfect match between observed and simulated values. During the steady-state condition, initial conditions of the hydraulic head were introduced by running the model without abstraction rates. Evaluation of model performance was done by considering the Nash–Sutcliffe efficiency (NSE) and correlation coefficient R^2. The closer the R^2 and NSE are to 1, the closer the estimated values are to the observed values.

2.4. Scenario Analysis

Two scenarios were analyzed using the calibrated and validated model as follows: With the present increasing trend of groundwater abstraction in NAS because of increasing water demand, the model was run to predict groundwater levels by 2030 as a way of checking Vision 2030 achievement. One of the sustainable development goals (SDG) is clean water and sanitation envisaged as goal 6, which seeks to substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity by 2030 [32]. The scenario explains the condition of the groundwater level by the year 2030 if no management interventions are made.

Assuming the Inter-basin water transfer is able to meet the water demands in NAS and the current abstraction rate is kept constant. With the increasing urbanization, the built-up areas land use/cover is expected to increase and consequently decrease recharge rates irrespective of the projected increase of rainfall amounts caused by climate change [33]. With a 6% decrease in recharge in two decades due to land-use changes in Nairobi according to the findings of Aghsaei et al. [34], the model was run on the scenario of reduced recharge to predict groundwater levels by 2063 to check the achievement of goal number 7 of Agenda 2063 of "the Africa we want "under the water security and climate change impact situation. The agenda focuses on environmentally sustainable and climate-resilient economies and communities, under the priority of water security [35].

3. Results and Discussions

3.1. Calibration and Validation of SWAT Model

SWAT calibration and validation results using monthly stream discharge for the period 2005 to 2011 and 2013 to 2014 was as shown in Figures 8 and 9. For calibration, R^2 and NSE objective functions were found to be 0.63 and 0.62 respectively while for validation R^2 and NSE was 0.64 and 0.63 respectively which showed that the model was satisfactory according to Moriasi et al. [36]. From the water balance equation 1, the SWAT model obtained showed recharge parameter to be 9.7%; surface runoff 35.4%; evapotranspiration was 53.7% and change in soil water content was 1.2% of the precipitation amount. Recharge portion was higher than 5% used by Oiro et al. [15].

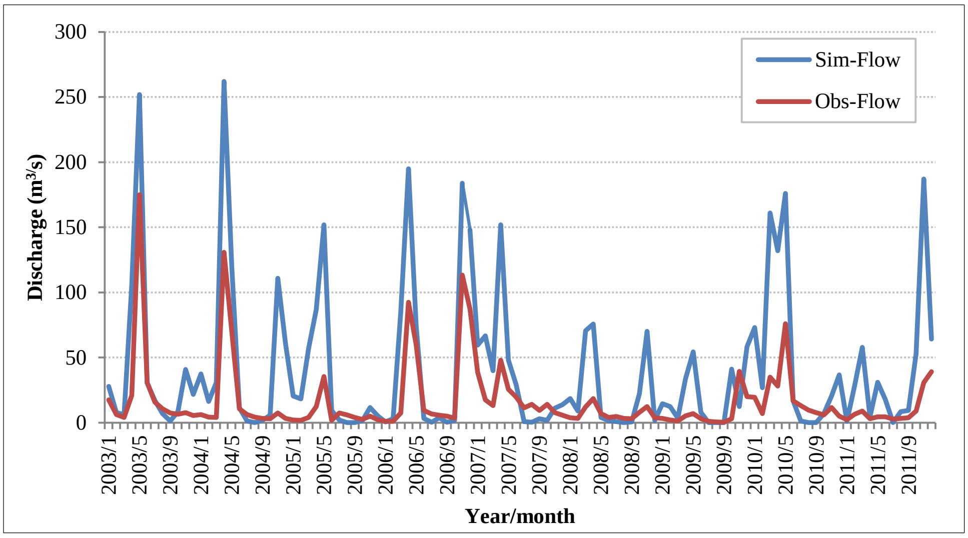

Figure 8. SWAT Calibration graph

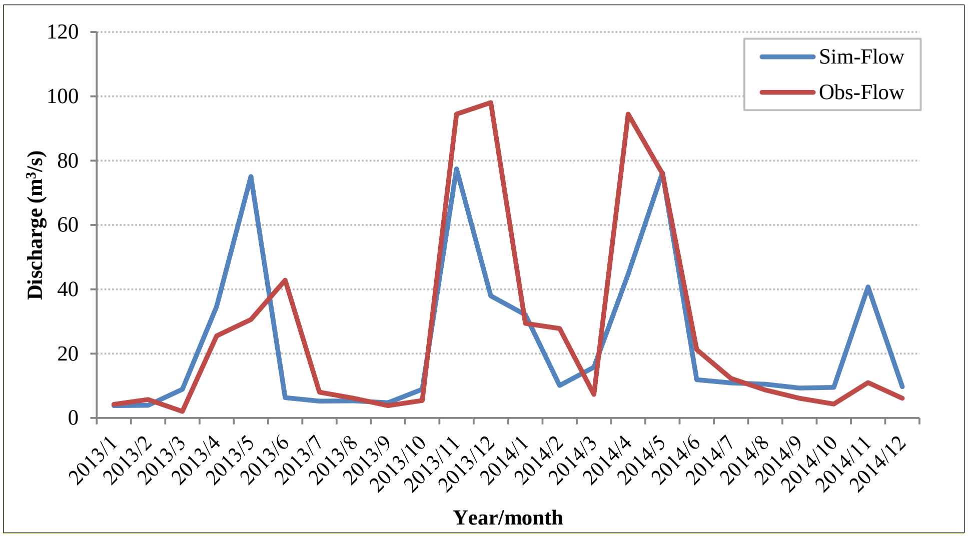

Figure 9. SWAT Validation graph

MODFLOW results showed an R^2 of 0.6517 for calibration and 0.5752 for validation showing the model performance was satisfactory [36] as shown in Figures 10 and 11.

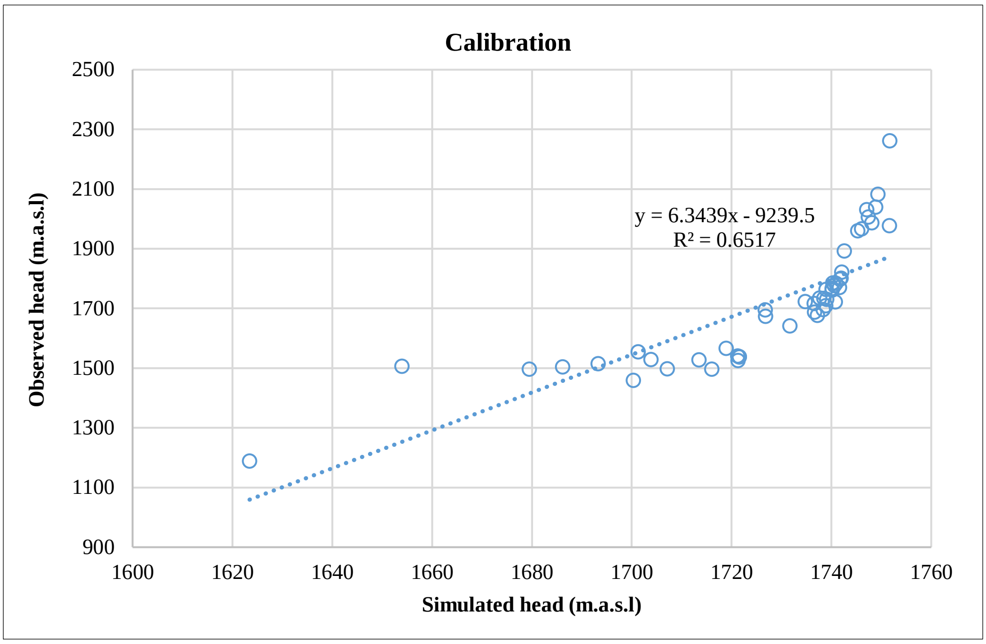

Figure 10. MODFLOW Calibration Graph

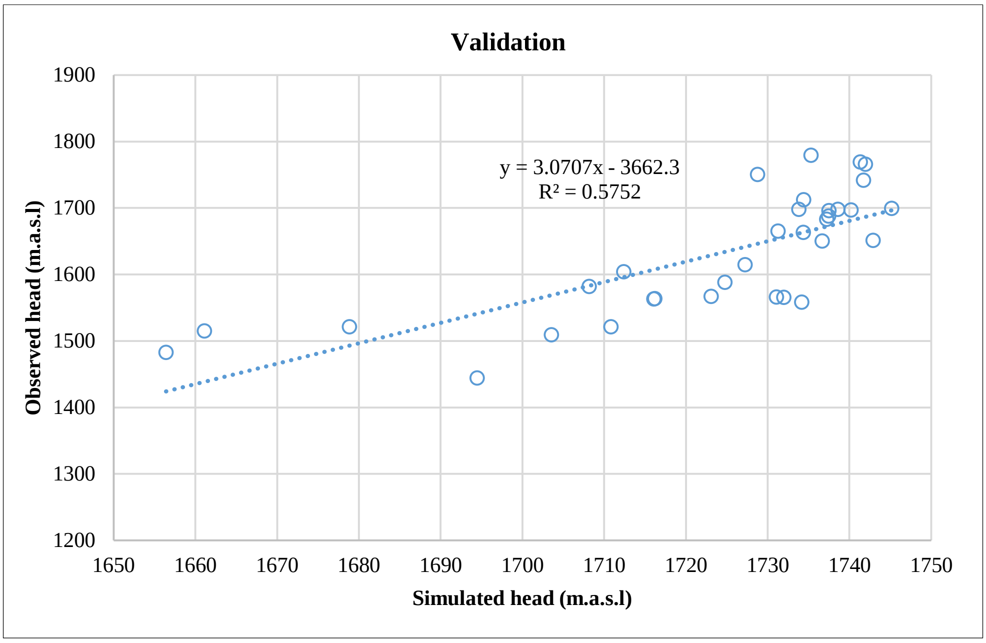

Figure 11. MODFLOW Validation Graph

3.2. Spatial and Temporal Distribution of Rainfall and Recharge

Spatial distribution of rainfall in NAS indicated that the average annual mean rainfall ranged from 550 mm in the south East parts of the study area which lies within Kajiado County and which is classified under the arid and semi-arid (ASAL) region to 934 mm northwards to the highlands of Kiambu and Thika as shown in Figure 12. Rainfall amounts are influenced by topography whereby highland areas seem to receive more rainfall. This agrees with the findings of Prajapati et al. [10].

Mean annual recharge ranged from 10-109 mm as shown in Figure 13. The southern part of the study area, showed relatively higher recharge rates compared to Nairobi region despite the fact the rainfall amounts are lower. This can be attributed to land cover which is a rangeland and sandy loamy soil which allows infiltration of rainwater to recharge the ground. Parts of Nairobi, Kiambu and Kajiado especially urban areas have low amounts of annual recharge (0-10mm) in spite of receiving relatively higher annual rainfall amounts of 607 to 934 mm. This is also attributed to paved areas which allow no infiltration of rain water to form recharge and instead generates more runoff. The Northern part of the study area has relatively low annual amounts of recharge apart from sub-basin 1 which is in forest land contrary to the fact that it receives high amounts of rainfall of 934 mm in the region. This low recharge in the northern part can be attributed to land use practice which is agriculture that encourages more runoff than infiltration. This shows that indeed land use/cover and rainfall amounts greatly influence the amount of groundwater recharge which agrees well with the findings of Ghimire et al. and Lam et al. [6, 9].

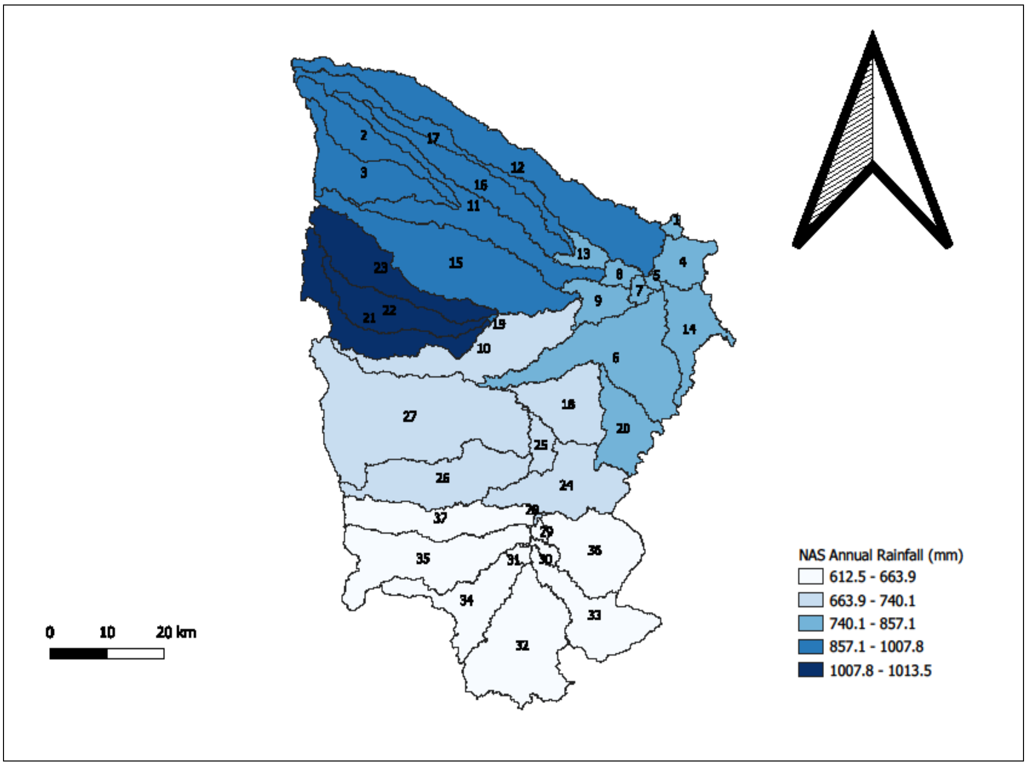

Figure 12. Rainfall Spatial distribution in NAS

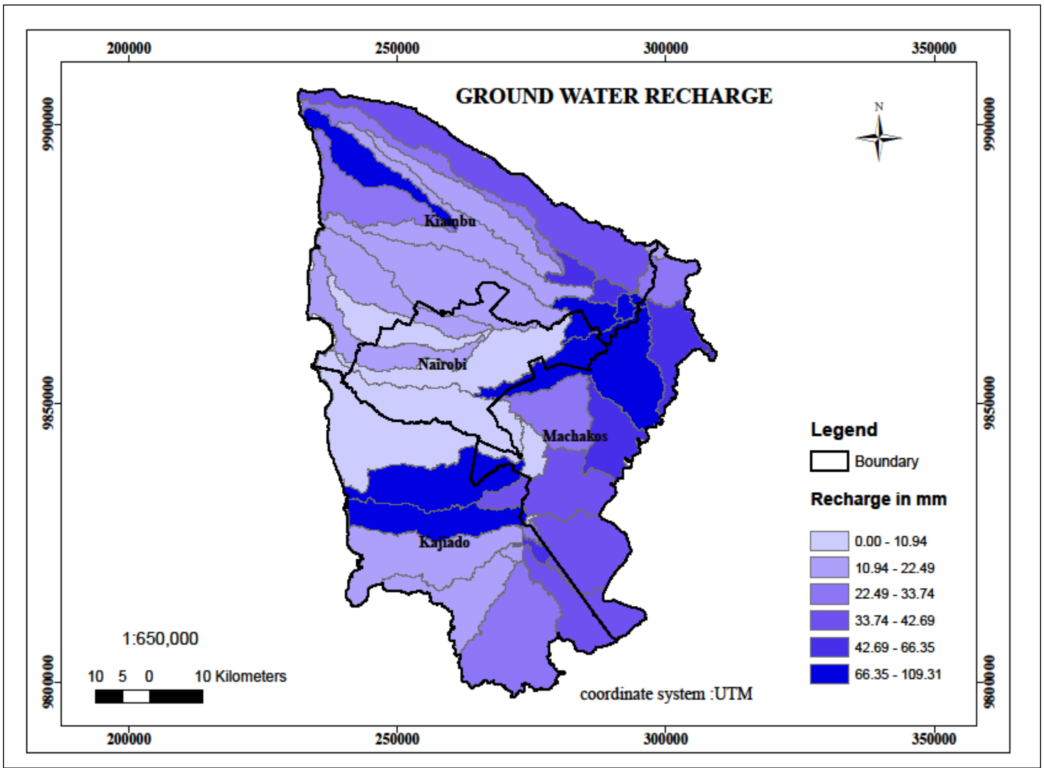

Figure 13. Spatial distribution of Recharge in NAS

Results showed that the average annual recharge rate NAS was 9.7 % of precipitation (73.05 mm) which was slightly above 57.04 mm/year recharge value estimated by JICA [37]; 52.5 mm/year estimated by Oiro et al. [15]. However the recharge estimate of 16.8mm/year given by Tuinhof et al. [38] was perceived to be too low.

The temporal variation of average annual recharge over the study area showed the highest value of 195 mm in the year 1999 and the lowest of 41mm in 2000 as shown in Figure 14. The highest amount of rainfall was above 1200 mm in 2018 while the lowest was about 500 mm in 2000 which corresponds well with recharge. Most of the recharge peaks occur during the wet months of the year such as March to May and October to December. This is associated with infiltration of the rainwater while during the dry periods recharge is low. High recharge amounts were witnessed at times of high rainfall amounts and vice versa. This implies that rainfall is a major component of recharge and influences recharge amount to a greater extent. This confirms the findings of Lam et al. [9]. The amount of recharge is not as high in 2018 as in 1999 as it could be expected in spite of the amount of rainfall is high. This implies that the decrease in recharge could be caused by an increase in pavement and built area in NAS from 1999 to 2018 due to increased urbanization. On the other hand, the previous years of 1997 and 1998 had relatively high amounts of rains consecutively leading to high recharge amounts in 1999.

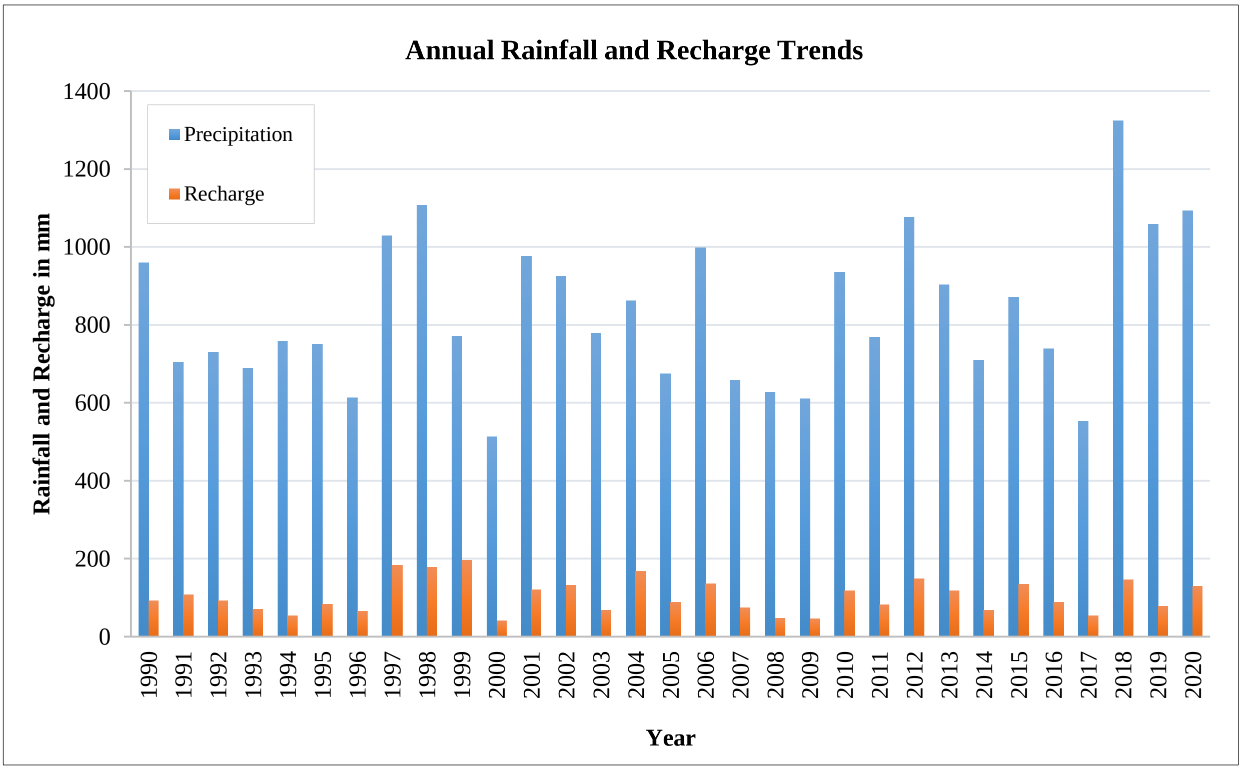

Figure 14. Temporal distribution of Rainfall and Recharge in NAS

3.3. Groundwater Levels of NAS 2020

Groundwater level contours developed from the model showed that they majorly follow the topography of the area which agrees well with Mutua et al. [39]. The western part of the study area showed high water levels of between 1706 m and 1791 m above sea level which can be attributed to its higher elevation, high rainfall amounts that lead to high recharge rates as compared to the eastern part where it ranged from 1386 to 1647 meters above sea level as shown in Figure 15. This is because of the impact of groundwater flow whereby groundwater flows from a high head zone to a low head zone. Recharge from the western high areas of the study area flows eastwards towards the low areas. This implies that the groundwater is likely to interact with the surface water as it flows from the west to the lower eastern part of the study area which agrees well with research findings by Oiro et al. [15].

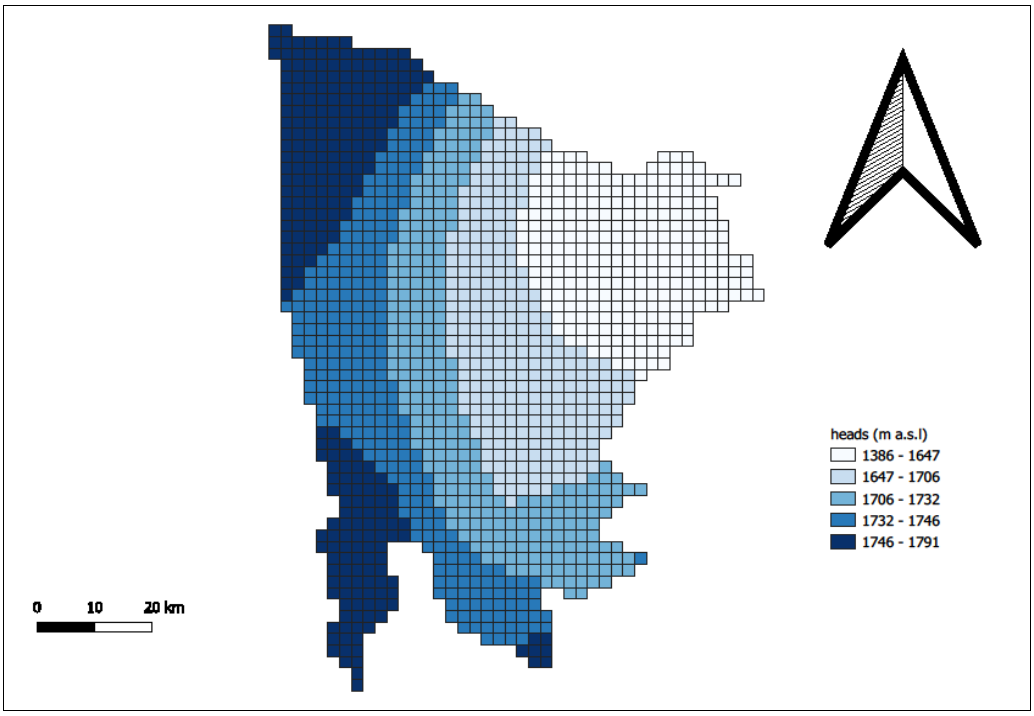

Figure 15. Groundwater levels contours in NAS

3.4. Scenario Analysis

In the first scenario, if the current trend of abstraction continues, while the recharge rate is kept constant, the model predicted that by the year 2030 groundwater levels will decrease by an average of 16m which is 1.6m per year as shown in Figure 16. Therefore, groundwater levels decrease with an increase in abstraction rates which agrees with the findings of Lancia et al. [40]. This implies that borehole depths will increase as groundwater levels decline, to which in turn will increase the cost of drilling and pumping, and finally increase the risk of depletion. With the rapid increase of population in NAS, the water demand is increasing leading to more drilling of boreholes. Areas with a dense population of boreholes are likely to experience this scenario of a decrease in groundwater levels if no intervention measures will be put in place. Therefore, by 2030 if the current trend continues then sustainable withdrawals will not have been achieved according to SDG goal number 6 since there will be a decline in groundwater levels indicating depletion of groundwater resources.

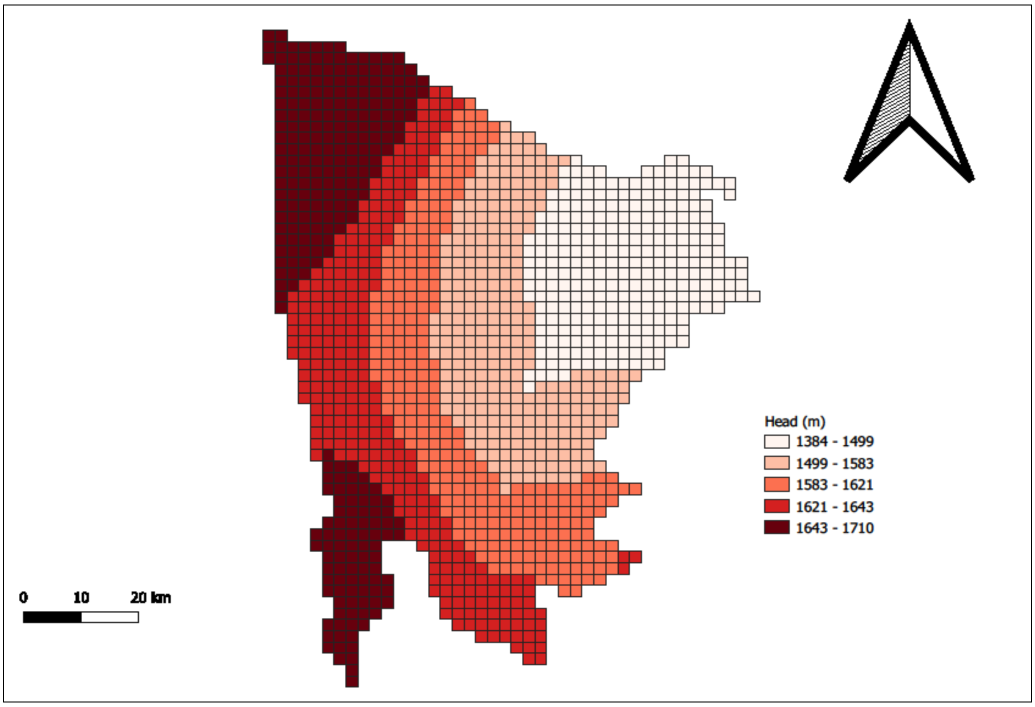

Figure 16. Groundwater levels contour with an increase in Abstraction rate in NAS

In the second scenario, the model was run for the entire period until the year 2063 (43 years), decreasing recharge by 6% according to the findings of Aghsaei et al. [34], while the abstraction rate was kept constant. The model showed that the groundwater levels will decrease by an average of 76m by 2063 if recharge decreases by 6% in two decades because of an increase in urbanization as shown in Figure 17. This means that built-up areas will experience a decline in groundwater levels even if the rainfall amounts increase, consequently increasing drilling and pumping costs and, in the worst-case scenario, decreased yield and depletion. This is because the amount of infiltration of rainwater into the aquifer is hampered by the land use/cover type. Therefore, changes in groundwater levels were influenced by recharge only, which showed a decreasing trend attributed to the increase in urbanization as built-up areas increased despite the projected increase in rainfall due to the effect of climate change. This research findings agreed well with the findings of Duy et al. and Akurugun et al. [8, 41], which shows recharge decrease with increase in urbanization and vice versa.

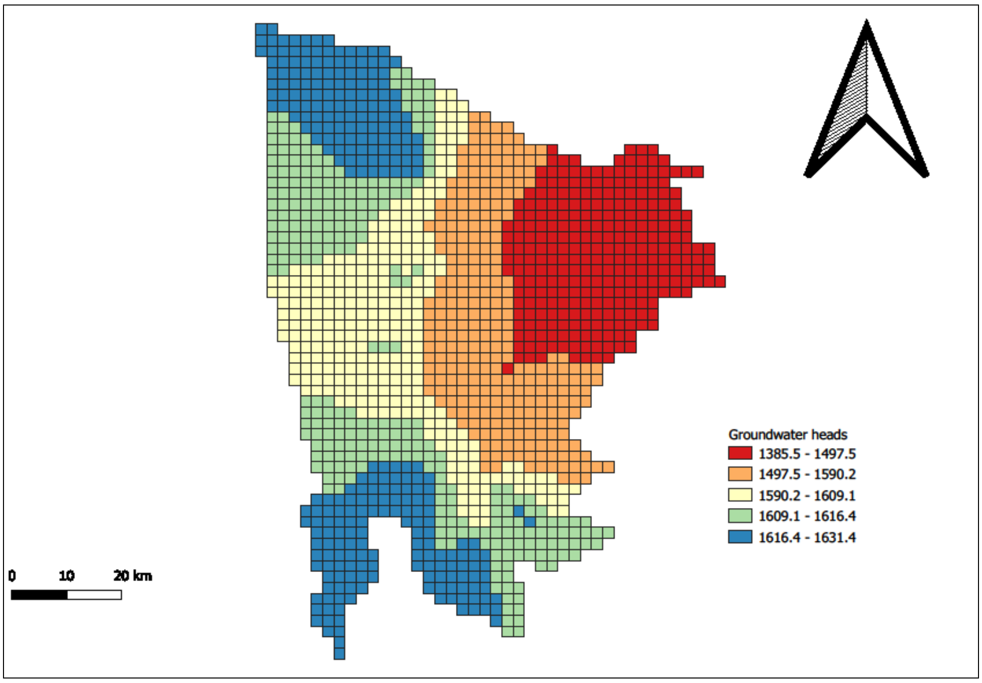

Figure 17. Groundwater levels contours with a decrease in recharge in NAS

4. Conclusions and Recommendations

The study estimated recharge using the SWAT model, which was used as input data to the MODFLOW model in the construction of a groundwater model to determine the effect of recharge and abstraction on groundwater levels. Abstraction rate data was obtained from WRA. Other input data included DEM, soil maps, land use/cover maps, and climatic data.

The average annual recharge for the Nairobi aquifer system area was estimated to be 9.7% of precipitation, which is 73 mm, with the highest of 109 mm per year using the SWAT model. There was a positive correlation when comparing the trends of rainfall and recharge, which showed that recharge increased with an increase in rainfall and decreased with a decrease in rainfall. Spatially, areas with built and pavement areas showed low recharge rates of up to 10 mm per year, while forested areas showed high recharge rates of 109 mm per year. Pavements sealed the areas, preventing the infiltration of rainwater, thus reducing recharge, while forests and rangeland increased the infiltration of rainwater, enhancing the recharge.

Results showed that groundwater levels followed the topography of the area where highlands had higher groundwater levels, which decreased towards the low areas. This was attributed to the effect of groundwater flow whereby water flows from higher to lower elevations. Scenario analysis findings showed that groundwater levels will decrease by 76 m by the year 2063, which is a span of 43 years if the recharge rate decreases as the abstraction rate was kept constant. With the intervention of inter-basin water transfer from the Tana catchment, pressure on groundwater abstraction will ease, thus maintaining the current abstraction rate. However, if the rate of urbanization continues to increase, the built areas and pavement recharge will decrease by 6% per decade. This implied that groundwater levels decreased with a decrease in recharge and vice versa. On the other hand, groundwater levels decreased by 16 m by the year 2030 while the abstraction rate trend continued in a span of 10 years as the recharge rate was kept constant. The rapid increase in the population in NAS triggered the increase in water demand and, consequently, groundwater abstraction if there is no other alternative source of water. The results implied that an increase in abstraction rates causes a decrease in groundwater levels and vice versa in NAS.

Therefore, to avoid a decline in groundwater levels and consequent depletion of the resource, it is recommended that recharge be enhanced to ensure that groundwater levels rise. The abstraction rate should also be regulated in line with available recharge through the adoption of alternative water sources such as the continuing inter-basin water transfer where possible.

The study presents a more realistic approach to estimating recharge value using the SWAT model since factors that influence recharge were considered, such as climatic factors, land-use/cover, soil type, and topography, and later coupled loosely with a numerical model (MODFLOW) to analyze groundwater level dynamics. These findings can be used by water resources managers and other stakeholders to guide regulations on sustainable utilization of groundwater resources to avoid future depletion. Despite the limitations of existing groundwater data, this research gives insights into groundwater dynamics and lays the basis for further research on methods of increasing groundwater monitoring data.

5. Declarations

5.1. Author Contributions

Conceptualization, R.N. and J.M.; methodology, R.N. and M.N.; software, R.M. and J.M.; validation, R.N., J.M. and M.N.; formal analysis, R.N.; investigation, R.N.; resources, R.N.; data curation, R.N.; writing—original draft preparation, R.N.; writing—review and editing, R.N., M.N. and J.M.; visualization, R.N.; supervision, M.N. and J.M.; project administration, R.N.; funding acquisition, J.M. and M.N. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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