

Assessment of Managed Aquifer Recharge System Using Numerical Groundwater Modelling

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ABSTRACT

Managed Aquifer Recharge (MAR) Systems are artificial recharge techniques that enhance groundwater levels and quality. MAR is a sustainable, comprehensive, cost-effective, and environmentally-friendly approach to replenishing aquifers. This study evaluates the application of MAR in Ilorin, North Central Nigeria, where groundwater serves as a critical alternative to the poor municipal water supply system. A numerical groundwater model was developed using FREEWAT to simulate groundwater flow and predict the effects of recharge and abstraction scenarios. In this study, a steady-state multi-layered groundwater flow model was conceptualised, and the numerical model was run over four stress periods, and hydraulic heads were computed. The baseline groundwater flow simulation under steady-state conditions confirmed that groundwater naturally flows from the western boundary toward the eastern boundary, with the river acting as a discharge zone. Raster analyses were performed to determine the changes in the hydraulic heads under various stress conditions. Results of the raster analysis showed that during well abstraction, there is a reduction in the hydraulic head by 13.6m and an increase in the hydraulic head by 16.6m due to recharge by the infiltration basins. The reduction in river leakage outflow indicates that unsustainable pumping could lead to long-term groundwater depletion. Model calibration carried out successfully as the deviations between the computed and the observed head values were insignificant and also as the Root Mean Square Error (RMSE) had a value of about 0.61 m (calibration target within ± 1 m). The study confirms that MAR is a viable solution for groundwater sustainability in Ilorin. When combined with controlled well abstraction, MAR can enhance water availability, reduce aquifer stress, and support Sustainable Development Goal 6 (SDG 6) on clean water and sanitation.

Keywords: Groundwater Sustainability, Managed Aquifer Recharge, Groundwater Depletion, Artificial Recharge, Ilorin.

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I. Introduction

Groundwater is the world's largest freshwater resource [1]. Groundwater contributes half of the human drinking water supply and more than 40% of water used for irrigation globally [2]. Surface water can contain high amounts of contaminants, which require rigorous treatment before being supplied to the community. Hence, groundwater serves as an alternative source because it requires less treatment to be potable and palatable.

Managed Aquifer Recharge (MAR) refers to the purposeful water recharge to aquifers to maintain, enhance, and secure groundwater systems under stress [3]. Figure 1 indicates the role of MAR in water resources management.

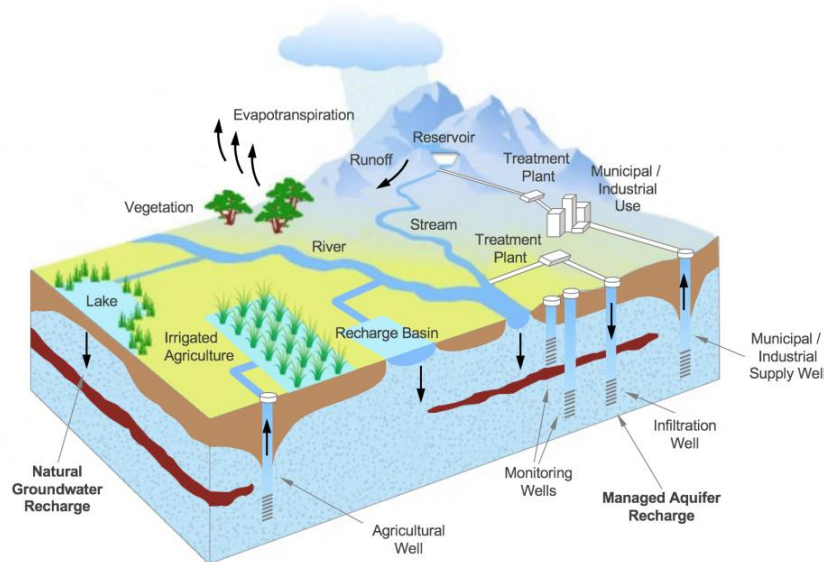


Figure 1: Managed aquifer recharge (MAR): concept and application[4]

The United Nations World Water Development Report launched on World Water Day, 22 March 2022, and asserted that MAR is a sustainable, comprehensive, cost-effective, and environmentally-friendly approach to replenishing aquifers [4]. United Nations Sustainable Development Goal 6 (SDG 6) seeks to ensure the availability and sustainable management of water and sanitation for all. Sustainable groundwater management requires in-depth knowledge of the rock composition of the aquifer, the recharge mechanism, the risks of pollution, and the safe yield. MAR is not a novel system as it has been in practice for ages. A study conducted by Zhang et al. [5] shows that MAR has been in use in the Central Valley California, United States, since the 1960s to help replenish groundwater basins using different types. Several countries have adopted MAR as a tool for groundwater sustainability. Orange County Water District's Groundwater Replenishment System in California, USA, and Kuwait's MAR System are examples of MAR projects. The benefits of MAR cannot be overemphasized. Data from the Global MAR inventory showed that there are 41 MAR sites in Africa, and two are located in Nigeria, the first is located at Michael Okpara University of Agriculture, Umudike, Abia State and the second MAR project is located at Kano River Irrigation Project (KRIP).

Low groundwater yield is a long-term problem facing some parts of Ilorin, North Central Nigeria. Due to the inconsistent distribution and non-availability of municipal water in some areas, the majority of residents rely on shallow well and borehole as a source of water supply for their domestic and industrial use. Some areas within the Ilorin metropolis experience slow recharge rate due to high rate of withdrawal from wells and boreholes [6].

MAR has been recognized as a sustainable groundwater management strategy that enhances the natural recharge, stabilizes groundwater level and mitigate over extraction. While several studies have explored groundwater dynamics in Ilorin, however, there is limited research on MAR implementation in Ilorin, where groundwater recharge is constrained by hydrogeological conditions and increasing water demand. Therefore, this research will assess the use of MAR system to find a sustainable solution to groundwater yield problem in the study area. However, due to the lack of observed field data, calibration and validation cannot be performed, which introduces uncertainty in model predictions. The study will, therefore, rely on assumed hydrogeological parameters based on existing literature and previous research. Therefore, the results should be viewed as preliminary assessments rather than definitive conclusions, and can provides the groundwork for future studies that incorporates field measurements for improved model accuracy.

This study has offers valuable insights for government agencies, environmental planners, and water resource managers to adopt MAR as a viable strategy for improving water sustainability. Additionally, it supports local communities in implementing small-scale MAR projects to enhance groundwater security. Furthermore, as climate change continues to alter rainfall patterns, MAR can serve as a climate adaptation strategy by ensuring groundwater availability during dry seasons.

This study seeks to achieve the following objectives:

- i. Develop a conceptual and numerical model of the study area.
- ii. Simulate the natural groundwater flow under a steady-state conditions .
- iii. Assess the impact of well abstraction on groundwater level.
- iv. Evaluate the effectiveness of infiltration ponds in replenishing groundwater level.

- v. Analyze the combine effect of well abstraction and infiltration ponds on groundwater balance.

II. Literature Review

A MAR system can be achieved through several ways. The spreading method of artificial recharge involves spreading water over an area with highly permeable soil in a basin that has been excavated and then allowing the water to percolate into the ground. This method includes Infiltration ponds or basins, ditches, furrow and excess irrigation. In-channel MAR often involves the use of water structures such as dams, subsurface dams, sand dams to route water to the recharge scheme. These structures intercept or delay runoff, which increases infiltration and groundwater recharge. Induced bank filtration technique uses a pumping well to draw surface water from a river or lake through its banks and bed. This process lowers the water table near the water source, causing water to seep into the aquifer. The water then passes through the aquifer and river or lake bed, where physical, chemical, and biological processes remove pollutants and pathogens. Other MAR techniques are well, shaft and borehole recharge technique and runoff harvesting.

2.1 Case Studies of MAR System Using Groundwater Numerical Model

Many countries of the world (United State, South Africa, Italy etc.) have used MAR for various reasons and purposes. Pokhrel et al. [7] carried out a study on Numerical simulation of a managed aquifer recharge system designed to supply drinking water to the city of Amsterdam, The Netherlands. The city of Amsterdam (The Netherlands) depends largely on the MAR in coastal dunes for water supply. 10 infiltration ponds, 25 recovery wells, minimum residence time of 60 days and maximum drawdown of 5 cm were some of the key input parameters for the model. The results demonstrated that 98% of the infiltrated water was captured by the recovery wells which accounted for 65.3% of the total abstraction. The results of the study demonstrated the importance of the numerical modelling approach and helped to gain insights for the implementation of the MAR.

An impact assessment of two MAR schemes on groundwater flow in the Tarnów area, Poland, was conducted by Innovative Groundwater Solutions[8] using MODFLOW. The model area of 15 km² was divided into 277 rows 198 columns, and a cell size of 20 x 20 m. A stratigraphy of model layers was determined based on data from over 150 bore logs. The Groundwater extraction was done through 26 pumping wells, located at 3 major well sites along the Dunajec River, a total average abstraction rate 17 000 m³/d. The results of the calibrated model were used to construct predictive scenarios to analyse the aquifer's sensitivity to changes in pumping rates. The use of infiltration ditches at one of the well fields effectively reduces the groundwater depression cone.

In West Coast, South Africa, Zhang et al. [9] carried out a site assessment for managed aquifer recharge (MAR), through the use of geographical information systems (GIS) and modelling. From the results, the GIS analysis combined with numerical modelling only provided acceptable references for identifying suitable areas for MAR implementation. However, they also noted that the analysis lacked sufficient data on groundwater seepage.

Zhang et al. [9] used Induced Riverbank Filtration (IRBF) technique in a model of a Managed Aquifer Recharge at Sant' Alessio IRBF plant, Lucca, Italy using FREEWAT and other modelling tools. IRBF is widely used when aquifers are hydraulically connected with surface water bodies. At the Sant' Alessio IRBF plant, aquifer storage is increased using a weir (raising groundwater head) and 12 vertical wells along the Serchio river embankment. Simulations were performed over an area of about 5.2 km², with a focus in the vicinity of the river embankment and the Sant' Alessio well field. The model demonstrated the importance of the weir in enhancing aquifer recharge in the Sant' Alessio plain and the efficiency of the IRBF scheme.

III. Methodology

3.1 Description of the Study Area

Ilorin is located approximately on Latitude 8° 30'N of the equator and Longitude 4° 35'E of the Greenwich Meridian and covers an area of about 100km². The population of Ilorin in 2024 was estimated at 1,064,000 [10]. The temperature in Ilorin varies between 25°C to 30°C in March which marks the hottest month [11]. The elevation ranges from 273m to 333m in the western part and from 273m to 364m in the eastern part. The annual mean rainfall is about 1,200mm between April and October of every year.

Ilorin lies on the Precambrian Basement Complex, made up primarily of gneiss, granite, schist, and undifferentiated metasedimentary rocks. The overlying soils consist mainly of clay, sand, and silt. These basement rocks are igneous and metamorphic in nature and are typically not porous or permeable, which means they don't easily allow water to pass through. However, groundwater can still accumulate in areas where the rocks have been deeply weathered or fractured due to natural features like faults, joints, and shear zones [12].

In addition to the basement complex, parts of Ilorin are also underlain by sedimentary formations containing both primary and secondary laterites as well as alluvial deposits. These alluvial areas are particularly important for groundwater, as they are directly recharged by rainfall and overflow from nearby rivers in both

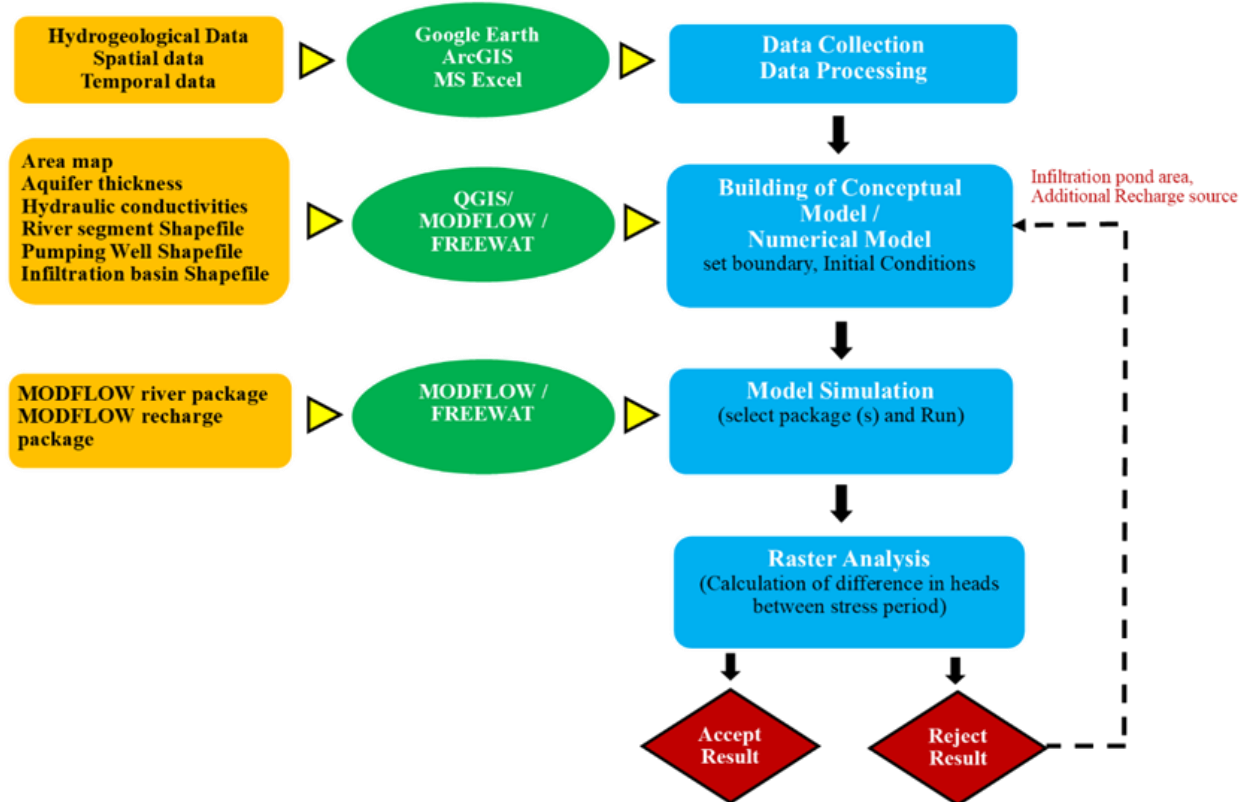


Figure 3: Managed Aquifer in Groundwater Modelling flow chart

3.3.1 Model Conceptualisation

The conceptual model for the study area was developed in QGIS using the FREEWAT plugin. The conceptual model depicts the groundwater aquifer system, which includes the interpretation of the hydrological and geological conditions of the aquifer as well as information about the water budget. Three hydro stratigraphic units (HUs) are identified from top to bottom in layers as shown in Figure 4 and are modelled in the form of rows and columns as depicted in Figure 5.

Layer 1 (upper aquifer) is a 9 m thick layer lateritic clay unit (HU1), representing the shallow aquifer, where infiltration and surface-groundwater interactions primarily occur. This layer includes areas affected by natural recharge and serves as the primary water source for shallow wells.

Layer 2 (aquitard Layer) is a fairly hard basement (HU2) with low permeability, about 27 m thick, that restricts vertical groundwater flow. It acts as a buffer between the shallow and deeper aquifers, limiting the rate of recharge to the lower layers.

Layer 3 (lower aquifer) is a weathered basement unit (HU3), 14 m thick, which acts as a confined aquifer bounded at the bottom by an indefinite depth of hard basement which is not considered in this study. The domain is bounded by Odoore Stream by the eastern part of the study area. The deeper confined aquifer, serves as the main groundwater storage unit and is exploited by deep boreholes.

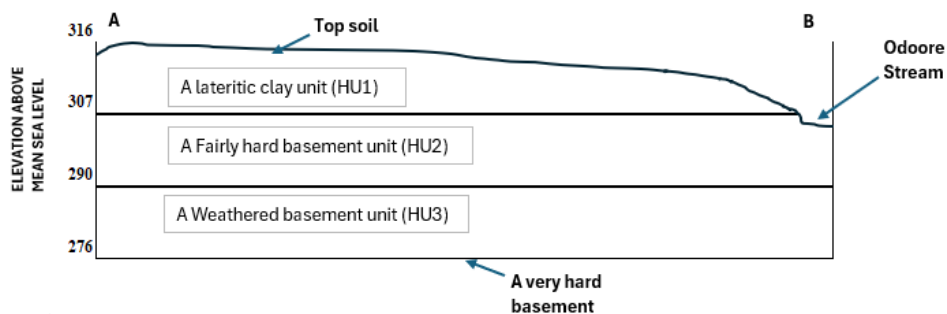


Figure 4: Hydro stratigraphic setup of the study area (adapted from In-depth Geophysics)

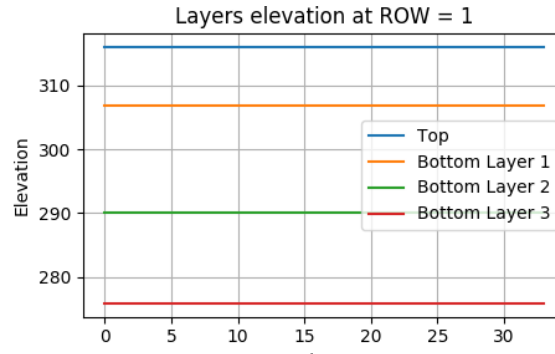


Figure 5: Model section at row 1

This conceptualization is consistent with previous studies on basement complex aquifers, where shallow aquifers are more vulnerable to seasonal variations, while deeper aquifers provide a more stable groundwater supply [9]. The presence of an aquitard layer aligns with findings from [14], who demonstrated that aquifer compartmentalization significantly influences groundwater recharge efficiency in semi-arid regions.

3.3.2 Boundary Conditions and Groundwater Flow Dynamics

The boundary conditions define how groundwater enters and exits the system. In this study, the eastern boundary is a river, which acts as a discharge zone, meaning groundwater flows toward it. However, in Layer 1, the river was assumed not to interact significantly with the aquifer and was therefore declared inactive in that layer. The western boundary was assigned a specified head, meaning groundwater enters the system at a constant level. The northern and southern boundaries were set as no-flow conditions, indicating that groundwater movement does not extend beyond these limits. The bottom boundary was also set as no-flow, assuming there is no vertical leakage below the lower aquifer.

The conceptualization of boundary conditions is consistent with previous regional groundwater models, such as that conducted Pokhrel et al. [7], where river-aquifer interactions were controlled by defining active and inactive zones based on hydrogeological characteristics.

3.3.3 Model Grid Design and Cell Assignments

For the horizontal discretization of the study Area, a grid resolution of 450 m × 510 m was employed, with each grid cell corresponding to an area of 15 m × 15 m. The horizontal grid consists of 30 rows and 34 columns as shown in Figure 6. This level of resolution is appropriate for regional groundwater modelling, balancing computational efficiency with spatial detail

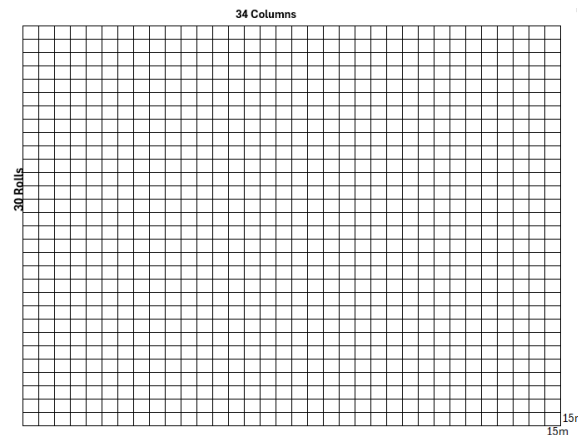


Figure 6: Horizontal discretization plan view

For the vertical Discretization of the Study Area, the HUs were represented by three model layers with flat surfaces as shown in Figure 7. Model layer 1 (HU1) is set at 316 m above the mean sea level (msl) and the bottom set at 309 m msl, the model layer 2 (HU2) has its the bottom set at 290 msl, and the bottom of model layer 3 (HU3) is set at 276 m msl. Figures 8, 9, 10 show the digital discretization of the model layers.

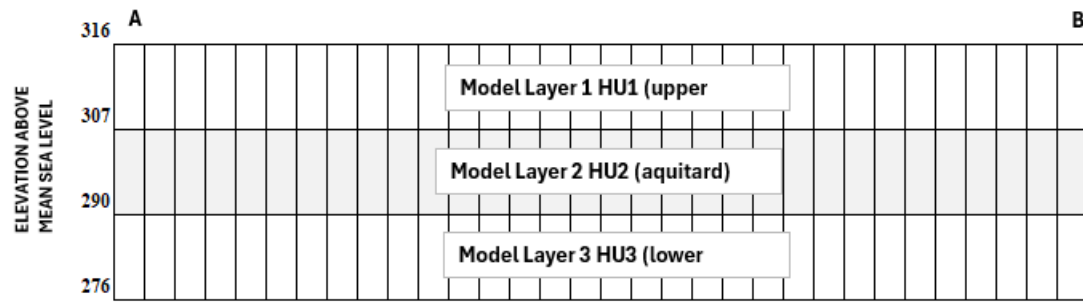


Figure 7: Vertical discretization view

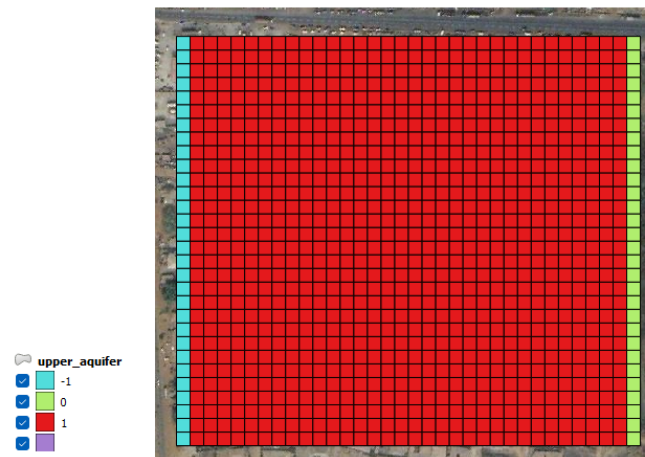


Figure 8: Discretization of upper aquifer.

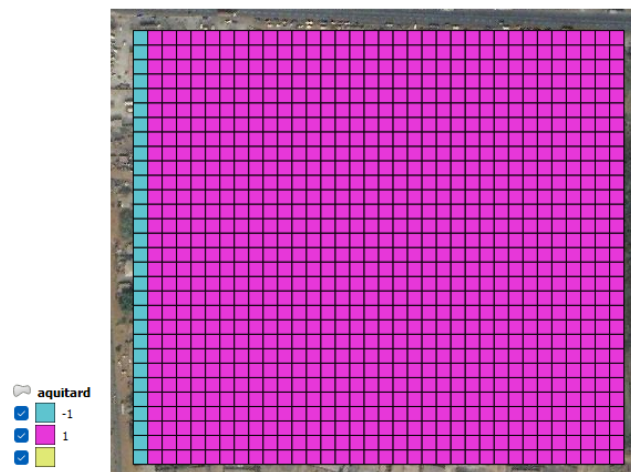


Figure 9: Discretization of second layer (aquitard).

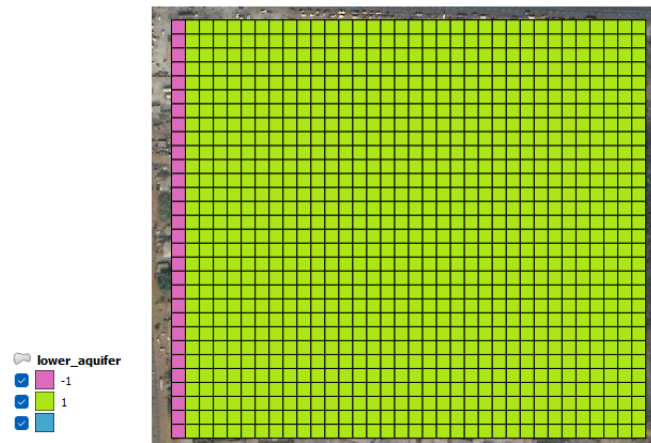


Figure 10: Discretization of third layer (lower aquifer).

The structured grid approach aligns with methods used in [2], where model grid refinement was crucial in improving groundwater simulation accuracy. However, refined local grid adjustments could further improve simulation precision, especially in areas with high hydraulic gradients.

3.3.4 Model Creation and Database

The model was created by assigning the model name, working folder, length unit, and time unit in FREEWAT. The first stress period was initially introduced, by assigning the length, time step, multiplier, and state. Initial date and time of the simulation were set. The model was set to WGS 84/UTM zone 31N (EPSG: 32631). MODFLOW executable MF2005 was uploaded into the model.

3.3.5 Defining the Grid and Model Layers

Base map of the study area was loaded in to the canvas as a raster layer. Model layers were created which represent the layers of aquifers as shown in Figure 11. The number of layers represents the number of aquifers present in the study area. All the model layers were set as confined aquifers. The elevation, wetting capability, vertical and horizontal hydraulic heads, and starting heads of each layer were assigned.

lpf_m1 :: Features total: 3, filtered: 3, selected: 0

	name	type	layavg	chani	laywet
1	upper_aquifer	confined	harmonic	1	No
2	aquitard	confined	harmonic	1	No
3	lower_aquifer	confined	harmonic	1	No

Figure 11: Representation of model layers in the model.

3.3.6 Assigning Aquifer Properties

Starting head for the upper aquifer, aquitard and lower aquifer were set to 309 m, 307 m and 312.7 m above msl. Individual layer thickness was assigned automatically by the model during the declaration of model layers.

The hydraulic properties of the aquifer were defined based on secondary data sources and literature values due to the unavailability of direct field measurements. The hydraulic conductivity value for model layers 1, 2, and 3 are $k = 4.56 \times 10^{-6} \text{ m/s}$, $k = 1.0 \times 10^{-7} \text{ m/s}$ and $k = 4.56 \times 10^{-6} \text{ m/s}$ respectively, with higher values in the shallow aquifer and lower values in the aquitard layer. The storage coefficient and specific yield were assigned based on the expected porosity and permeability characteristics of each layer. The recharge rates were derived from climate data, with an assumption of natural recharge through infiltration and additional recharge through artificial infiltration basins.

This parameterization follows the standard approach in MODFLOW-based groundwater modelling, similar to the approach in [4], where recharge assumptions were validated against observed groundwater levels. However, due to the lack of field calibration in this study, these values introduce uncertainty in model accuracy.

3.3.7 Numerical Boundary Conditions

Specified head boundary conditions were defined for the stress periods (SPs). The specified head is along the western boundary, there is no flow at the northern and southern boundaries, and the bottom of the system and river are along the eastern boundary. River boundary conditions were created to represent the Odoore stream in the model. Shapefile to represent the Yemoja stream was created using QGIS layer tool. The river parameters were created for the four stress periods. The boundary condition packages that were run for this simulation are the River package (RIV), Well package (WELL), and Recharge package (RCH).

3.3.8 Defining the Stress Periods (Time Discretization)

The entire model was run for four stress periods. For the aim of this study, all the SPs are steady-state, which means that the solution of the model (the hydraulic head) does not change in time. By the default, the first stress period is configured during model creation phase. At the first stress period, there is no stress as this represents the natural state of the groundwater system. The flow terms involved during the 1st SP are constant-head and river leakage.

The introduction of the pumping well to the model represents the second stress period. Nine (deep wells) out of the eighty wells were extracting water from third layer while others are extracting water from upper aquifer. Flow rates were assigned to the well differently based on the use. The negative value of the flow rate represents the withdrawer. New river layer for second stress period was created and river parameters were assigned. The MODFLOW well package and River package are the only boundary condition active at this stress period.

The third stress period represents the introduction of an infiltration pond to the model. Figure 12 shows the representation of infiltration basins and well shapefiles. The model was amended by deactivating the abstraction wells and activating the infiltration pond. The MODFLOW packages involve in this stress period are River, Well and Recharge. River package was updated with the new river parameters, a new well layer was created but pumping was not activated. Recharge fluxes were assigned to cells that represented the infiltration pond.



Figure 12: Representation of infiltration basins and well shapefiles

Then, a fourth stress period was run to represent a further configuration of the model, with both the wells and the infiltration pond activated. The necessary boundary conditions were set, The MODFLOW Recharge (RCH) Package was used to simulate rainfall recharge to groundwater. Table 1 summarises the time discretization for the model.

Table 1: Model Time Discretization

Stress period	From (sec)	To (sec)	Length (days)	State	Time step	Stress Involved
1	0	86400	1	steady	1	None
2	86400	2678400	30	steady	1	Wells
3	2678400	5270400	30	steady	1	Recharge
4	5270400	7862400	30	steady	1	Recharge + Wells

3.4 Raster Analysis

In the raster analysis, for stress periods 1 and 2 head differences in heads due to pumping from the lower aquifer were evaluated. This raster analysis involves subtracting the head calculated for each model layer at the end of stress period 2 and subtracting from the head calculated for each model layer at the end of stress Period 1 and these were done in the GIS environment. The raster analysis was performed at the end of the simulation of stress periods 3 and 4. The difference between hydraulic heads simulated at the end of Stress periods 4 and 2 were evaluated.

IV. Results and Discussion

The results of this study provide insight into the effects of well abstraction and artificial recharge on groundwater levels in the study area.

4.1 Baseline Groundwater Flow (Steady-State Condition - SP1)

The initial simulation represents the natural groundwater flow in the absence of external stress such as pumping or artificial recharge. The results indicate that groundwater flows from the western boundary to the eastern boundary, following the natural topographic gradient. The river on the eastern boundary serves as a discharge point, as shown in Figure 13, meaning that groundwater moves toward the river, conforming to rivers as natural discharge areas for aquifers. The hydraulic head contour maps, as shown in Figures 14, 15, and 16, confirm that the groundwater movement aligns with the general surface water flow in the study area. This natural state serves as a reference condition for evaluating the impacts of human-induced stresses in subsequent simulations.

Similar findings were reported by Pokhrel et al. [7] in their numerical simulation of MAR in Amsterdam, where they found that groundwater naturally flows toward lower elevations and discharge areas under steady-state conditions. However, the baseline results in this study differ slightly from those of [9], where strong seasonal variations influenced natural groundwater flow due to highly variable recharge conditions. The relatively stable hydrogeological setting of Ilorin's basement complex may contribute to the uniformity of the steady-state flow observed in this study.

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 =	4056.3391	CONSTANT HEAD =	1.4163E-02
RIVER LEAKAGE =	0.0000	RIVER LEAKAGE =	0.0000
TOTAL IN =	4056.3391	TOTAL IN =	1.4163E-02
OUT:		OUT:	
----		----	
STORAGE =	0.0000	STORAGE =	0.0000
CONSTANT HEAD =	0.0000	CONSTANT HEAD =	0.0000
RIVER LEAKAGE =	4056.4104	RIVER LEAKAGE =	1.4163E-02
TOTAL OUT =	4056.4104	TOTAL OUT =	1.4163E-02
IN - OUT =	-7.1289E-02	IN - OUT =	-2.4866E-07
PERCENT DISCREPANCY =	-0.00	PERCENT DISCREPANCY =	-0.00

Figure 13: Model balance report at the end of SP1

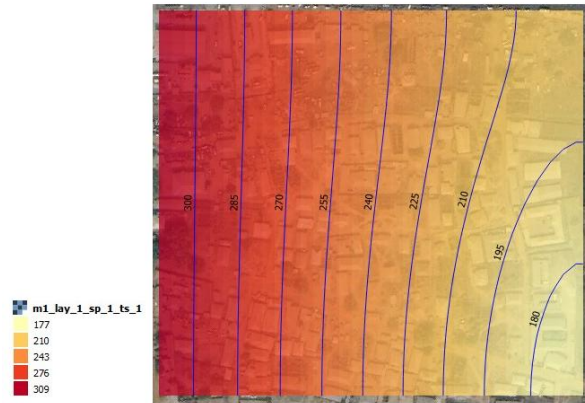


Figure 14: Hydraulic head simulated at the end of SP1 (layer 1)

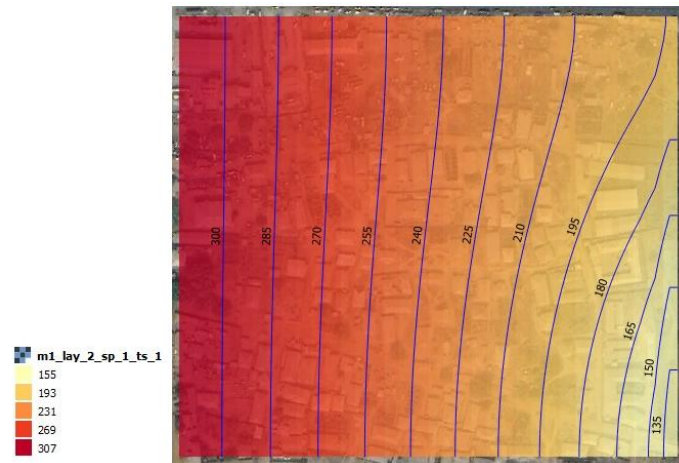


Figure 15: Hydraulic head simulated at the end of SP1 (layer 2)

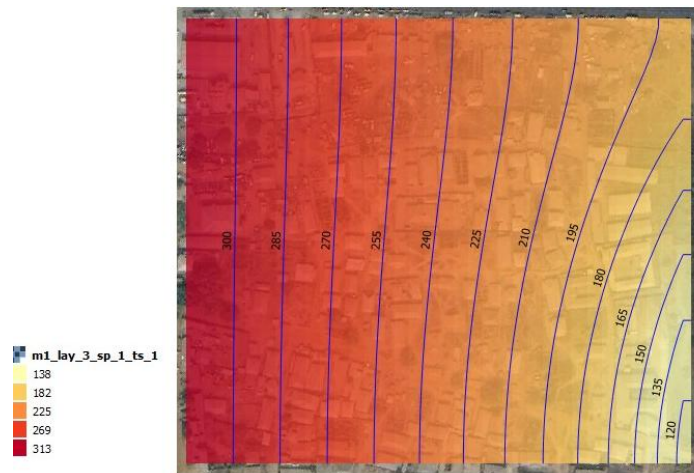


Figure 16: Hydraulic head simulated at the end of SP1 (layer 3)

4.2 Impact of Well Abstraction on Groundwater Levels (SP2)

In the second simulation, 80 wells were introduced, with 9 deep boreholes penetrating the lower aquifer (Layer 3) while the remaining wells extracted water from the upper aquifer (Layer 1). The hydraulic heads simulated at the end of SP2 are shown in Figures 17, 18, and 19, respectively. The results indicate a significant decline in hydraulic head, particularly in areas with a high concentration of wells. The most pronounced drop occurred in Layer 3, where boreholes caused a hydraulic head reduction of up to -13.6 m (Figure 21). The constant head was also depleted (Figure 20), indicating that pumping reduced groundwater discharge to the river.

These findings are consistent with those of [14], who demonstrated that excessive pumping can lead to groundwater depletion, reduced baseflow to surface water bodies, and long-term aquifer stress. A similar pattern was observed in [2], where well abstraction in Tunisia's aquifer system led to a sharp decline in water levels, necessitating MAR interventions. However, this study differs from the findings of [8] in Poland, where groundwater depletion was less severe due to the presence of a shallow, highly permeable aquifer that allowed rapid recharge. The relatively low recharge capacity of Ilorin's basement complex aquifer may contribute to the more pronounced drawdown effects observed in this study.

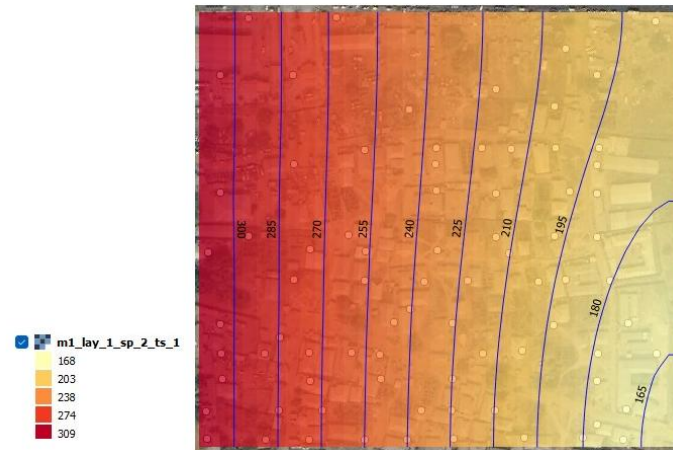


Figure 17: Hydraulic head simulated at the end of SP2 (layer 1)

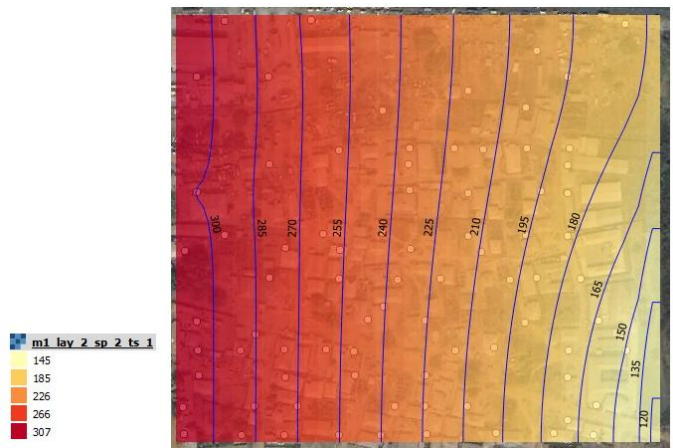


Figure 18: Hydraulic head simulated at the end of SP2 (layer 2)

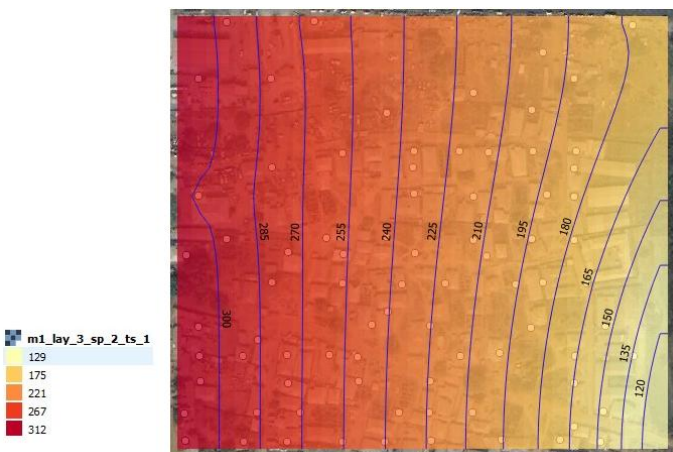


Figure 19: Hydraulic head simulated at the end of SP2 (layer 3)

VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP 1, STRESS PERIOD 2			
CUMULATIVE VOLUMES		RATES FOR THIS TIME STEP	
L**3		L**3/T	
IN:		IN:	
---		---	
STORAGE =	0.0000	STORAGE =	0.0000
CONSTANT HEAD =	56087.0625	CONSTANT HEAD =	2.0074E-02
WELLS =	0.0000	WELLS =	0.0000
RIVER LEAKAGE =	0.0000	RIVER LEAKAGE =	0.0000
TOTAL IN =	56087.0625	TOTAL IN =	2.0074E-02
OUT:		OUT:	
----		----	
STORAGE =	0.0000	STORAGE =	0.0000
CONSTANT HEAD =	0.0000	CONSTANT HEAD =	0.0000
WELLS =	15320.7939	WELLS =	5.9108E-03
RIVER LEAKAGE =	40768.0547	RIVER LEAKAGE =	1.4163E-02
TOTAL OUT =	56088.8477	TOTAL OUT =	2.0074E-02
IN - OUT =	-1.7852	IN - OUT =	-6.6310E-07
PERCENT DISCREPANCY =	-0.00	PERCENT DISCREPANCY =	-0.00

Figure 20: Model balance report at the end of SP2

4.3 Effect of Infiltration Basin Recharge on Groundwater Levels (SP3)

The third simulation introduced artificial recharge through infiltration basins, designed to enhance groundwater replenishment. The hydraulic head simulated at the end of SP3 is shown in Figures 21, 22, and 23, respectively. The results indicate a positive impact on the hydraulic head, with water levels increasing by up to +10.5 m in the first layer (Figure 27). This suggests that infiltration basins are an effective method for augmenting groundwater storage, counteracting the negative effects of abstraction.

This result aligns with the work of Dillon et al. [4], who highlighted that MAR significantly improves groundwater levels by facilitating controlled infiltration, especially in areas with declining water tables. Similarly, Rossetto et al. [15] demonstrated that riverbank filtration recharge in Italy improved groundwater storage and maintained stable water supplies for over 300,000 residents. However, the magnitude of recharge in this study appears higher than in [5], where MAR-induced water level rises were limited to 5–10 m due to lower infiltration efficiency in their study area. The effectiveness of MAR in Ilorin may be due to localized recharge in confined areas, leading to more concentrated hydraulic head recovery.

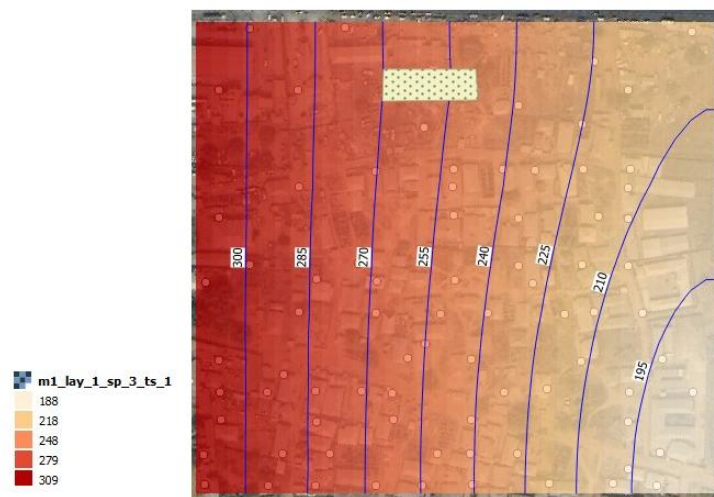


Figure 21: Hydraulic head simulated at the end of SP3 (layer 1)

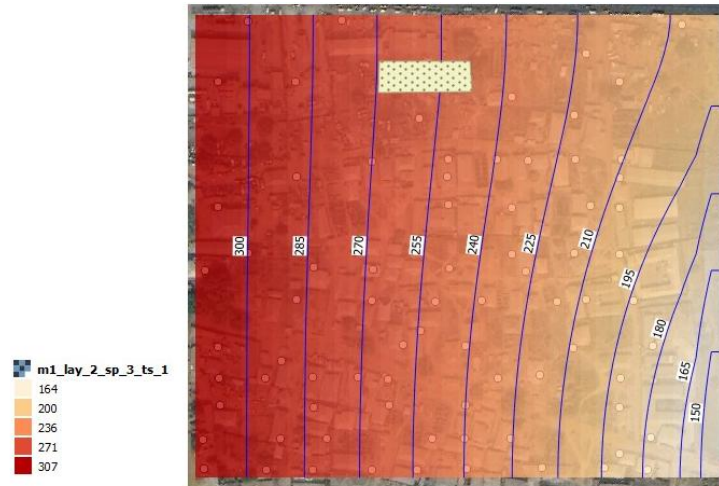


Figure 22: Hydraulic head simulated at the end of SP3 (layer 2)

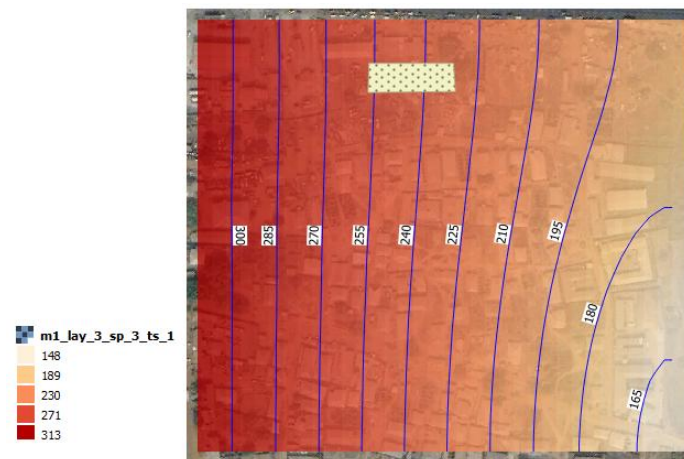


Figure 23: Hydraulic head simulated at the end of SP3 (layer 3)

4.4 Combined Effect of Well Abstraction and Recharge (SP4)

The fourth simulation evaluated the combined impact of well abstraction and artificial recharge. The results indicate that while MAR successfully counteracted the negative effects of groundwater pumping, some areas still experienced localised drawdown. Figures 24, 25, and 26 show the increase in the hydraulic heads as a result of MAR. The river leakage remained similar to the natural state, suggesting that MAR helped maintain a more balanced groundwater system.

These findings are consistent with studies that emphasise the importance of balancing recharge and extraction to achieve groundwater sustainability. Mark Smith & Laban (n.d.) highlighted that an effective MAR system must be properly managed to avoid localised over-extraction and ensure long-term benefits. The study also aligns with Pokhrel et al. [7], who demonstrated that MAR projects in Amsterdam captured over 98% of infiltrated water, improving overall water security. However, the lack of calibration in this study limits the precision of the simulated impact, highlighting the need for field data validation in future studies.

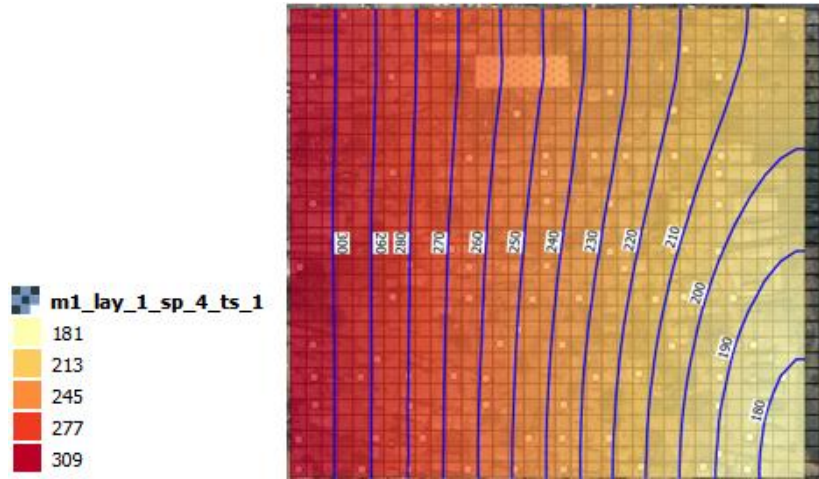


Figure 24: Hydraulic head simulated at the end of SP4 (layer 1)

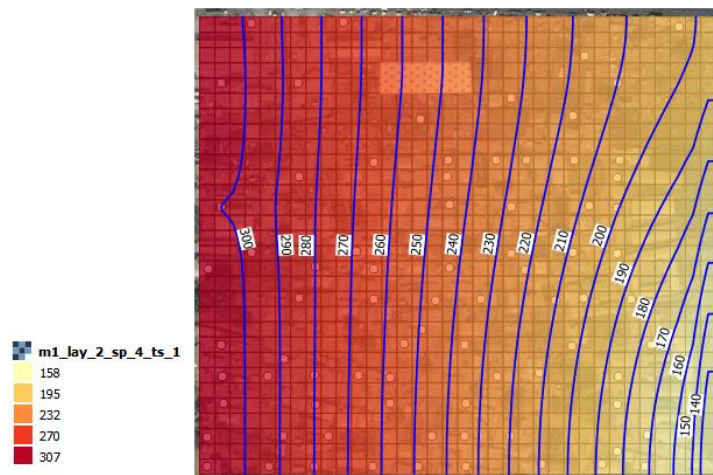


Figure 25: Hydraulic head simulated at the end of SP4 (layer 2)

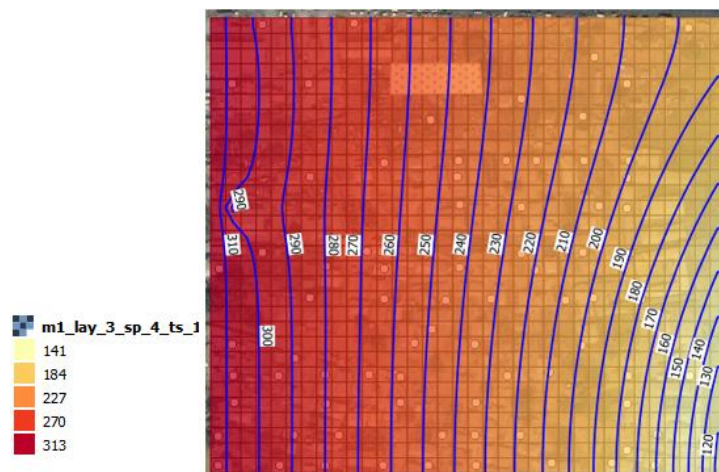


Figure 26: Hydraulic head simulated at the end of SP4 (layer 3)

4.5 Raster Analysis of Groundwater Head Differences

Raster analysis was performed to visualize spatial variations in the hydraulic head across different stress periods. The results indicate negative head differences in areas affected by pumping (Figures 27, 28, 29) while positive differences were observed near infiltration basins (Figures 30, 31, 32, 33, 34, 35). This confirms that MAR can effectively restore groundwater levels when implemented in strategic locations. The balance achieved in SP4 suggests that a well-designed MAR system can offset water losses from abstraction, supporting long-term groundwater sustainability.

Studies by Harizi et al. [2] and Dillon et al. [4] support the use of raster analysis to evaluate MAR performance, demonstrating its effectiveness in identifying recharge zones and assessing water table recovery. However, the absence of field validation in this study means that the actual impact of MAR may vary in real-world conditions, requiring further field-based assessment.

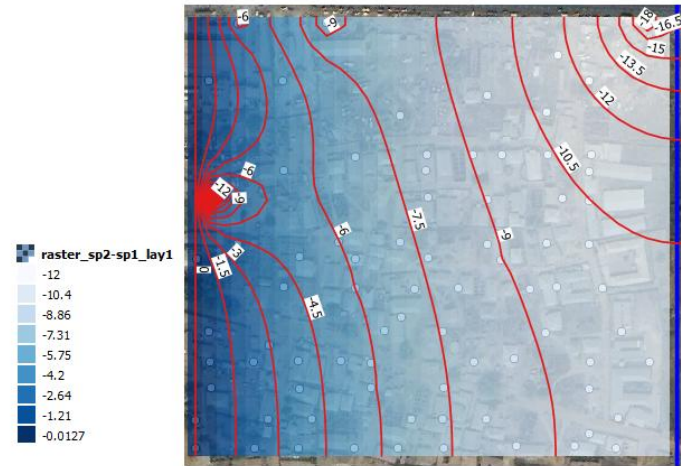


Figure 27: Difference between hydraulic heads simulated at the end of SPs 1 and 2 (layer 1)

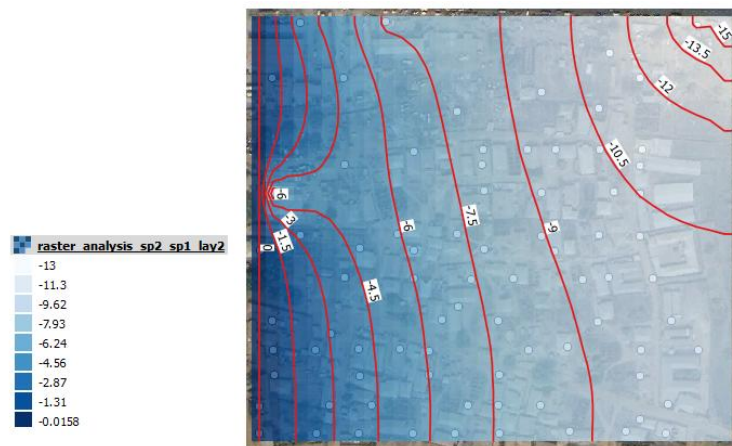


Figure 28: Difference between hydraulic heads simulated at the end of SPs 1 and 2 (layer 2)

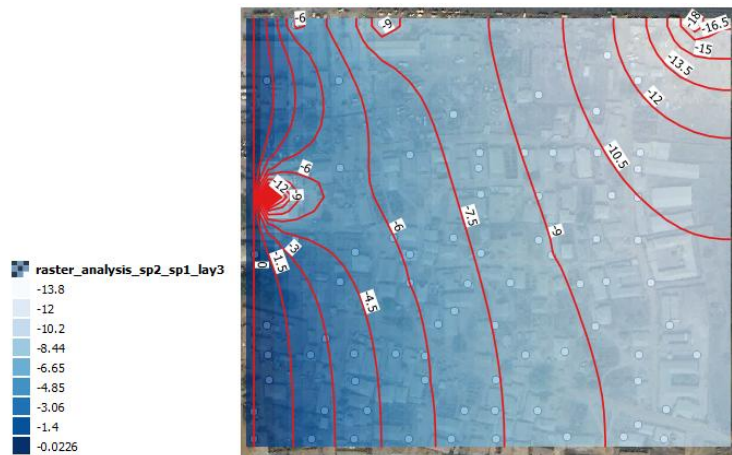


Figure 29: Difference between hydraulic heads simulated at the end of SPs 1 and 2 (layer 3)

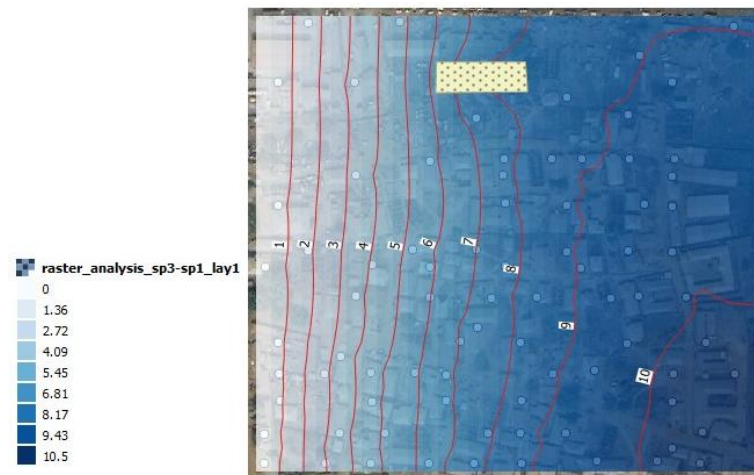


Figure 30: Difference between hydraulic heads simulated at the end of SPs 3 and 1 (layer 1)

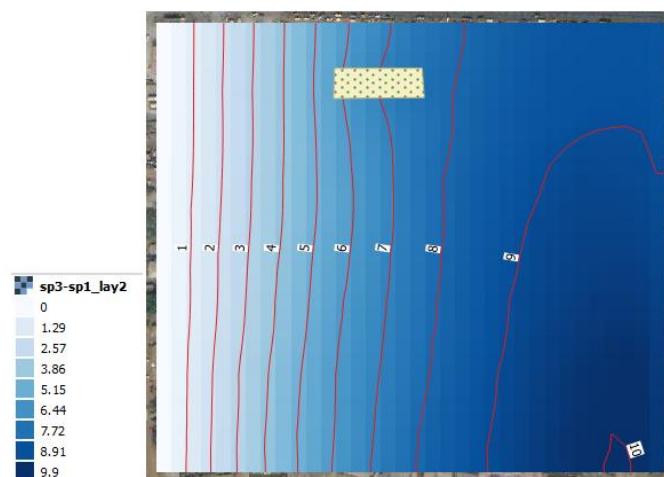


Figure 31: Difference between hydraulic heads simulated at the end of SPs 3 and 1 (layer 2)

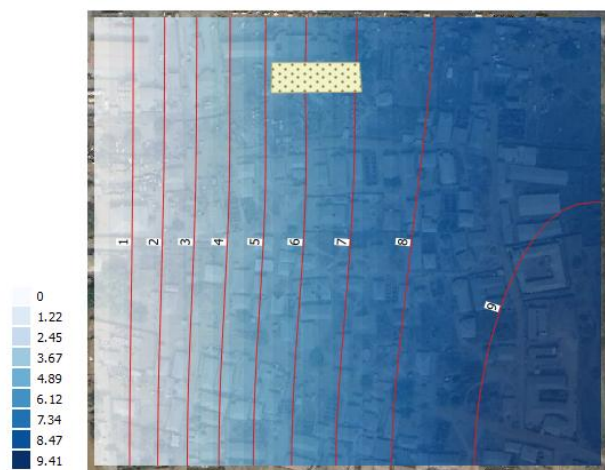


Figure 32: Difference between hydraulic heads simulated at the end of SPs 3 and 1 (layer 3)

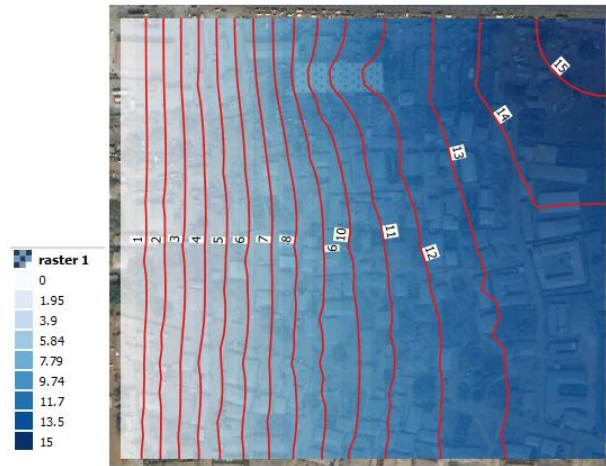


Figure 33: Difference between hydraulic heads simulated at the end of SPs 4 and 2 (layer 1)

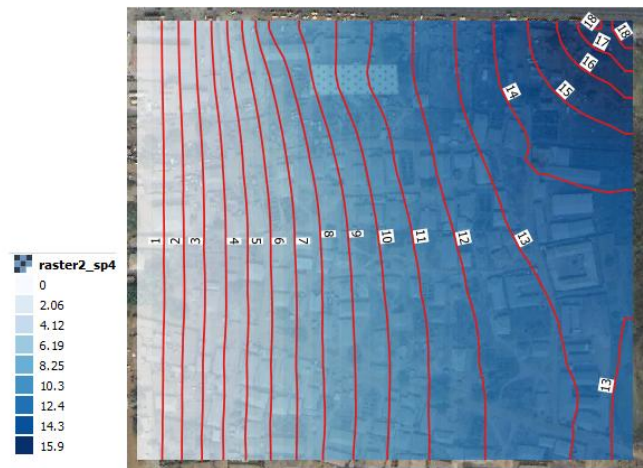


Figure 34: Difference between hydraulic heads simulated at the end of SPs 4 and 2 (layer 2)

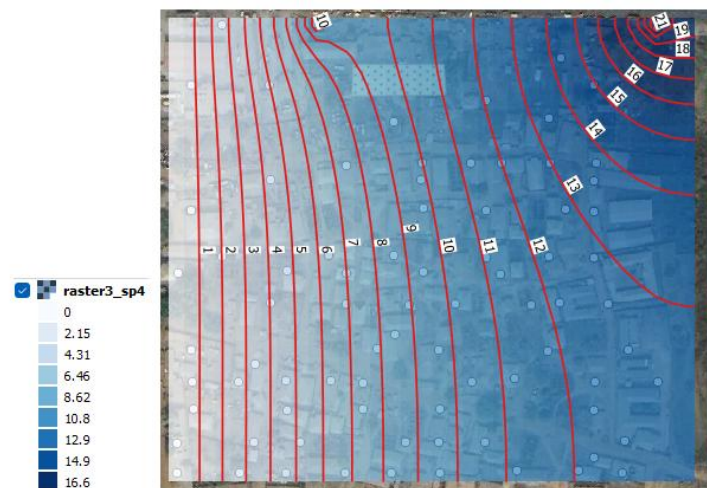


Figure 35: Difference between hydraulic heads simulated at the end of SPs 4 and 2 (layer 3)

4.6 Model Calibration

For purposes of this study, a simulation is defined as a test using quantified hydrologic data (recharge and infiltration) and the hydrogeologic parameter K (hydraulic parameter) in which the results (hydraulic head and spring discharge) are computed with a mathematical groundwater flow model. The analysis of the simulation was made by comparing the computed results with measured data. Model calibration was carried out by manual trial and error adjustments of the parameters.

Model calibration can be made either for steady state flow or for transient state flow. In this study, the steady state flow was selected as a model type. The calibration was made for the period of May 2024.

V. Conclusion

This study assessed the effectiveness of Managed Aquifer Recharge (MAR) systems in mitigating groundwater depletion using a numerical groundwater modelling approach. This study was conducted in Ilorin, North Central Nigeria, where groundwater serves as an alternative source to the inconsistent municipal water supply. However, the groundwater is increasingly under stress due to over-extraction and limited natural recharge. Using FREEWAT, various scenarios were simulated to analyse the impact of well abstraction, infiltration basin recharge, and their combined effects on groundwater levels. Based on the outcome of the research, the following can be concluded:

- i. A conceptual and numerical groundwater model was developed for the study area, providing insights into groundwater flow dynamics and system behaviour under different stress conditions.
- ii. The baseline groundwater flow simulation under steady-state conditions confirmed that groundwater naturally flows from the western boundary toward the eastern boundary, with the river acting as a discharge zone. This established a reference condition for evaluating the effects of abstraction and recharge.
- iii. The impact of well abstraction on groundwater levels revealed that excessive pumping led to significant drawdowns, with hydraulic head reductions of up to -13.6 m in deep boreholes. The reduction in river leakage outflow indicates that unsustainable pumping could lead to long-term groundwater depletion.
- iv. The effectiveness of infiltration basins in replenishing groundwater was demonstrated, with hydraulic head increases of up to +16.6 m in recharge zones. This confirms that MAR is an effective strategy for stabilizing groundwater levels and mitigating depletion.
- v. The combined effect of well abstraction and recharge showed that MAR could partially offset the negative impacts of groundwater pumping, leading to a more balanced system. While some areas still experienced localized declines, the overall results indicate that a well-managed MAR system can help sustain groundwater resources over time.
- vi. Model calibration carried out successfully as the deviations between the computed and the observed head values were insignificant and also as the Root Mean Square Error (RMSE) had a value of about 0.61 m (calibration target within ± 1 m).

This study confirms that MAR is a viable solution for groundwater sustainability in Ilorin. When combined with controlled well abstraction, MAR can enhance water availability, reduce aquifer stress, and support Sustainable Development Goal 6 (SDG 6) on clean water and sanitation.

Due to the lack of observed field data, model calibration and validation were not performed, and this introduced uncertainty in the accuracy of the results. There is a need for future studies to incorporate field measurements for improved model reliability. Despite these limitations, the study provides preliminary insights into the potential of MAR as a groundwater management tool. Future research should focus on field-based data collection, climate variability impacts, and economic feasibility assessments to strengthen MAR implementation strategies. Additionally, economic feasibility studies should be conducted to evaluate the cost-effectiveness of MAR implementation in Ilorin.

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