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SIMULATION OF GROUNDWATER FLOW REGIME: A CASE OF YALA RIVER CATCHMENT, KENYA

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Abstract — The hydrogeological regime that includes the vadose and phreatic zones significantly supports the hydrological cycle and influences surface and groundwater bodies for a sustainable ecosystem. Since these zones are unseen, they are prone to anthropogenic threats, which include groundwater overabstraction, reduced infiltration or aquifer recharge, and adversity from climate change. There is also inadequate knowledge of groundwater capacity and flow regime in catchments. This study developed hydrogeological knowledge to understand the groundwater flow regime and provide a decision tool for catchment management. The model was developed using Visual MODFLOW and ran through a set of scenarios to widely understand hydrogeological aspects in the Yala River catchment. While running the model through day 147 to 190, the trends indicated a maximum head of 0.00624 m and a minimum of -0.00676 m. The head changes recorded a maximum of 0.00524 m and a minimum of -0.0068 m with the residual of less than 2, indicating that the verifications were within acceptable levels. It was observed that the catchment storage improved from 0.050238 m^3/day in the reference scenario to 7.16 m^3/day, and when the catchment was assumed to be well managed, the model's groundwater inflow-outflow difference increased to 429 m^3/day, an increase of 422.4 m^3/day in the zonal unit, which gave a 98.33% increase. There was evidence of groundwater backflow at the midblock, indicating the development of a cone of depression that requires further research. It is worth noting that the boundary conditions used in the calibrated model were representative combinations of selected parameter values and boundary conditions. This model can be replicated for simulation of the hydrogeological flow regime in other catchments with similar or relative geographical characteristics.

Keywords: aquifer, groundwater, hydrogeology, recharge, visual-MODFLOW

1.0 INTRODUCTION

This study simulated the groundwater flow regime of the Yala River catchment using Visual-MODFLOW. The ArcGIS tool was used to delineate the catchment and map the model boundaries. This study, for the first time in the Yala River catchment, integrated GIS and Visual-MODFLOW in the investigation of the hydrogeological flow regime with an objective of understanding the spatial variation in groundwater flow within the study area against hydrogeological and anthropogenic factors.

This catchment faces uncertainties and potential challenges to the hydrogeological system. Groundwater, due to its nature being invisible and coupled with a lack of information, leads to poor planning and management of phreatic sources – over-abstraction. Its aquifer system has experienced significant water level decline, depletion, and exploitation, and it has suffered from the impacts of climate change [1]. Groundwater resources have also been degraded by anthropogenic activities such as groundwater quality deterioration [2]. A previous study by Okune 2019 [3] established that the threats to the Yala River's survival and effects on the local communities came from sand mining, pollution, deforestation, poor agricultural activities and climate change. This catchment also experiences increased water demand for various competing human and industrial needs, leading to increased groundwater exploitation with drilling activities that result in dry pits, dry wells, and, at times, low discharge wells. Challenges experienced were attributed to droughts, floods, rising temperatures, and irregular and unpredictable rainfalls, which caused nexuses in the hydrologic cycle [4]. Through a review of literature about the catchment, most research focused on surface water routing, balancing, allocation, groundwater pollution, and vulnerability assessment, with less focus on phreatic (zones of saturation) or groundwater quantity risks. This study therefore explains the groundwater flow regime in the catchment.

Many studies had been advanced in the catchment, including, among others, the study by Kiluva et al., 2011 [5], which involved modelling the hydrologic processes in the Yala River catchment using the Geological Stream Flow Model (GeoSFM) and Muskingum Cunge (M-C) to develop a flood early warning system for the mitigation of potential flood hazard risks to downstream inhabitants. This study focused on modelling the hydrogeological flow regime in the catchment. The study by [6] advanced research on the modelling of water balance and allocation in the Yala River catchment using the Water Evaluation and Adaptation Planning (WEAP) model. The study focused on surface water allocation with more emphasis on demand and water balance. Another study in the catchment was done by Kanda et al., 2023 [7], where the authors investigated shallow well contamination in the mid-block of the Yala River catchment and observed that the presence of bacteriological indicators suggested that the water from shallow wells was harmful to human health if consumed untreated. This study confirmed there was movement of water molecules transporting particles within the vadose zone, thus contaminating the underlying saturated zones.

The study by Anderson et al., 2015 [8] advanced that the groundwater flow regime was a transformational three-dimensional flow path resulting from nexuses generated by the hydrogeological stresses within the aquifer regime. The flow regime occurred in both the vadose and phreatic zones, while storage mostly occurred in the sinks of the aquifer's phreatic zones. This study demonstrated that the vadose and phreatic zones were key regions for consideration in understanding nexuses in flow regimes. The study by Waswa and Lorentz 2019 [9] opined that the rate and direction of groundwater flow were a function of the gradient of the hydraulic head, whose components were the gravity head and pressure head. The argument supports this study's investigation of parameters of groundwater flow that are fundamental to groundwater modelling. In another relevant study by Fitts 2012 [10], it was observed that a specific set of flow patterns in a zone was influenced by a particular set of driving conditions whereby the discharge rates for any point, including groundwater discharge wells, springs and boreholes, had independent factors influencing their flow dynamics around them and further confirming the varied nature of sources and their surrounding hydrogeological regime.

The study by Bradford and Acreman 2003 [11] in the river floodplains and coastal grazing pastures of Pevensey Levels in East Sussex, UK, manipulated ditch water levels to understand common management techniques in-stream and in-field habitats that influenced water table levels. The study observed that in wet grasslands with low soil conductivities, the water table in the centre of each field was not closely coupled to variations in ditch stage. Therefore, it was concluded that rainfall and evaporation had a greater influence on both the depth to the water table and the fluctuation of the water table. This informs the current study, although other aspects perceived to affect groundwater level, including river leakage and well abstraction, are to be considered. Further, the study concept was shaped by other valued literature, including the study by Fatapour et al., 2026 [12] in the Khorramabad River catchment, where they employed an integrated approach that combined advanced hydrological and hydraulic models and GIS-based data analysis with an objective of comprehensively developing an accurate model for flood prediction and high-risk area identification. The study anticipated a rise in temperature, with a projection indicating a potential 2°C rise in Iran's temperature by 2030 against runoff and escalating drought conditions that exacerbated the frequency and severity of intense floods in the catchment.

It is appreciated that all these studies advanced knowledge in the hydrogeological regime. From this study’s perspective, it is imperative to provide additional information as a basis for decision-making on: Policies, guidelines, and water resource planning, allocation, and environmental management—along with implementing climate change interventions for both the public and private sectors—prioritise water resources as a driver for sustainable environmental management.

2.0 MATERIALS AND METHODS

2.1. Study Area

The Yala River catchment lies in the western part of Kenya, and the river drains through Nandi, Kakamega, Vihiga, Siaya and Busia Counties with an approximate area of 3,351 km². It flows westward until it empties into Lake Victoria. The digital elevation model with a grid size covering the study area is depicted in Figure 1.

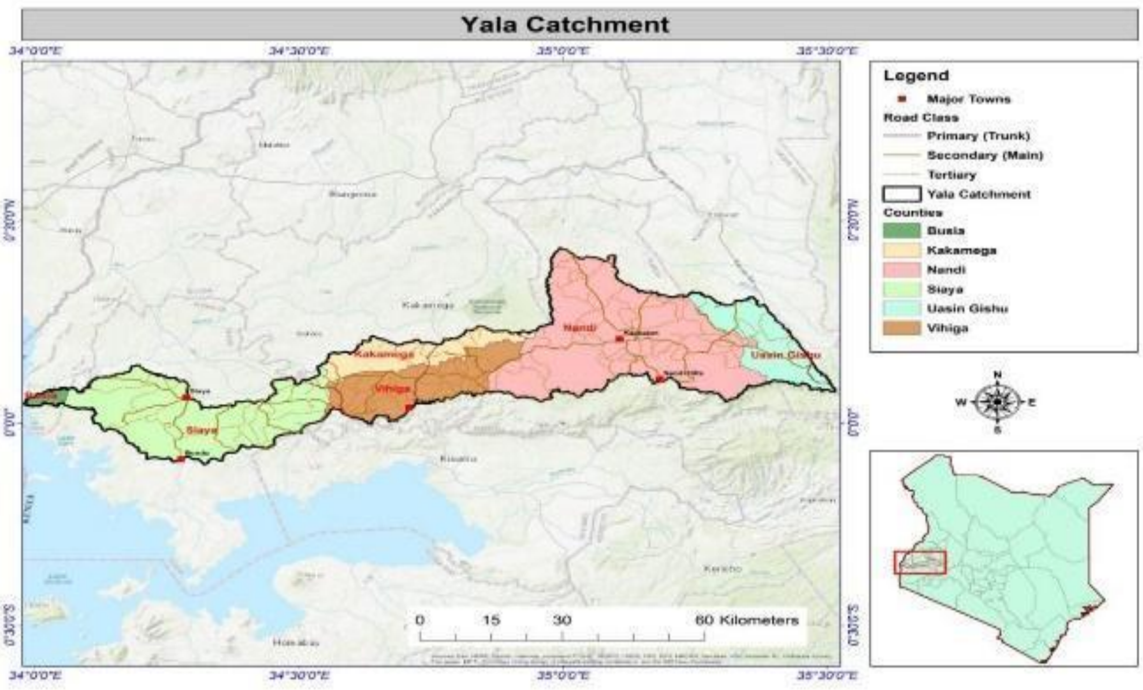


Figure 1 Map of the Yala River Catchment

In this study, thirty-four (34) pumping/observation wells and river flow data were used in the phreatic/groundwater flow model. Calibration and validation for a steady-state experience were done using data collected in the catchment. The study area was hydrogeologically unbounded on all its sides except at the discharge to the lake. Its extent as defined in this study was such that long-term hydraulic gradients at those boundaries were negligible, and any groundwater fluxes computed using reasonable hydrogeological values in comparison to the total changes in storage due to vertical stresses were applied to the entire study area.

2.2. Visual-MODFLOW Model

2.2.1. The governing MODFLOW equations

Darcy's Law provides the relationships between the discharge of the groundwater, the perpendicular aquifer plane of reference to flow, the hydraulic conductivity and the hydraulic gradient. Darcy’s Law treats an aquifer as a simple, homogeneous porous medium over the scale being tested. The quantity, K, is a measure of the aquifer’s ability to conduct water flow and is obtained from any of a variety of field or laboratory tests [13].

This study considered unconfined flow for the water table aquifer. The governing flow equation for three-dimensional saturated flow in saturated porous media [14] is as in Equation 1:

$$\frac{\partial}{\partial x}\left(Kx\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Ky\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(Kz\frac{\partial h}{\partial z}\right)=Ss\frac{\partial h}{\partial t} \tag{1}$$

Kx, Ky, Kz = K = hydraulic conductivity along the x, y, and z axes, which are assumed to be parallel to the major axes of hydraulic conductivity; h = piezometric head; Q = volumetric flux per unit volume representing source/sink terms; Ss = specific storage coefficient defined as the volume of water released from storage per unit change in head per unit volume of porous material.

When the storage is zero, the equation is represented as in Equation 2:

$$\frac{\partial}{\partial x}\left(Kx\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Ky\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(Kz\frac{\partial h}{\partial z}\right)=0 \tag{2}$$

2.2.2 Groundwater sources or sinks

Groundwater sources are recharge or inflow into the aquifer, and groundwater sinks are pumping or outflow from the aquifer [14]. The equation, therefore, is written as in Equation 3:

$$\frac{\partial}{\partial x}\left(Kxh\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Kyh\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(Kzh\frac{\partial h}{\partial z}\right)\pm Q(x,y,z,t)=Ss\frac{\partial h}{\partial t} \tag{3}$$

Where Q is the volumetric source rate and/or sink rate per unit volume of the unconfined/confined aquifer. Therefore, if a groundwater source exists, there will be '+Q', and if a groundwater sink exists, there will be '-Q' [14].

These equations are built into the numerical engine, and the boundary conditions vary to mimic the catchment's hydrogeological conditions. The results are generated in the graphical user interface (GUI) window as graphs, figures, and maps for easier interpretation. This study presented the output information as summarised in the results section.

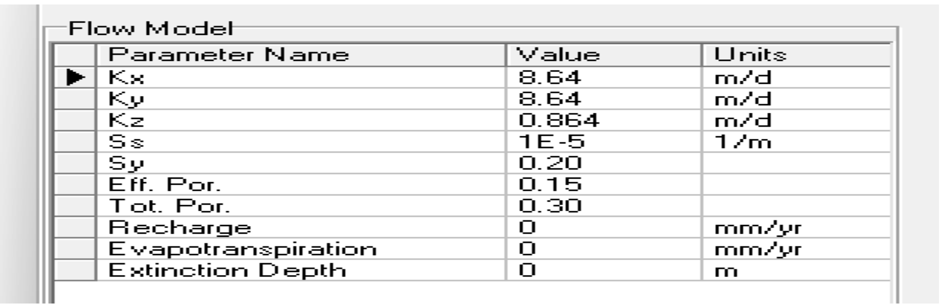
2.2.3. Setting up the model

The numerical model developed was based on a rectangular-celled, centred grid network that covered the entire model domain. Visual-MODFLOW requires model data to be entered into consistent units, which are metres and time in days. The model structure was set with the specifications as outlined in Table 1.

Table 1 Model Structure

S. No.	Specification	Value
1	Maximum model elevation	2000m
2	Maximum model elevation	0
3	Layers	6
4	Grid cell size	25
5	Rows	30
6	Columns	30

The other parameters considered were the rate of pumping, recharge, and evapotranspiration, which were derived from field measurements, while Kx, Ky, Ss, Sy, effective porosity, and total porosity were evaluated with respect to the catchment conditions, as shown in Figure 2.



Flow Model

	Parameter Name	Value	Units
▶	Kx	8.64	m/d
	Ky	8.64	m/d
	Kz	0.864	m/d
	Ss	1E-5	1/m
	Sy	0.20	
	Eff. Por.	0.15	
	Tot. Por.	0.30	
	Recharge	0	mm/yr
	Evapotranspiration	0	mm/yr
	Extinction Depth	0	m

Figure 2 Parameters in the flow model of Yala River catchment

2.3. Boundary Conditions

Boundary conditions represent the relationship of the systems with the surrounding areas, in which Visual-MODFLOW includes general head, constant head, net recharge, and river boundary conditions, among others. These are inherent parts of partial differential equations. In terms of groundwater flow modelling, they typically represent features that add fluxes to the system or specify constant head values, and they may vary in space and time. Visual-MODFLOW allows multiple ways to ‘group’ boundary conditions (e.g., Dirichlet, Neumann, and Cauchy types) and can be placed in one of two groups: Those representing discrete spatial features (e.g., rivers, wells, drains) and those representing continuous spatial features (e.g., recharge, evapotranspiration). In this study, river and recharge boundary conditions were employed as model inputs. The General-Head Boundary (GHB) package was used to simulate flux boundaries depending on head. It was proportioned to the differences in heads at the boundary of the model domain.

2.3.1 River

The representation of the hydrogeological system interacts with its surroundings and the associated catchment drainage. The Arc-GIS tool was used to develop river polyline shapefiles and export them into the model domain.

2.3.2 Recharge

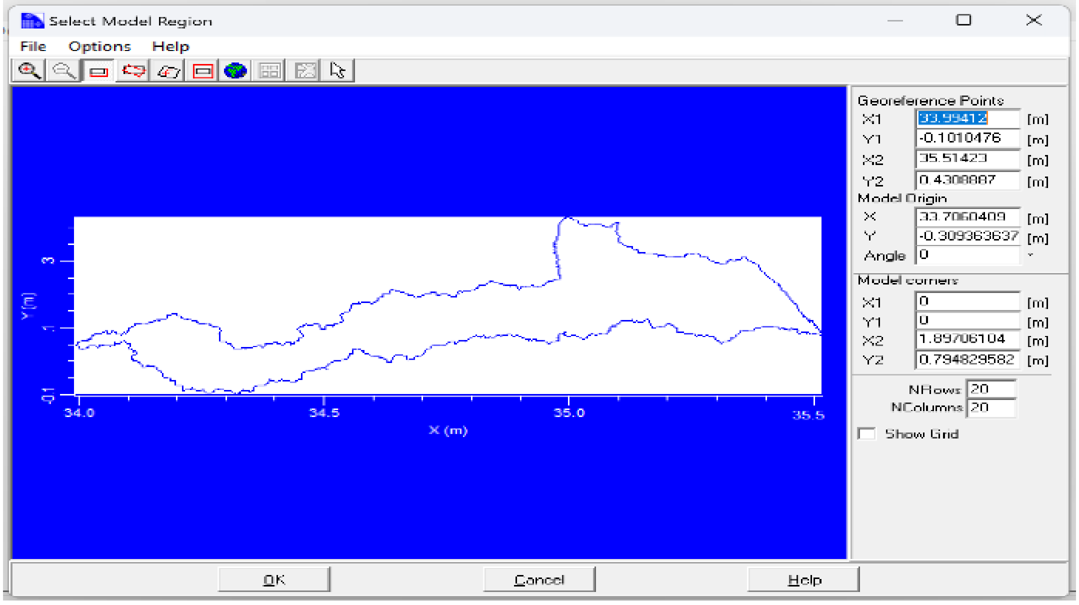
The recharge package in Visual-MODFLOW defines the recharge values in the model domain. As there were no surface water storage facilities built there, only precipitation served as the primary source of recharge in the study area. The precipitation and subsequent processes of infiltration and percolation recharged the phreatic zones in the catchment. There were also leakage and transient flows from the rivers and recharge from the nearby aquifers.

2.3.3. Well condition

The wells were considered pumping and observation wells. The pumping or outflow rates were collected from the Water Resources Authority – Kakamega, between 2015 and 2023.

2.4. Model Region

The model region was selected as depicted in Figure 3. It was delineated, and geo-referenced points were picked as X1 33.99412, Y1 -0.1010476, X2-35.51423 and Y2 0.4308887.

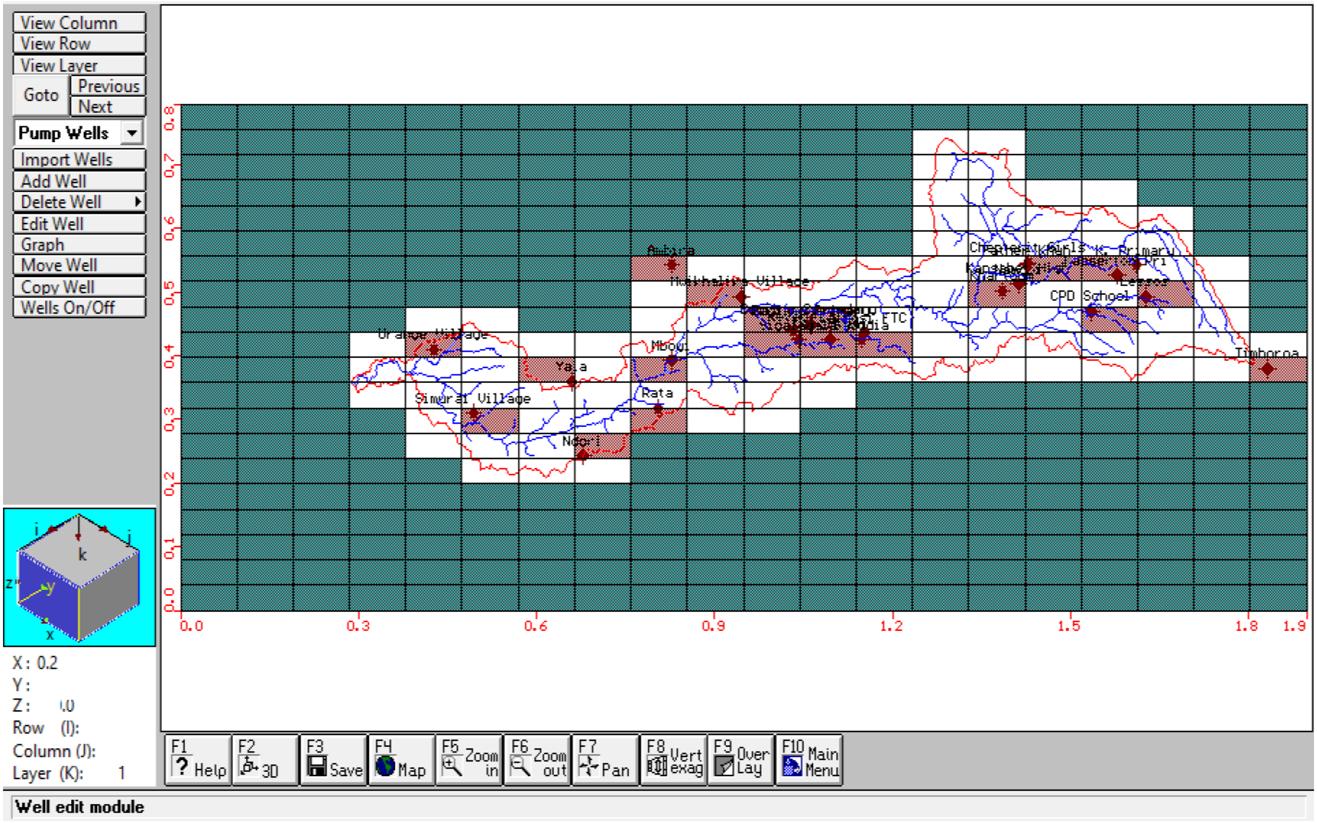


Georeference Points
X1 33.99412 [m]
Y1 -0.1010476 [m]
X2 35.51423 [m]
Y2 0.4308887 [m]
Model Origin
X 33.7060409 [m]
Y -0.309363637 [m]
Angle 0
Model corners
X1 0 [m]
Y1 0 [m]
X2 1.89706104 [m]
Y2 0.794829582 [m]
NRows 20
NColumns 20
☐ Show Grid

Figure 3 Model region

2.5. Cells and Boundaries

The model required that the cells, which covered the catchment polygons, be marked and assigned values with respect to the boundary conditions. A total of 110 cells were assigned as shown in Figure 4.

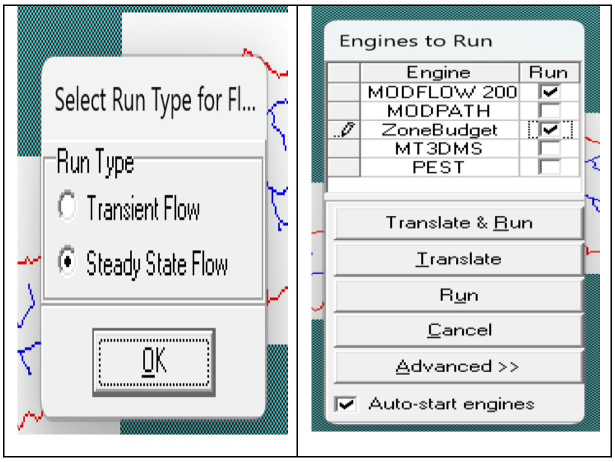


X: 0.2
Y:
Z: 0
Row (I):
Column (J):
Layer (K): 1

Well edit module

Figure 4 Model cells and boundaries

To set and run the model in Visual-MODFLOW, the authors set the type of flow (i.e., either transient or steady flow) and selected the engines to run (i.e., MODFLOW 2000, MODPATH, Zone Budget, MT3DMS or PEST). Before running the model, the type of solver was set. These processes are presented in Figure 5 and Figure 6.


Select Run Type for Fl...

Run Type

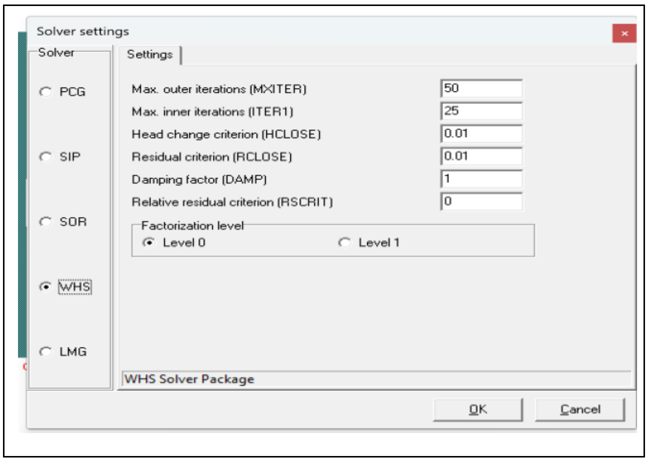
○ Transient Flow

● Steady State Flow

Engines to Run

Engine	Run
MODFLOW 200	☑
MODPATH	☐
ZoneBudget	☑
MT3DMS	☐
PEST	☐

☑ Auto-start engines


Solver settings

Solver

○ PCG

○ SIP

○ SOR

● WHS

○ LMG

Settings

Max. outer iterations (MXITER)	50
Max. inner iterations (ITER1)	25
Head change criterion (HCLOSE)	0.01
Residual criterion (RCLOSE)	0.01
Damping factor (DAMP)	1
Relative residual criterion (RSCRIT)	0

Factorization level

● Level 0 ○ Level 1

WHS Solver Package

Figure 5 Running of the model

Figure 6 Setting the model solver

2.6. Calibration and Verification

Important issues in calibrating and validating models include parameter definition or parameterisation, which is the process used to generate a tractable and hopefully meaningful representation of a model. Calibration is meant to search for the best possible representation of real system representation in the model and compensates for model insufficiencies and errors, which are unavoidable and therefore reduce the differences between the simulated results and the real-world conditions [15].

The process of calibrating the groundwater flow model involves simulating the hydraulic properties of the vadose zone material, which is normally adjusted to fit the observed heads and discharges. Due to the large catchment coverage, the estimates are usually averaged properties, resulting in uncertainties [10]. These uncertainties include uncertain initial and boundary conditions, assumed discharges (such as recharge rates and base flow discharges), and incomplete knowledge of the actual distribution of subsurface material.

2.7. Sensitivity Analysis

Sensitivity analysis entails altering model input parameters and assessing the resultant changes in model outcomes. Sensitivity analysis provides valuable understanding of both model implementation and the underlying physical processes, thus providing insight into both system and model behaviour [16]. The parameters considered were both inputs and outputs. These parameters included precipitation, recharge, hydraulic conductivity, storage coefficients, transmissivity, and specific yield. The results of the sensitivity analyses guide both model calibration and the prioritisation of future data collection plans.

2.8. Groundwater Flow Regime

The groundwater flow regime is a transformational three-dimensional flow path resulting from nexuses generated by the hydrogeological stresses within the aquifer regime. The flow regime occurs in both the vadose and phreatic zones, while storage mostly occurs in the sinks of the aquifer's phreatic zones [8]. The specific set of flow patterns in a zone is influenced by a particular set of driving conditions. The study shows that discharge rates for any point, including groundwater discharge wells, springs and boreholes, have independent factors influencing their system dynamics around them and further confirms the varied nature of discharge of these sources for any pumping rates with the nearby sources [10].

2.9. Scenarios Assessment

The U.S. Geological Survey built a zone budget tool into the Visual-MODFLOW model to help compute water budgets for desired areas in the model. This study used such a tool to determine the water balance and inflows into the aquifer system, which are the phreatic zones [17]. The mass balance method was used to track the water sources and sinks in the catchment. Three scenarios were formulated as described below.

2.9.1. Scenario 1: reference scenario

This was the “status quo” that represented the existing status of soil water, rivers and the boreholes’ water levels. The assessment was done using data randomly chosen from the study area.

2.9.2. Scenario 2: management option

The exercise involved two management scenarios. First, a controlled abstraction of groundwater was simulated, with recharge equal to the abstraction. The second was a hypothetical scenario where the efficiency of the borehole/well was improved.

Second, a controlled abstraction along with management of the riparian areas by planting cover crops was simulated to improve groundwater recharge and reduce losses due to evapotranspiration. These were simulated for wet periods to determine the riparian management measures that could be adopted to accommodate water demand without impairing the normal water levels of the sources. Both management scenarios assumed that the surface and groundwater sources from phreatic zones were hydrogeologically connected.

3.0 RESULTS AND DISCUSSION

3.1. Model Catchment Boundary

Precipitation recharge zones were identified with the spatial precipitation-infiltration coefficient ranging from 0.01 to 0.3 for the entire calibration time of one year. A trade-off had to be done to achieve the best fit. Spatial distribution of the recharge rate across the model domain was evident, with the eastern area ranging from 0.11 to 4.28 mm/a, the western area ranging from 17.82 to 18.56 mm/a, and the central area ranging from 7.18 to 13.67 mm/a.

The evapotranspiration was assumed to be from the top of the saturated zone at a transition depth of 0.05 m. The river's bed material conductance also varied within the model domain, with the upper reaches having about 23 m^2/d, the middle reaches having about 38 m/d, and the lower reaches having about 67 m^2/d. The river's stage data was also obtained from four meteorological stations and varied between and along the main river and its tributaries.

Other surface water bodies were also taken as boundaries, e.g., rivers, streams, and channels that were in contact with the aquifer. The assignment of GHB was necessitated by the fact that there was overland flow from the outside of the model area. Due to lack of data on the runoff and the aquifer boundary, or phreatic zones could not be extended infinitely, the GHB values were based on heads as watched in the observation wells and rivers in the modelled area at the initial stage. The entire aquifer bottom was treated as an impermeable boundary, as shown in Figure 7.

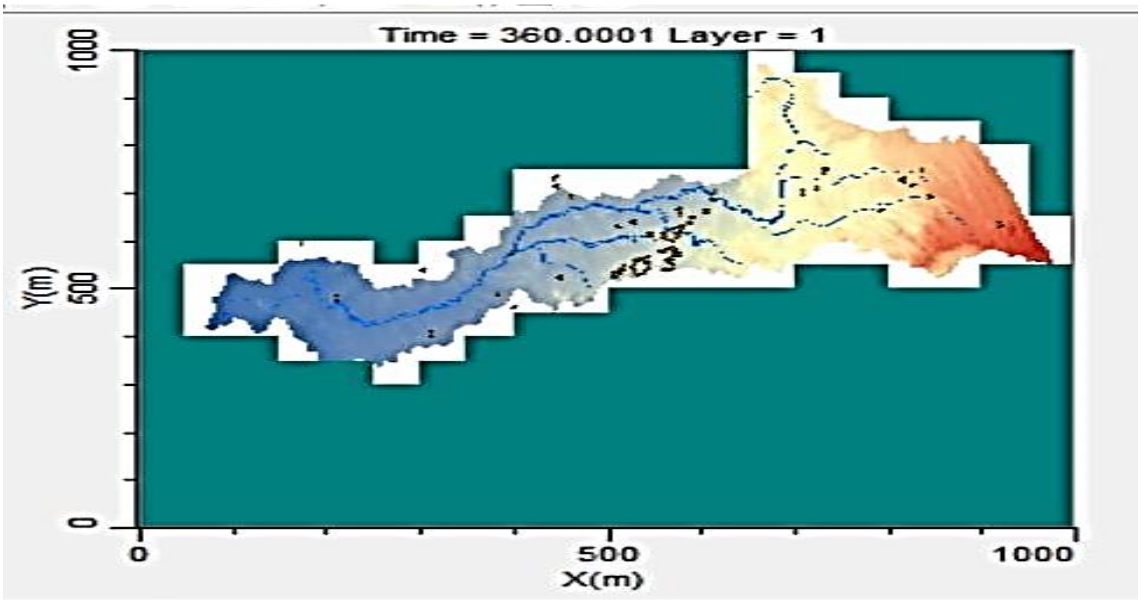


Figure 7 The catchment surface boundary

3.2. Model Calibration and Verification

The phreatic/groundwater flow was assumed to be under transient-state conditions represented by groundwater conditions from 2015 to 2023. The groundwater flow did not change significantly with time. The WHS was used as a solver. The model was simulated based on the observation wells for 12 months, with a simulation period of 360 days and time step multipliers of 10 and 1.19, respectively. Thereby, the model was calibrated relating to residual recharge and hydraulic conductivities and resulted in a low residual error of 0.01 m at the observation wells. The wells are spatially positioned as in Figure 8.

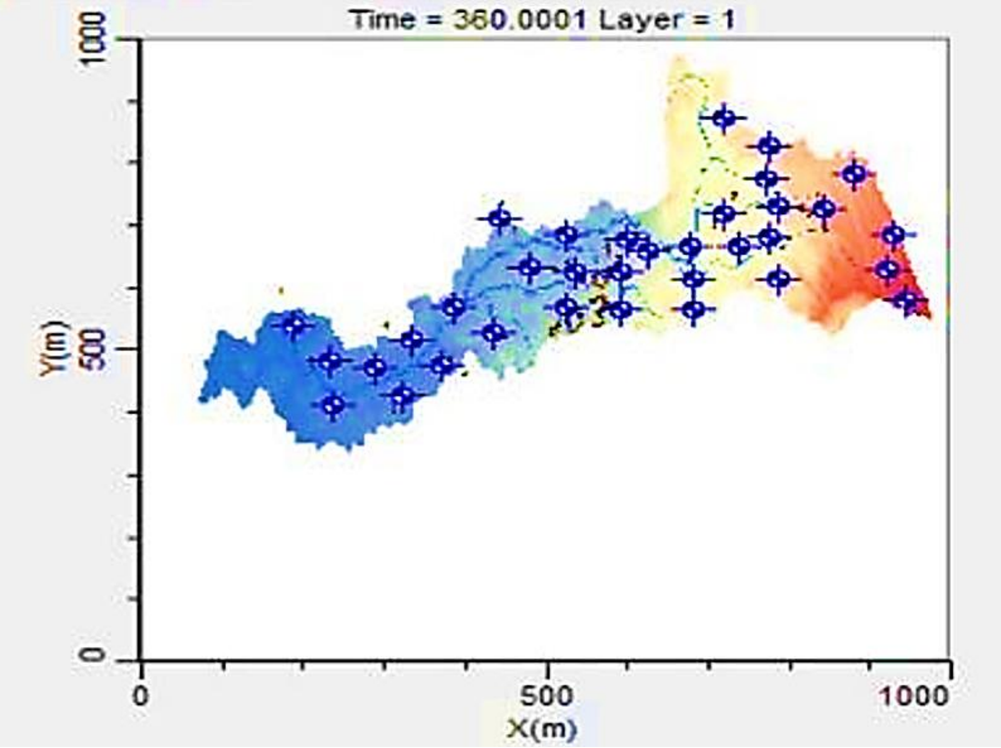
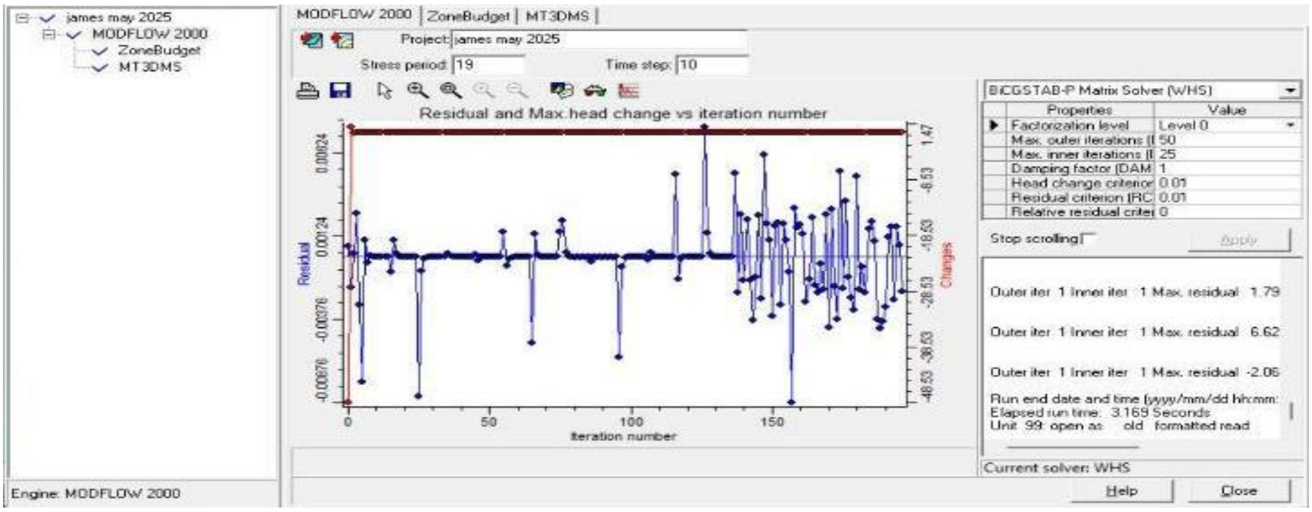


Figure 8 Pumping wells or observation wells

The calibration results indicate that the differences between the simulated heads and observed heads at observation wells were all less than 2.0 m in Figure 9, while the verification results are in Figure 10.



Project: james may 2025

Stress period: 19

Time step: 10

BiCGSTAB-P Matrix Solver (WHS)

Properties	Value
Factorization level	Level 0
Max. outer iterations (I	50
Max. inner iterations (I	25
Damping factor (DAM	1
Head change criterior	0.01
Residual criterion (RC	0.01
Relative residual criter	0

```
Outer iter  1 Inner iter   1 Max. residual   1.79

Outer iter  1 Inner iter   1 Max. residual   6.62

Outer iter  1 Inner iter   1 Max. residual  -2.06
Run end date and time (yyyy/mm/dd hh:mm:
Elapsed run time:  3.169 Seconds
Unit  99: open as     old   formatted read
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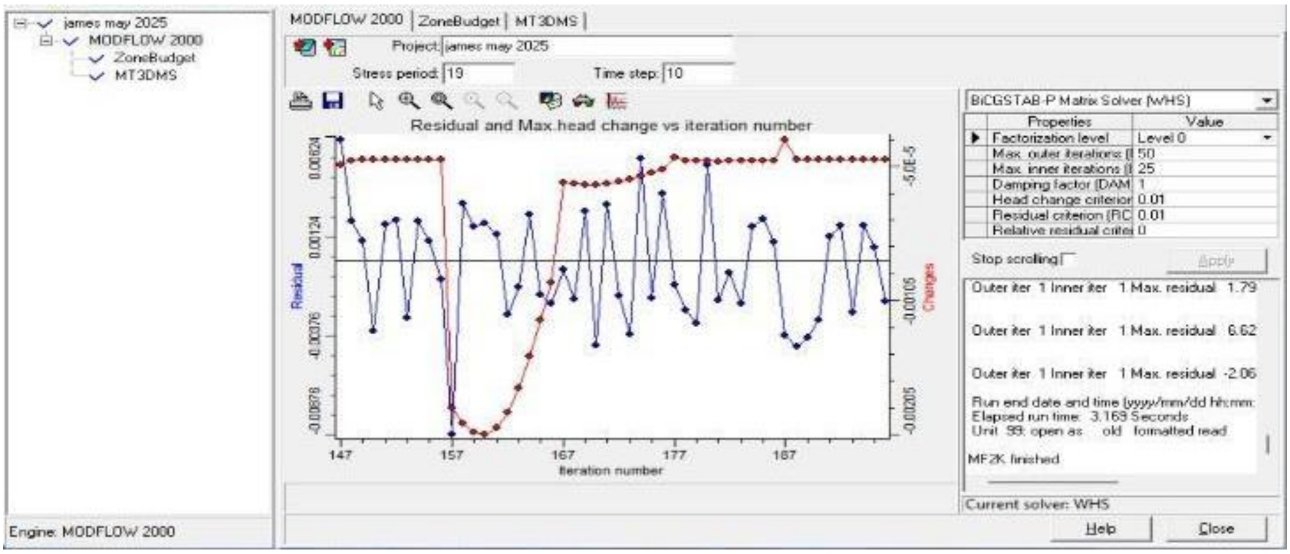
Current solver: WHS

Engine: MODFLOW 2000

Figure 9 First iteration from day 1-190



Project: james may 2025

Stress period: 19

Time step: 10

BiCGSTAB-P Matrix Solver (WHS)

Properties	Value
Factorization level	Level 0
Max. outer iterations (I	50
Max. inner iterations (I	25
Damping factor (DAM	1
Head change criterior	0.01
Residual criterion (RC	0.01
Relative residual criter	0

Stop scrolling ☐

```
Outer iter  1 Inner iter   1 Max. residual  1.79

Outer iter  1 Inner iter   1 Max. residual  6.62

Outer iter  1 Inner iter   1 Max. residual  -2.06

Run end date and time (yyyy/mm/dd hh:mm:
Elapsed run time:  3.169 Seconds
Unit  99: open as     old   formatted read

MF2K finished
```

Current solver: WHS

Engine: MODFLOW 2000

Figure 10 Second iteration from day 147-190

The damping factor was 1, the head-change criterion was 0.01, and the residual criterion was 0.01. The fact that the residuals were all less than 10 per cent of the variability in the field data across the model domain in each of the cases of the stress periods and that the calibrated model hydrogeological parameters, i.e., hydraulic conductivities, specific yield and storage coefficient, were within the aquifer pumping test data also had confirmed the validity of the groundwater flow model for the Yala River catchment.

While running the model for days 147 to 190, the trends indicated a maximum head of 0.00624 m and a minimum of -0.00676 m. The head changes recorded a maximum of 0.00524 m and a minimum of -0.0068 m. If the residual is less than 2, then the verification is within acceptable levels.

The observed trends indicated consistency as shown in Figure 9 and Figure 10. The significant drop at iteration 160 hit a maximum low of -0.0068 m for both the residual and the changes of hydraulic heads, confirming the presence of a cone of depression in the catchment.

3.3. Catchment Flow Direction

The phreatic/groundwater flow regime, as shown by the flow lines, provided a detailed understanding of the flow direction and indicated the groundwater movement paths within the catchment area and, consequently, the groundwater discharge. The groundwater flowed into the Yala River catchment and came from the upper and lower reaches, and converged at the cone of depression with little leakage at the upper boundary, which mirrored the historic flow pattern in the second iteration of days 147–190. In all cases, the upstream Yala River and its tributaries were found to act as a losing river, while the downstream was the opposite, a gaining river, as indicated by the head contours and flow direction lines in Figure 11.

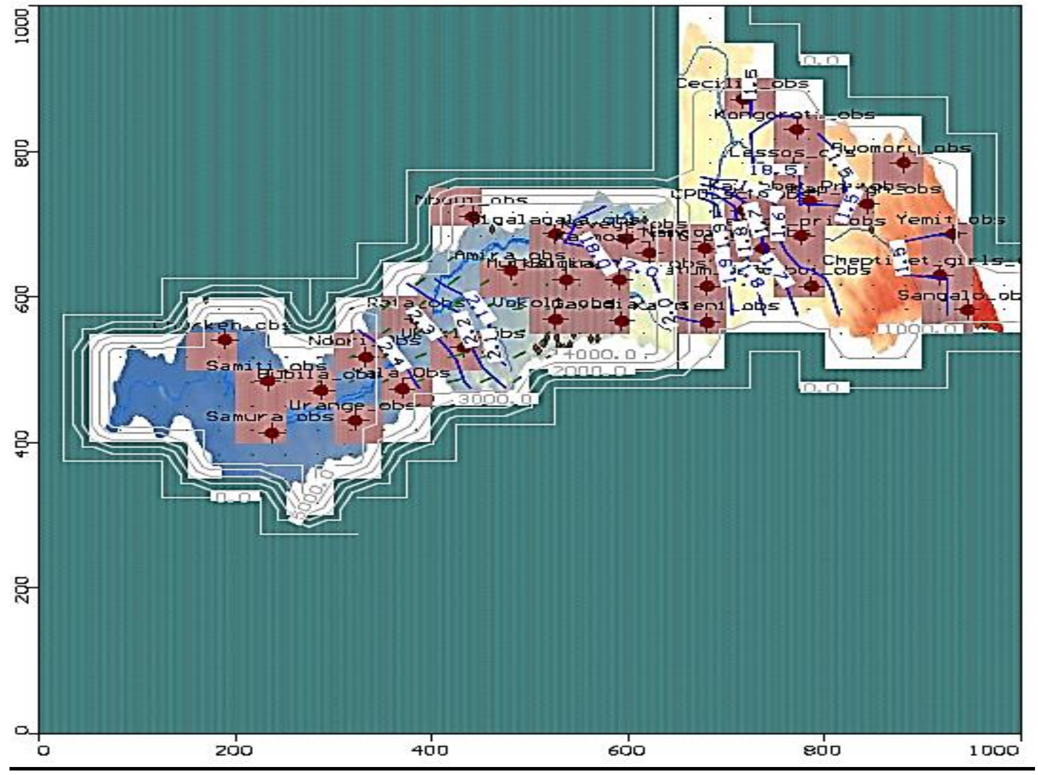


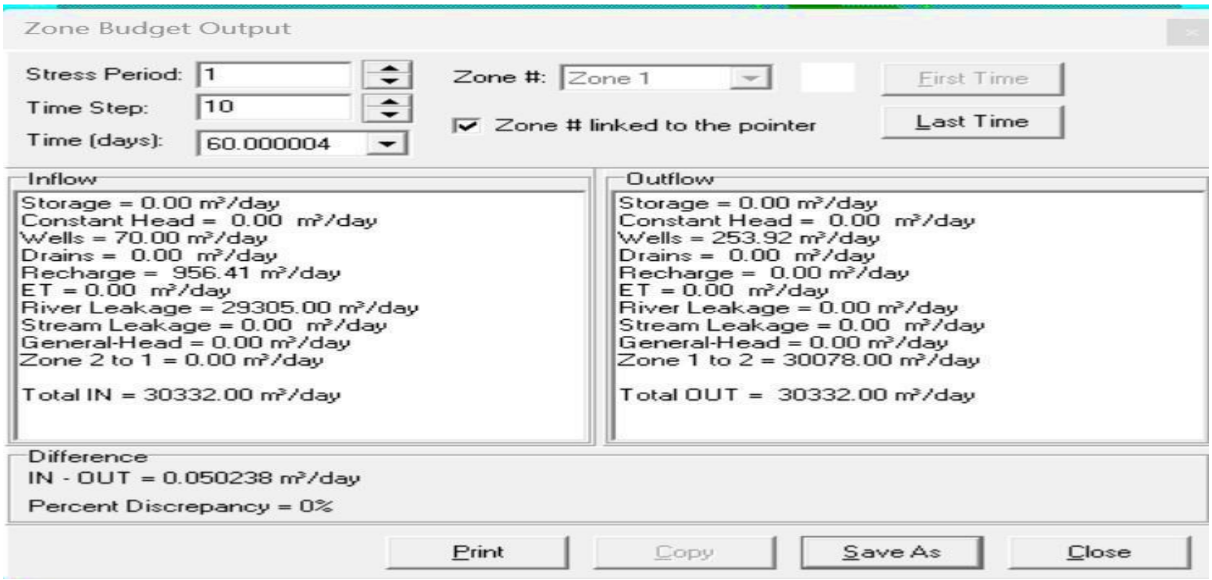
Figure 11 Flow regime

3.4. Mass Balance

In mass balance and zone budget, all flow terms (i.e., zone-to-zone) were provided with IN and OUT terms, regardless of whether the specific boundary condition type allowed inflows or outflows. In Visual-MODFLOW and ZoneBudget, the sign/naming convention indicated that all terms in the mass balance referred to the phreatic cells in the zone. Thus, IN always meant that the boundary condition (or other zone) was adding water to the phreatic zones, while OUT meant that the boundary condition (or other zone) was removing water from the specified groundwater or phreatic zone. With these facts in mind, 'drain OUT' refers to the amount of water leaving all phreatic cells in the specified zone through a drain boundary condition within that zone. Drain IN was the amount of water entering groundwater cells in the specified zone by means of a drain boundary condition within that zone. However, by definition, since drains could not add water, this term was always reported as 0.

3.4.1. Scenario 1: reference scenario

This scenario was the “status quo”, in which the catchment’s phreatic budget analysis was calculated from the phreatic data collected as presented in the output table for the zone budget in Figure 12. In this regard, the catchment received a total of 30332.050238 m^3/day and discharged 30332.000001 m^3/day. In the reference scenario, the discrepancy was maintained at 0.00 to ensure the model ran in an ideal situation. Figure 13 shows the zonal budget for this reference scenario.


Zone Budget Output

Stress Period: 1

Time Step: 10

Time (days): 60.000004

Zone #: Zone 1

☑ Zone # linked to the pointer

Inflow

Storage = 0.00 m^3/day
Constant Head = 0.00 m^3/day
Wells = 70.00 m^3/day
Drains = 0.00 m^3/day
Recharge = 956.41 m^3/day
ET = 0.00 m^3/day
River Leakage = 29305.00 m^3/day
Stream Leakage = 0.00 m^3/day
General-Head = 0.00 m^3/day
Zone 2 to 1 = 0.00 m^3/day

Total IN = 30332.00 m^3/day

Outflow

Storage = 0.00 m^3/day
Constant Head = 0.00 m^3/day
Wells = 253.92 m^3/day
Drains = 0.00 m^3/day
Recharge = 0.00 m^3/day
ET = 0.00 m^3/day
River Leakage = 0.00 m^3/day
Stream Leakage = 0.00 m^3/day
General-Head = 0.00 m^3/day
Zone 1 to 2 = 30078.00 m^3/day

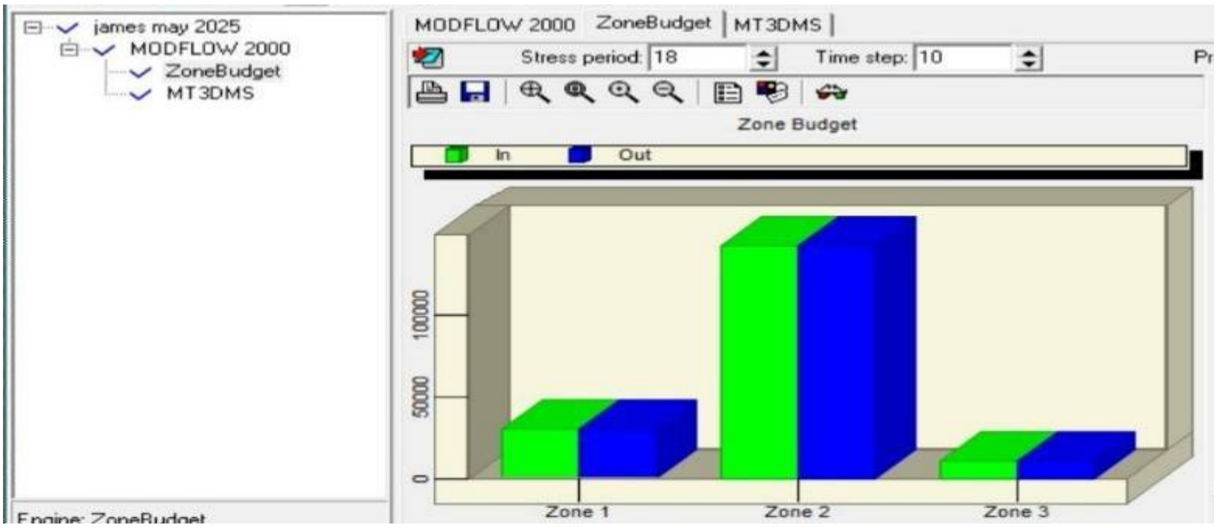
Total OUT = 30332.00 m^3/day

Difference

IN - OUT = 0.050238 m^3/day

Percent Discrepancy = 0%

Figure 12 Zone budget output


Stress period: 18

Time step: 10

Figure 13 The zonal budget

These results provided the IN–OUT difference of 0.050238 m^3/day with a 0.00 percentage discrepancy in Figure 14. In this scenario, almost all water that entered the catchment's phreatic zones was discharged with insignificant storage, which did not enhance sustainable phreatic storage in the catchment.

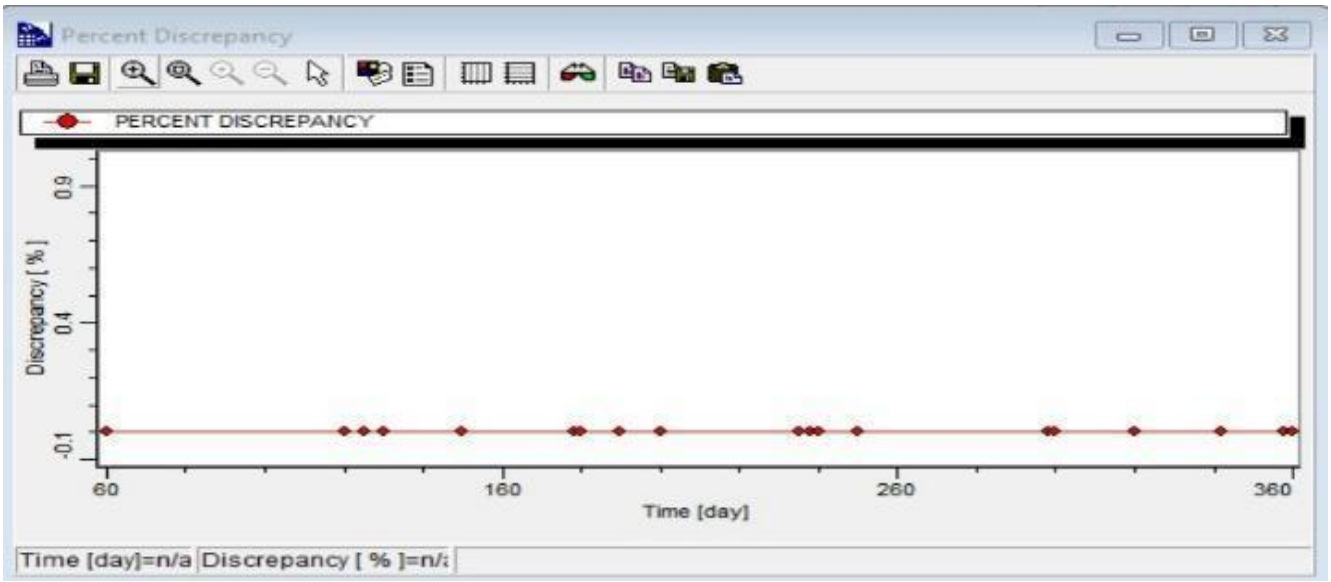


Figure 14 Discrepancy against time period

3.4.2. Scenario 2: management options

The scenario involved the two management scenarios previously stated, as discussed, respectively, below.

i. Controlled abstraction of groundwater

Controlled abstraction of groundwater operations was based on the assumption that groundwater abstraction from wells was regulated and that the only recharge came from river leakages. This was a hypothetical scenario in which groundwater abstraction was effectively managed for all boreholes and wells.

Mass balance in the simulation was undertaken for 360 time periods (days), and the report provided that the recorded inflow was 70.00 m^3 in wells, 0 storage, 0 constant head, 0 drains, 2265.89 m^3 for recharge, 0 evapotranspiration, 151171.44 m^3 for river leakage, and 0.00 for stream leakage with a general head of 0.00, with the total cumulative inflow amounting to 153507.33 m^3. The outflow recorded 0.00 for storage, 0.00 for constant head, 1904.98 m^3 for wells, 0.00 for drains, 0.00 for recharge, 0.00 for evapotranspiration, 151595.19 m^3 for river leakage, 0.00 for stream leakage, and 0.00 for general head, and the cumulative outflow recorded a total of 153500.17 m^3. The zonal summary is as tabulated in Table 2.

Table 2 Zone Budget Summary Calculations – Controlled Groundwater Abstraction

Boundary condition	Inflow (m^3/day) -	Outflow (m^3/day)
Recharge	2265.89	0
River leakage	151171.44	-151595.19
Wells	70.00	-1904.98
Evapotranspiration	0.00	0.00
Constant head	0.00	0.00
Drains	0.00	0.00
Storage	0.00	0.00
Total	153507.33.	-153,500.17
Inflow-Outflow	7.16	

The IN–OUT difference was 7.16 m^3, with a 0.00 per cent discrepancy. The total discrepancy remained at 0.00 throughout the simulation, showing that the model was able to perform as expected. The discrepancy curve is presented in Figure 15. The dipping of the curve shows the transient nature of flow, pointing at a depressant flow regime.

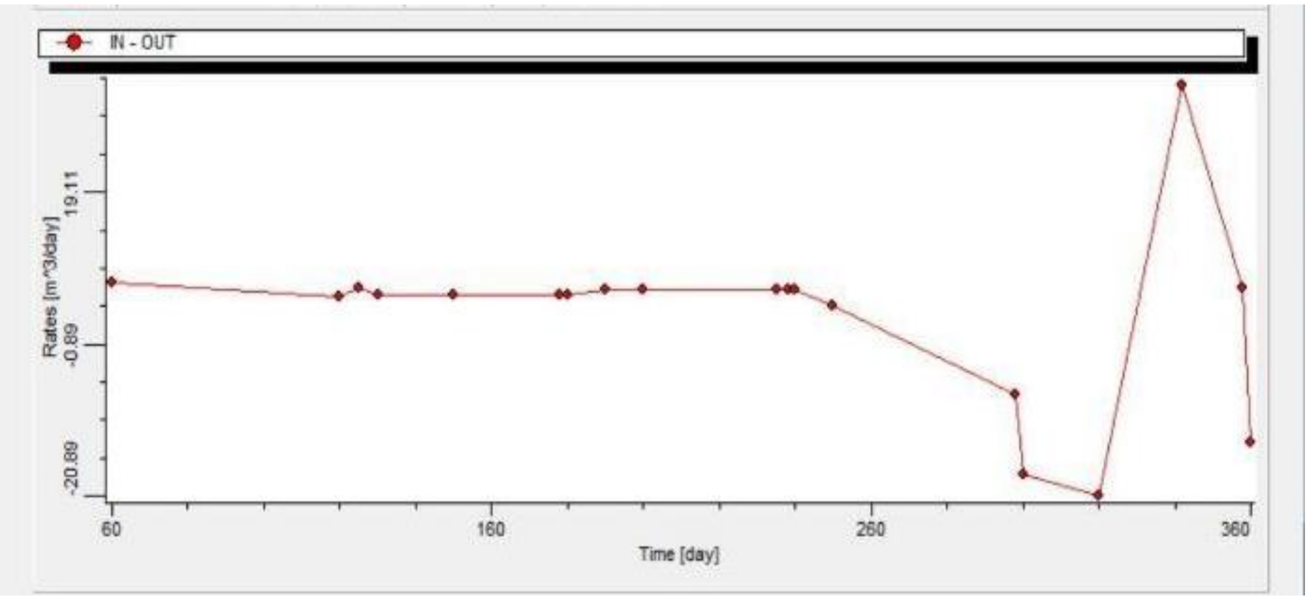
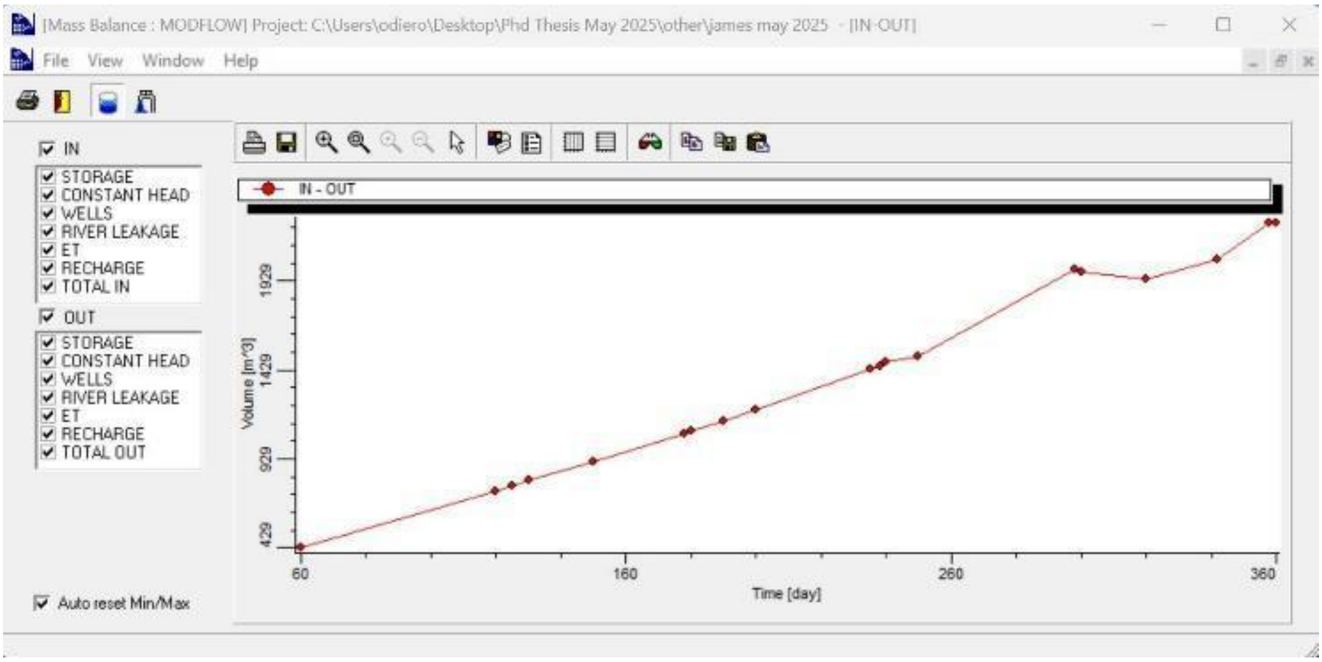


Figure 15 Zonal curve for volume vs time step from 60 to 360 days Map of the Yala River Catchment

ii. Controlled abstraction and management of the catchment

The exercise was done with assumptions that phreatic water abstraction and river leakages were managed. This was a hypothetical scenario where the phreatic/groundwater abstraction was effectively managed for all the boreholes/wells, and the catchment phreatic zones were managed to improve the river discharge while losses through evapotranspiration were reduced. The figure above shows the zonal budget where there was increased river leakage in all the zones of over 100,000 m^3/annum. Other external sources were accounted for, which were assumed to be base flows from other zones. Groundwater/phreatic zone storage showed an increase from 7.6 to 429 m^3 in the zonal unit after the model ran from day 60 to 360. This increase was confirmed as evident in Figure 16, demonstrating an improved groundwater flow regime.



☑ IN
☑ STORAGE
☑ CONSTANT HEAD
☑ WELLS
☑ RIVER LEAKAGE
☑ ET
☑ RECHARGE
☑ TOTAL IN
☑ OUT
☑ STORAGE
☑ CONSTANT HEAD
☑ WELLS
☑ RIVER LEAKAGE
☑ ET
☑ RECHARGE
☑ TOTAL OUT
☑ Auto reset Min/Max

Figure 16 Mass balance curve for volume vs time step from 60 to 360 days

Figure 17 represents the output of all the input parameters and phreatic storage responses in the model. The report provided inflow volumes recorded at 42,000 m^3 in wells, 0 constant head, 0 drains, 135953.00 m^3 for recharge, 0 evapotranspiration, 9,070,286.00 m^3 for river leakage, 0.00 for stream leakage with a general head of 0.00, and the total cumulative inflow amounted to 9,210,439.00 m^3.

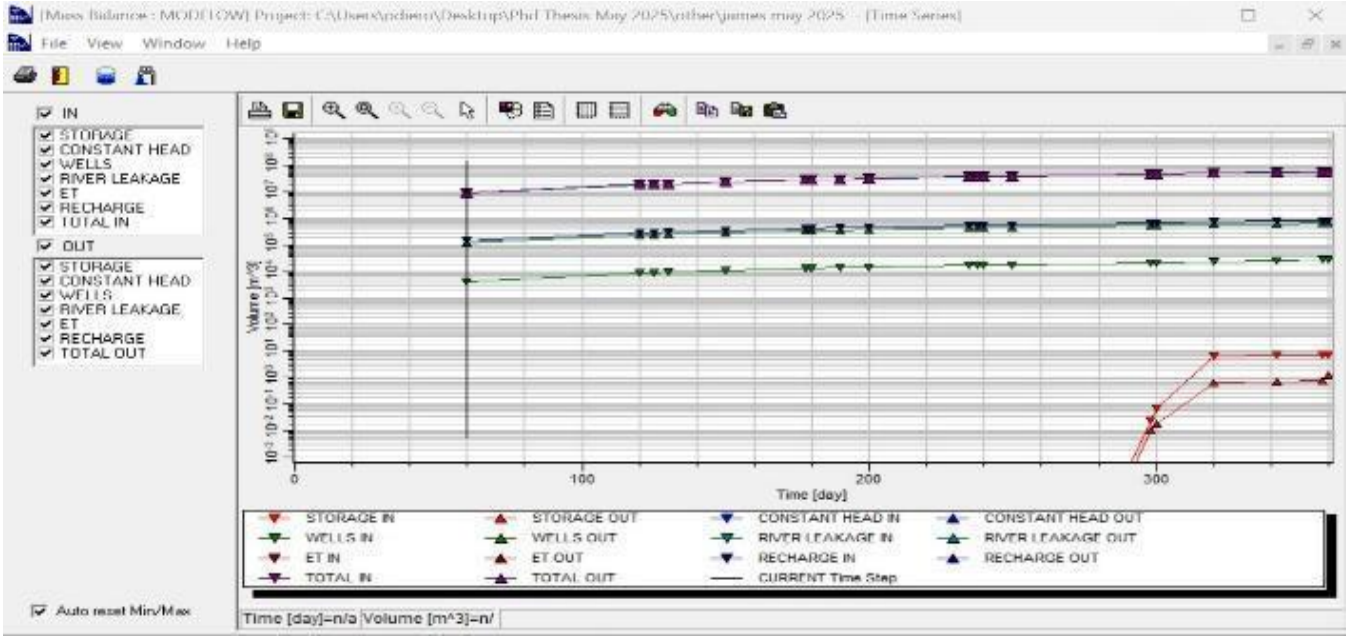


Figure 17 Rates for time step report from 0 to 360 days

The outflow recorded 0.00 for storage, 0.00 for constant head, 114,298.00 m^3 for wells, 0.00 for drains, 0.00 for recharge, 0.00 for evapotranspiration, 9095711.00 m^3 for river leakage, 0.00 for stream leakage, and 0.00 for general head, and the cumulative outflow recorded a total of 9,210,010.00 m^3. The managed catchment scenario is summarised in Table 3 below.

Table 3 Zone Budget Summary Calculations – Catchment Managed

Boundary condition	Inflow (m^3/day)-	Outflow (m^3/day)
Recharge	135,953.00	0
River leakage	9,070,286.00	-9095711.00
Wells	42,000.00	-114298.00
Evapotranspiration	0.00	0.00
Constant head	0.00	0.00
Drains	0.00	0.00
Storage	0.00	0.00
Total	9210439.00	-9210010.00
Inflow-Outflow	429.00	

The IN–OUT difference was 429.00 m^3 with a 0.00 percentage discrepancy. This demonstrates that when the catchment was managed, recharge was expected to increase and consequently increase the aquifer storage by 98.33%, i.e., from 7.16 to 429 m^3.

3.5. Sensitivity Analysis

The parameters varied with an increment and decrement of 5% to 20% in Table 4a and Table 4b. Recharge was one of the main factors determining the head and contaminant variations in addition to the stresses applied to the phreatic system. Analysis was conducted on changing the hydraulic conductivity and recharge values of parameters in zones simultaneously. Corresponding percentage changes were plotted against the change in the percentage of parameters. In this scenario, the recharge being the dependent variable, it was assumed to be a normally and spatially distributed random variable.

Table 4a Sensitivity Analysis 1

Parameter	Value	Parameter	Value
kx	8.64	Ss	1,000
Ss	1.00E-05		
Sy	0.2	L	100
Eff Porosity	0.15	T	864
Total Poro	0.3		

Table 4b Sensitivity Analysis 2

	Parameters				**Changes in K**			
H	**dh/dl**	**R (q)**	**0.05**	**0.1**	**0.15**	**0.2**	**0.25**	**0.3**
10	0.1	0.864	0.0432	0.0864	0.1296	0.1728	0.216	0.2592
20	0.2	1.728	0.0864	0.1728	0.2592	0.3456	0.432	0.5184
30	0.3	2.592	0.1296	0.2592	0.3888	0.5184	0.648	0.7776
40	0.4	3.456	0.1728	0.3456	0.5184	0.6912	0.864	1.0368
50	0.5	4.32	0.216	0.432	0.648	0.864	1.08	1.296
60	0.6	5.184	0.2592	0.5184	0.7776	1.0368	1.296	1.5552
70	0.7	6.048	0.3024	0.6048	0.9072	1.2096	1.512	1.8144
80	0.8	6.912	0.3456	0.6912	1.0368	1.3824	1.728	2.0736
90	0.9	7.776	0.3888	0.7776	1.1664	1.5552	1.944	2.3328
100	1	8.64	0.432	0.864	1.296	1.728	2.16	2.592

Figure 18 shows that when the value of hydraulic conductivity was constant, recharge was constant as well. However, when K increased, recharge increased linearly. Therefore, K had a direct effect on the recharge of the hydrogeological regime.

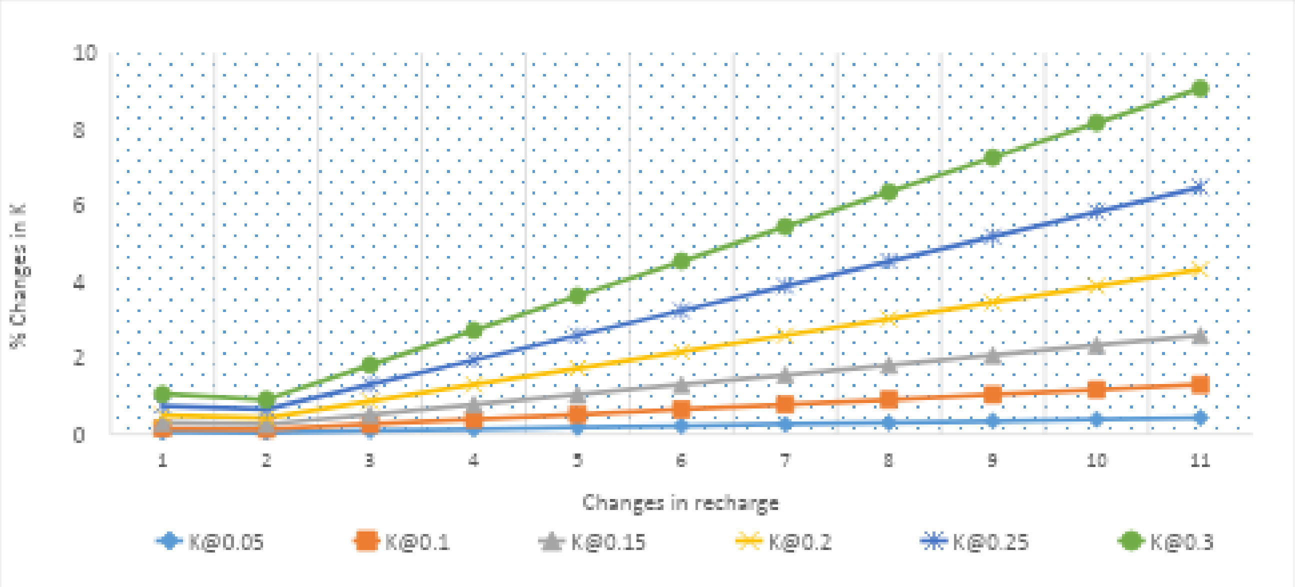


Figure 18 Rates of change in K against recharge

4.0 CONCLUSION AND RECOMMENDATIONS

4.1. Conclusion

The transient state simulation was undertaken for 360 days. While running the model for days 147 to 190, the trends indicated a maximum head of 0.00624 m^3 and a minimum of -0.00676 m^3. The head changes recorded a maximum of 0.00524 m^3 and a minimum of -0.0068 m^3. If the residual is less than 2, then the verification is within acceptable levels.

While observing the trends in this regard, it indicated a consistent trend with a significant drop at iteration 160, hitting a minimum model of below -0.0068 m^3 for both the residual and the changes in hydraulic head backflow from the lower level to the mid-block of the catchment.

The result of the budget for the reference scenario provided the IN–OUT difference of 0.050238 m^3/day with a 0.00 percentage discrepancy. In this scenario, the consequence of insufficient phreatic storage was unfavourable.

Contradictorily, the zonal budget for the management scenario when only abstraction was controlled provided the IN–OUT difference was 7.16 m^3, with a 0.00 per cent discrepancy. In this controlled scenario, catchment phreatic storage improved from 0.050238 m/day in the reference scenario to 7.16 m/day. Furthermore, when the entire catchment was well managed, the model groundwater IN-OUT difference increased to 429 m/day, resulting in a 422.4 m/day increase in the phreatic zonal unit, which corresponds to a 98.33% increase. Therefore, it is concluded that integrated catchment management was fundamental in the management of the catchment's hydrogeological flow regime.

4.2. Recommendations for Future Studies

Since the aquifer's phreatic storage increased by 98.33% from 7.16 to 429 m^3 in a model unit, it is therefore recommended that catchments require strategic catchment management interventions for sustainable groundwater resources.

The cone of depression in the middle-upper reaches of the catchment should inform further research in this region.

The model results can be used as a basis for investigating hydrogeological flow regimes in other catchments with similar or relative geographical characteristics.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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