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Hydrological modeling of the Guptamani watershed using MIKE SHE: Calibration and simulation of groundwater and surface water interactions

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Abstract
This study applied the MIKE SHE model to the Guptamani Watershed in West Bengal, India, to assess water balance and groundwater recharge. MIKE SHE, a spatially distributed, physically-based model, simulates the interactions between surface water and groundwater. The model was calibrated from June 2007 to April 2008 using observed groundwater levels and surface runoff, and then applied to simulate hydrological conditions from May 2008 to April 2009. Results showed that the model accurately simulated groundwater levels (Nash-Sutcliffe coefficients of 0.71 to 0.82) and surface runoff (0.73). The study revealed that actual evapotranspiration accounted for 72.28% of total rainfall, with significant variations in water content across the watershed. These findings provide valuable insights for water management strategies in the face of climate variability and water scarcity.

Keywords: MIKE SHE model, Groundwater recharge, Water balance, Surface runoff, Hydrological modeling

1. Introduction
The hydrological processes within a region play a crucial role in determining water availability and agricultural practices, both of which are fundamental to sustainable development (Kundzewicz 1997) [7]. Effective water management is increasingly recognized as a critical factor in ensuring long-term water security, particularly in areas that are highly dependent on agriculture (Falkenmark 2013; Sadoff and Muller, 2009) [2, 9]. These processes, including precipitation, infiltration, groundwater recharge, and surface runoff, are interconnected and require a comprehensive understanding to ensure that water resources are used efficiently (Huntington and Niswonger 2012) [4]. The ability to model and predict these processes, particularly groundwater recharge and surface runoff, provides valuable insights for developing effective water management strategies tailored to the unique needs of the region (Gorelick and Zheng 2015) [3].

In many rural areas, the majority of agricultural practices rely on seasonal rainfall, making water availability highly variable. During periods of drought or irregular rainfall, this dependency on natural sources of water can lead to water shortages, affecting both crop productivity and water security (Bodner *et al*., 2015; Kang *et al*., 2009) [1, 6]. As climate change continues to influence weather patterns, the challenges of managing water resources become even more pressing. Increasingly erratic rainfall, rising temperatures, and shifting seasonal patterns amplify the risk of both flooding and drought, which makes it crucial to accurately assess and manage water resources (Trenberth 2005) [10]. Understanding the dynamics of water movement and storage in such regions is therefore essential for developing strategies that ensure agricultural productivity while preserving water resources for future generations.

This study applies the MIKE SHE model, a comprehensive, physically-based, spatially distributed modeling system, to simulate the hydrological water balance of the region. MIKE SHE is specifically designed to simulate the complex interactions between surface water and groundwater, providing a robust framework for understanding water movement across a landscape. By integrating various hydrological processes such as interception, evapotranspiration, surface runoff, and groundwater recharge, MIKE SHE allows for a more detailed and accurate assessment of the water cycle. The ability to simulate these processes at different spatial scales makes MIKE SHE an ideal tool for studying regions where water management is critical (Ma *et al*., 2016; Jaber and Shukla., 2012; Xevi *et al*., 1997) [8, 5, 11].

The primary focus of this research is to investigate groundwater recharge and surface runoff,

two key components of the hydrological cycle that are vital for determining water availability. Groundwater recharge, the process by which water percolates through the soil to replenish underground aquifers, is crucial for maintaining the base flow of rivers and providing a consistent water supply, especially during dry periods. Surface runoff, on the other hand, refers to the water that flows over the land surface, often leading to erosion or flooding if not managed properly. Together, these processes influence both the quantity and quality of water resources available for agricultural use and other purposes. Through the use of the MIKE SHE model, this study aims to improve our understanding of how water moves through the landscape under different climatic and land-use conditions. By examining how various factors—such as rainfall intensity, soil properties, land cover, and vegetation—affect water availability, this research provides critical insights that can guide water management practices. These findings are expected to support the development of more efficient irrigation systems, as well as improve water conservation efforts across agricultural sectors. Furthermore, by simulating different water management scenarios, the model can assist in formulating adaptive strategies that respond to changing climatic conditions and evolving water demands.

The importance of this research lies not only in filling existing knowledge gaps but also in providing actionable information for improving water management in the region. As climate change continues to exacerbate the variability of rainfall and temperature, effective water management becomes more complex and necessary. By offering a scientific framework for assessing the water balance and its components, this study contributes to the broader goal of ensuring sustainable water use in agricultural landscapes. The findings from this study are expected to have far-reaching implications for policymakers, farmers, and water resource managers, helping to create a more resilient and water-secure future for the region.

2. Methodology

2.1 Study area

The study area is the Guptamani watershed, situated in the western part of the West Midnapore district, West Bengal (Fig. 1). This watershed is managed by the Soil Conservation Department of the Government of West Bengal, with several water management structures in place, including six drop structures, one of which is located at the watershed outlet, and two straight inlet chute spillways. The watershed is geographically located between latitudes 22°20' and 22°23'N, and longitudes 87°09' and 87°11'E. It forms part of the 66-B sub-watershed of the Kangsabati Catchment and encompasses a total area of 694 hectares. The watershed has been extensively studied, with a wealth of data previously collected, including its use for testing hydrological models such as GIUH_CAL and HYDROMOD.

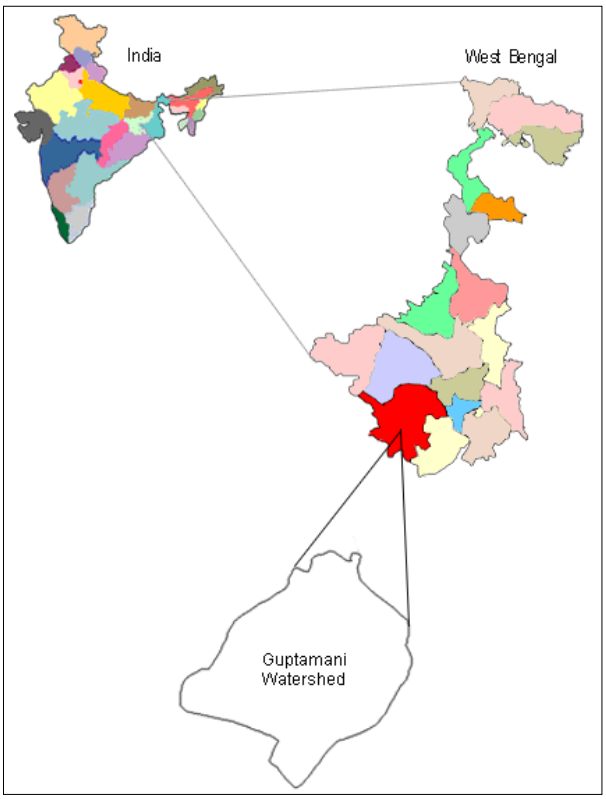

Fig 1: Location map of the study area

2.2 Physical Characteristics of the Watershed

To delineate the watershed boundary and assess topography, Shuttle Radar Topography Mission (SRTM) data with a 90 m resolution were downloaded from the Consultative Group on International Agricultural Research-Consortium for Spatial Information (CGIAR-CSI) website. Additionally, multispectral remote sensing data from LANDSAT-7 (ETM+) with a spatial resolution of 30 m, corresponding to path 139 and row 44 from 12th March 2007, were acquired from the Global Land Cover Facility (GLCF) website for the preparation of the land use/land cover map. Soil surveying within the watershed was conducted through field traverses, with soil profiling sites selected based on variations in soil characteristics and land use patterns identified in the previous study by Panigrahy (2002). Eight distinct soil series were identified within the watershed. The area-wise distribution of

these soil series is presented in Fig. 2.

Further, the bed levels, bank levels, and channel widths were measured at various locations along the channels within the watershed. The total length of the main channel within the watershed was found to be 3441 meters.

The region experiences a tropical sub-humid climate, characterized by significant seasonal variation in temperature and humidity. The minimum temperature during January ranges from 7.8 °C to 10 °C, while the maximum temperature in May fluctuates between 37 °C and 46 °C. Relative humidity in the area varies considerably, ranging from 20% to 99% throughout the year.

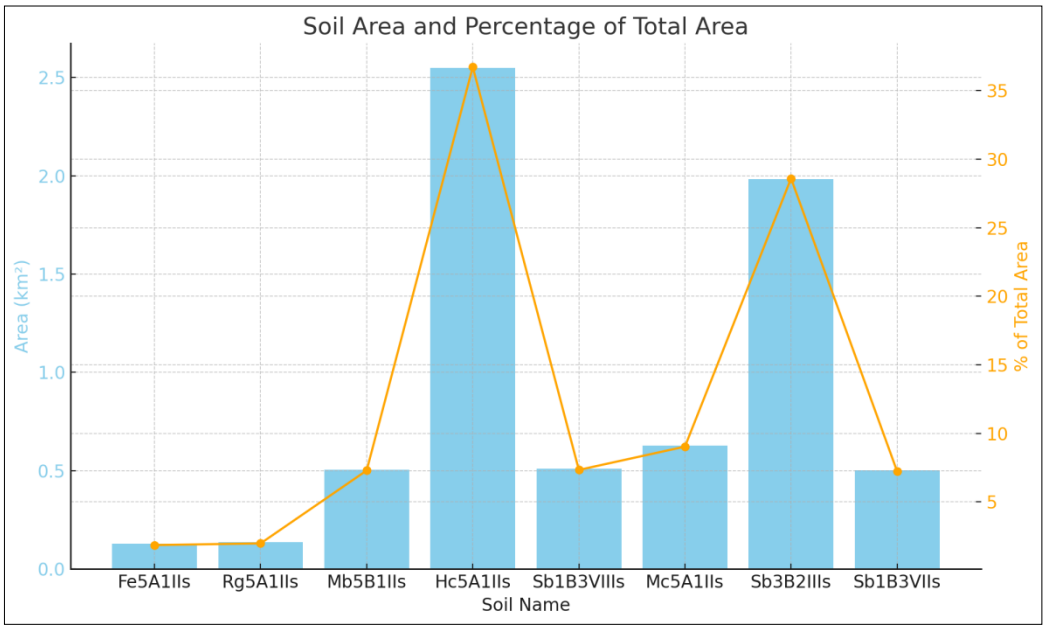

Fig 2: Area under different soils of the treated watershed

2.3 Soil Properties

To solve Richards' equation, two key hydraulic functions—namely, the soil moisture retention curve, Ψ(θ), and the hydraulic conductivity function, K(θ)—are required to characterize the soil profiles within the watershed. Additionally, several parameters must be specified, including the soil moisture at saturation (θ_s), soil moisture at effective saturation (θ_e), capillary pressure at field capacity (pF_fc), capillary pressure at wilting point (pF_W), residual soil moisture content (θ_r), the exponent in the hydraulic conductivity function (n), and the saturated hydraulic conductivity (K_s).

The van Genuchten empirical model was employed to describe the relationships between h-θ and K-θ:

$$K = K_{sat} \times S^n \quad \text{(Equation 1)}$$

$$S_e = \frac{\theta - \theta_r}{\theta_S - \theta_r} \quad \text{(Equation 2)}$$

Where:

- θ = volumetric water content,
- θ_r = residual water content,
- θ_S = saturated moisture content,
- h = suction head,
- K = hydraulic conductivity,
- K_s = saturated hydraulic conductivity,
- S_e = effective saturation,
- α, n, and m = empirical parameters.

For determining soil moisture retention curve and hydraulic conductivity function, data from earlier work of Panigrahy (2002) were taken for watershed (Table 1).

Table 1: Hydraulic properties and VGM parameters for different soils of the watershed

Soil	Depth, cm	θs, v/v	θr, v/v	Ks, m/s	VGM parameters	
					α, 1/cm	n
Fe5A1IIs	0-22	0.4288	0.0917	1.30E-08	0.0297	1.67
	22-42	0.4770	0.0926	7.46E-08	0.0500	1.64
	42-69	0.4000	0.1117	4.52E-08	0.0233	1.39
Rg5A1IIs	0-26	0.3598	0.1854	2.13E-06	0.0450	1.54
	26-57	0.4345	0.0950	4.71E-06	0.0550	1.43
	57-105	0.4036	0.1208	1.29E-06	0.0297	1.47
Mb5B1IIs	0-15	0.3210	0.1095	1.74E-06	0.0410	1.62
	15-40	0.4560	0.0447	3.12E-06	0.0400	1.44
	40-60	0.4530	0.0398	2.84E-06	0.0380	1.41
Hc5A1IIs	0-15	0.4485	0.0768	7.61E-08	0.0320	1.60
	15-30	0.4756	0.0439	2.82E-08	0.0390	1.56
	30-50	0.4343	0.0583	4.03E-07	0.0480	1.37
Sb1B3VIIIs	0-15	0.3088	0.0578	1.06E-06	0.0448	1.73
	15-30	0.3910	0.0816	2.66E-06	0.0337	2.26
	30-45	0.4210	0.0913	2.47E-06	0.0370	2.22
Mc5A1IIs	0-15	0.4550	0.0440	2.65E-06	0.0480	1.50
	15-29	0.5110	0.0768	4.90E-06	0.0187	1.65
Sb3B2IIIs	0-15	0.3150	0.0438	2.65E-06	0.0223	1.43
	15-29	0.3440	0.0403	5.31E-06	0.0149	1.46
	29-51	0.3910	0.1421	5.18E-06	0.0192	1.65
Sb1B3VIIs	0-15	0.4010	0.1142	1.02E-06	0.0316	2.33
	15-30	0.4500	0.0947	1.09E-06	0.0350	2.92
	30-45	0.4520	0.0330	1.08E-06	0.0159	1.42

2.4 Meteorological Data

A hydrological station was established within the watershed to continuously monitor key meteorological parameters, including rainfall, daily pan evaporation, temperature, and discharge. The station was equipped with a siphon-type automatic rain gauge, a standard USWB class-A pan evaporimeter, a thermometer, and an automatic water level recorder to ensure accurate data collection. A local technician

was employed to collect and record the daily meteorological data. Figure 3 illustrates the temporal variations in daily rainfall and pan evaporation for the watershed.

Groundwater levels were monitored on a fortnightly basis using an electronic water level indicator in the observation wells. A total of seven observation wells were strategically located within the watershed to measure groundwater levels (Fig. 4). Figure 5 depicts the temporal variation in the depth to groundwater levels at various well locations throughout the watershed.

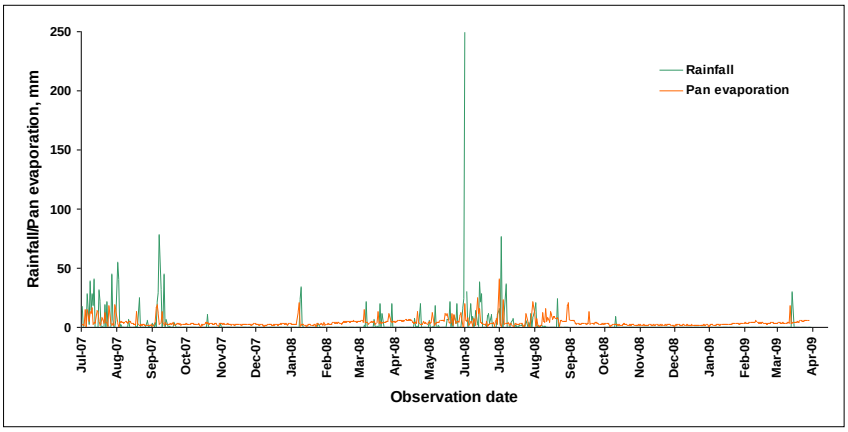

Fig 3: Daily rainfall and pan evaporation for the watershed

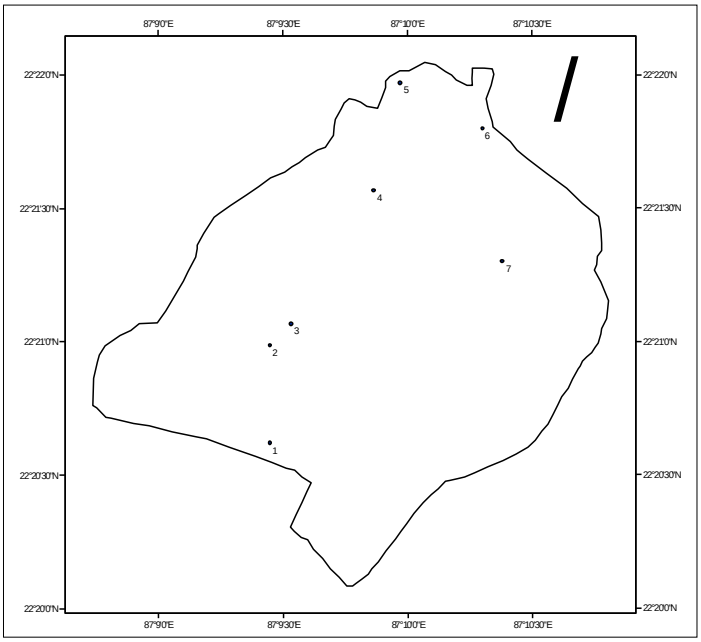

Fig 4: Observation well locations in the watershed

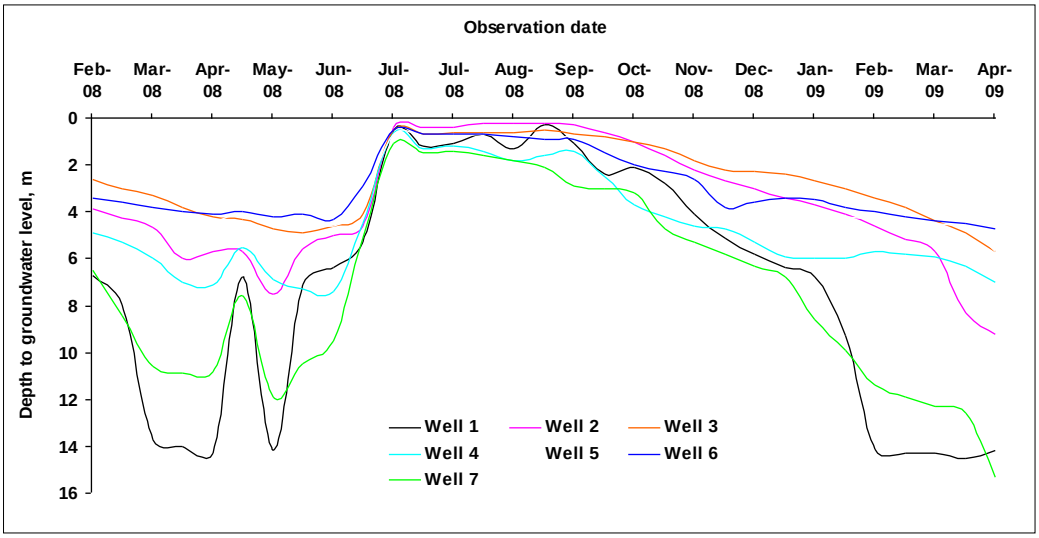

Fig 5: Temporal variation of the groundwater levels in the watershed

2.5 Model description

MIKE SHE is a comprehensive, deterministic, physically-based, spatially-distributed, integrated surface water and groundwater modeling system (DHI, 2005). It is capable of simulating both surface and groundwater movement and the interactions between these systems. The MIKE SHE system is not constrained by watershed size, allowing for the modeling of a wide range of hydrological scenarios. Input files for the model can be generated by overlaying model parameters with a grid network. The system features a graphical user interface (GUI) with both pre- and post-processing capabilities. Input spatial data can be read in GIS format, and spatial outputs can be saved in GIS-compatible formats, such as shapefiles. Most of the data preparation and model setup can be efficiently performed using Geographic Information System (GIS) software, specifically ArcGIS, in conjunction with MIKE SHE's built-in graphical pre-processor.

When coupled with MIKE 11, MIKE SHE is capable of modeling the primary processes in the land phase of the hydrological cycle, including interception, evapotranspiration, one-dimensional open channel flow, two-dimensional overland flow, one-dimensional unsaturated soil flow, and three-dimensional groundwater flow. Separate modules within the system are dedicated to solving the different components of the hydrological cycle. A brief description of the MIKE SHE modules is provided below:

- **Interception/Evapotranspiration (ET)**

a) **Interception:** Jensen model (1983).

b) **Evapotranspiration:** Kristensen and Jensen model (1975).

- **Overland and Channel Flow (OC):** Diffusive wave approximation of the Saint-Venant equation.
- **Unsaturated Zone (UZ):** One-dimensional Richards' equation.
- **Saturated Zone (SZ):** Nonlinear Boussinesq equation.

3. Results and Discussion

This chapter presents the results of the calibration and simulation of the MIKE SHE model applied to the Guptamani Watershed. The model's calibration is discussed first, followed by an analysis of the water movement simulations performed during the study period.

3.1 Model Calibration

As detailed in Section 3.5, the MIKE SHE model was set up for the Guptamani Watershed, with calibration carried out for the period from 1st June 2007 to 30th April 2008. The calibration process involved varying the selected input parameters, with a trial-and-error approach used to adjust them, followed by multiple simulations to achieve an adequately calibrated model. After each parameter adjustment, simulated groundwater levels and surface runoff were compared with observed data to evaluate model performance. The model's accuracy was assessed through graphical comparisons and performance criteria. Below, we discuss the calibration results for groundwater levels and surface runoff.

3.1.1 Groundwater Levels

Figures 6, 8, and 10 present the temporal variations of observed and simulated groundwater levels for three representative observation wells. These figures demonstrate that the simulated depths to groundwater levels align closely with the observed values in all three wells. To further emphasize this, Figures 7, 9, and 11 show a comparison between the observed and simulated groundwater levels plotted on a 1:1 line, where the close proximity of the data points to the 1:1 line indicates the model's strong performance in predicting groundwater levels.

The Nash-Sutcliffe coefficients (R^2) for these observations, presented in Table 2, range from 0.71 to 0.82. These values confirm that the simulated groundwater levels match the observed data well.

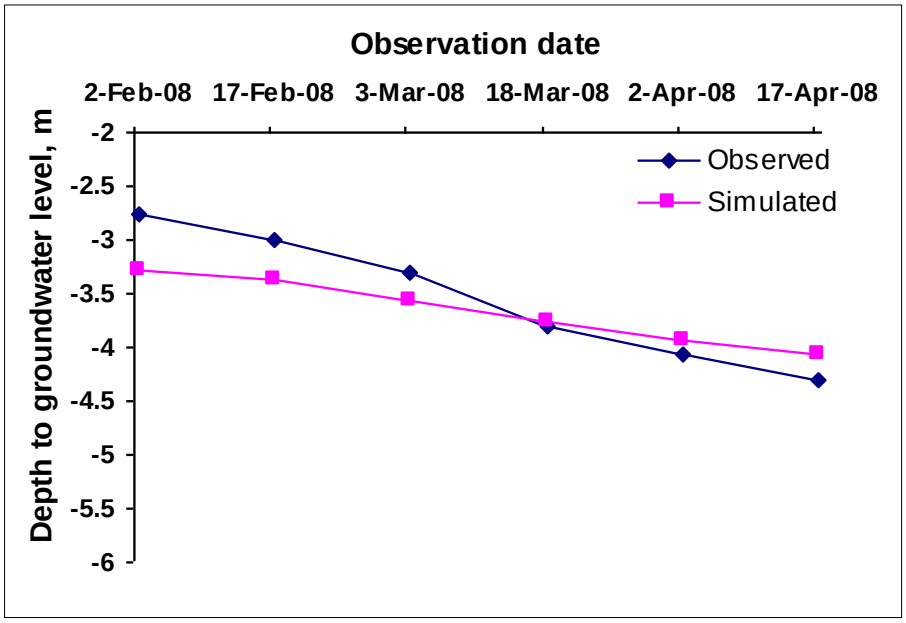

Fig 6: Temporal variation of observed and simulated groundwater levels at well 3

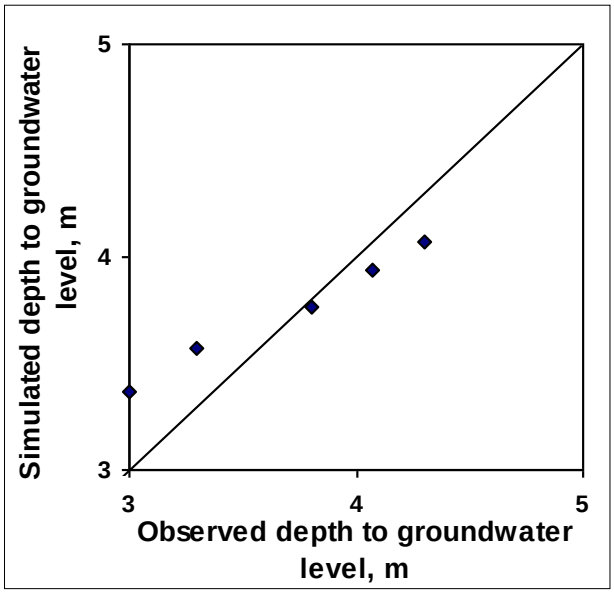

Fig 7: Comparison between observed and simulated groundwater levels at well 3

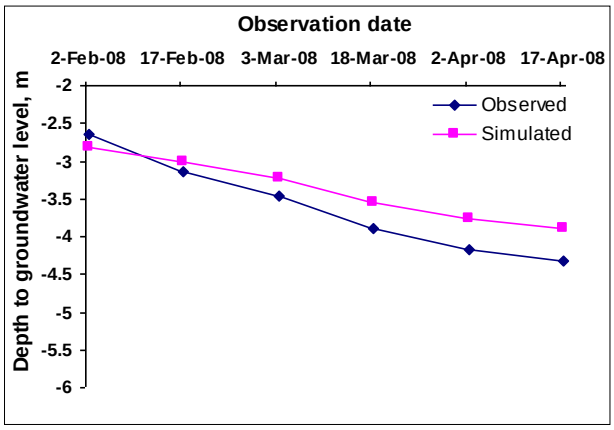

Fig 8: Temporal variation of observed and simulated groundwater levels at well 5

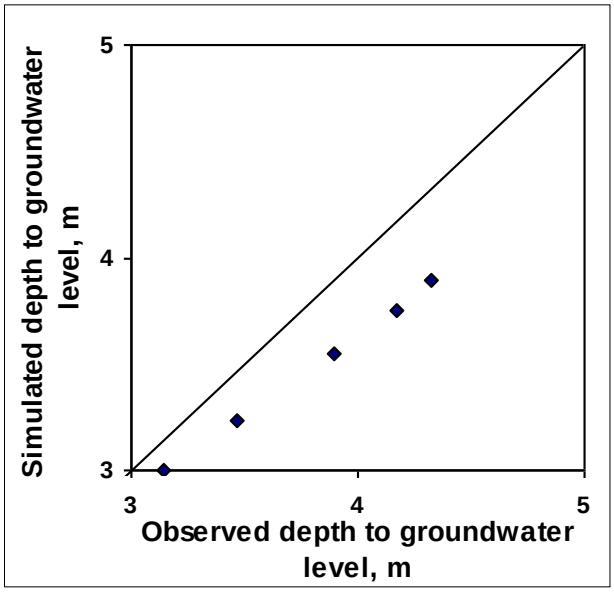

Fig 9: Comparison between observed and simulated groundwater levels at well 5

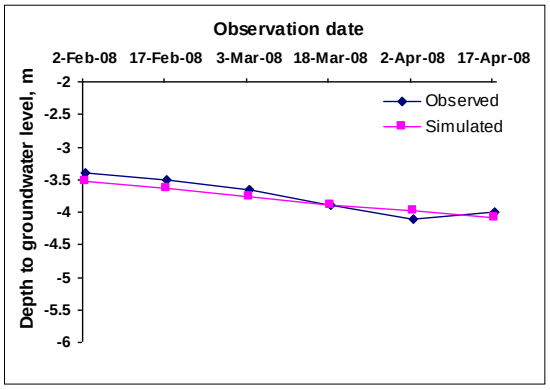

Fig 10: Temporal variation of observed and simulated groundwater levels at well 6

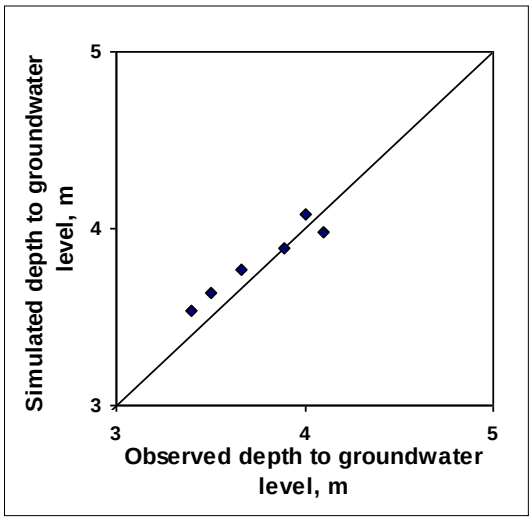

Fig 11: Comparison between observed and simulated groundwater levels at well 6

Table 2: Performance Criteria for Groundwater Depths at Various Locations in the Watershed

Location	Average Depth to Groundwater Level (m)	Nash-Sutcliffe Coefficient (R^2)
Well 3	Observed: 3.54, Simulated: 3.66	0.71
Well 5	Observed: 3.61, Simulated: 3.38	0.72
Well 6	Observed: 3.76, Simulated: 3.81	0.82

3.1.2 Surface Runoff

Figure 12 displays the temporal variations of observed and simulated surface runoff at the watershed outlet. A visual comparison of the two data sets suggests that the MIKE SHE model simulates the surface runoff accurately. Figure 13 provides a comparison between observed and simulated runoff on a 1:1 line, further confirming the model's satisfactory performance. The Nash-Sutcliffe coefficient (R^2) for the runoff simulation is 0.73, indicating good agreement between observed and simulated runoff data.

Based on the results presented, it can be concluded that the MIKE SHE model has been successfully calibrated for the Guptamani Watershed.

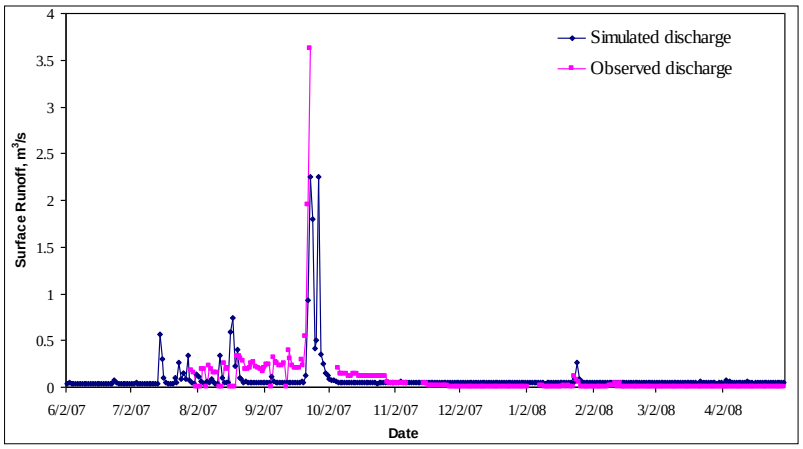

Fig 12: Temporal variation of observed and simulated average daily discharge in the watershed during calibration

3.2 MIKE SHE Simulations

Following the calibration, the MIKE SHE model was applied to simulate the hydrological water balance of the watershed from 1st May 2008 to 30th April 2009. The results of these simulations are presented below.

3.2.1 Groundwater Levels

Figures 13, 15, and 17 show the temporal variations of observed and simulated groundwater levels for wells 2, 4, and 7, respectively. As in the calibration phase, the simulated groundwater levels closely match the observed values. Figures 14, 16, and 18 present the observed and simulated groundwater levels on a 1:1 line, further reinforcing the reliability of the model's performance in predicting groundwater behavior.

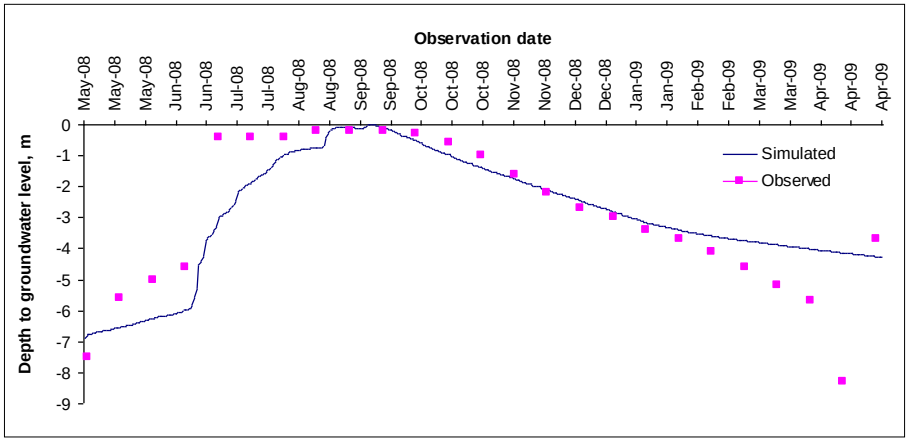

Fig 13: Temporal variation of observed and simulated groundwater levels at well 2

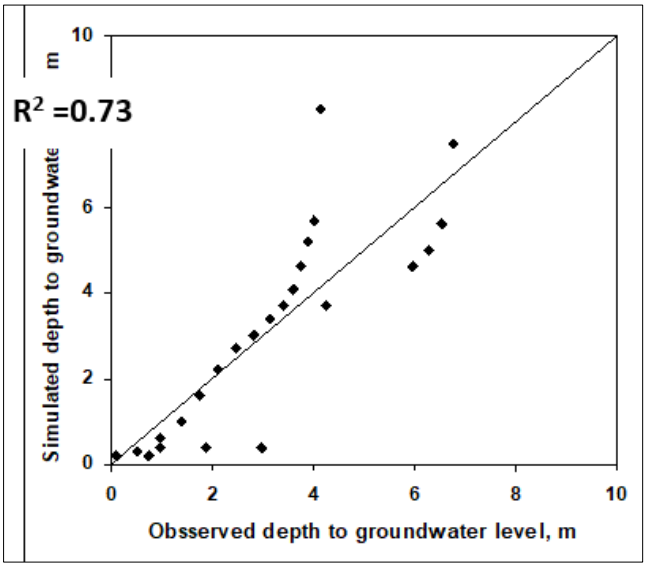

Fig 14: Comparison between observed and simulated groundwater levels at well 2

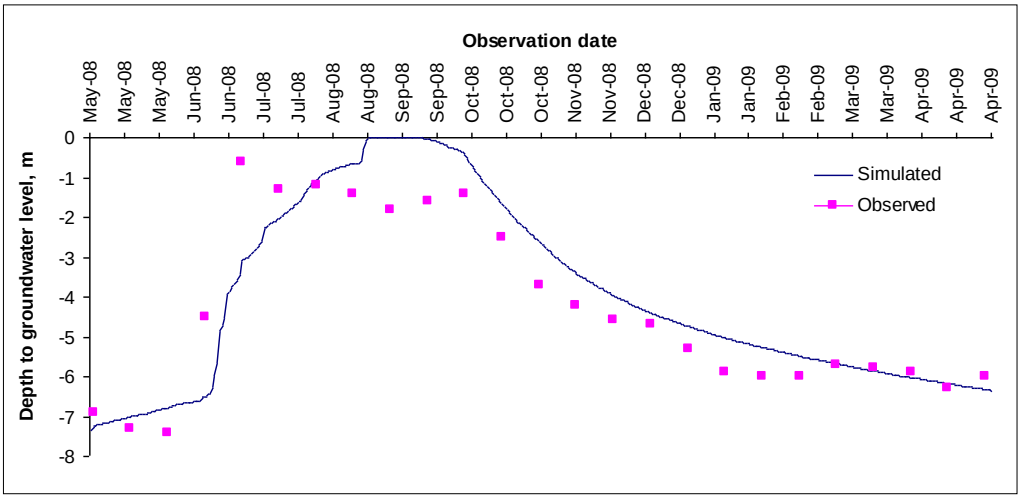

Fig 15: Temporal variation of observed and simulated groundwater levels at well 4

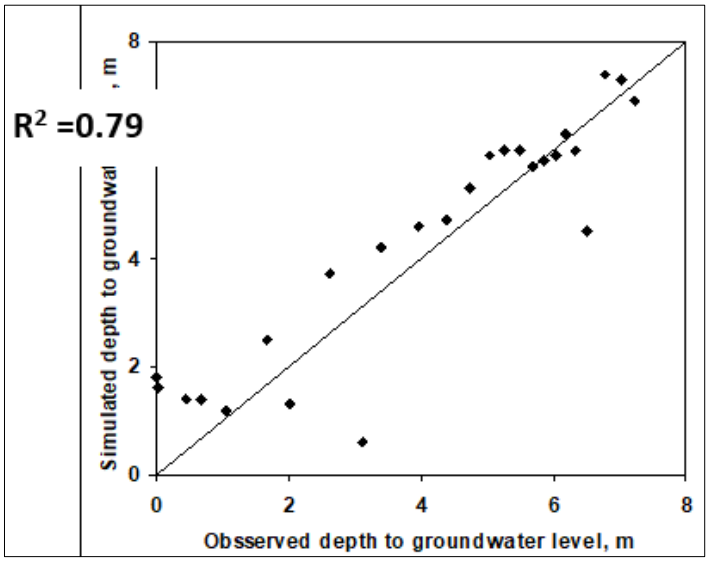

Fig 16: Comparison between observed and simulated groundwater levels at well 4

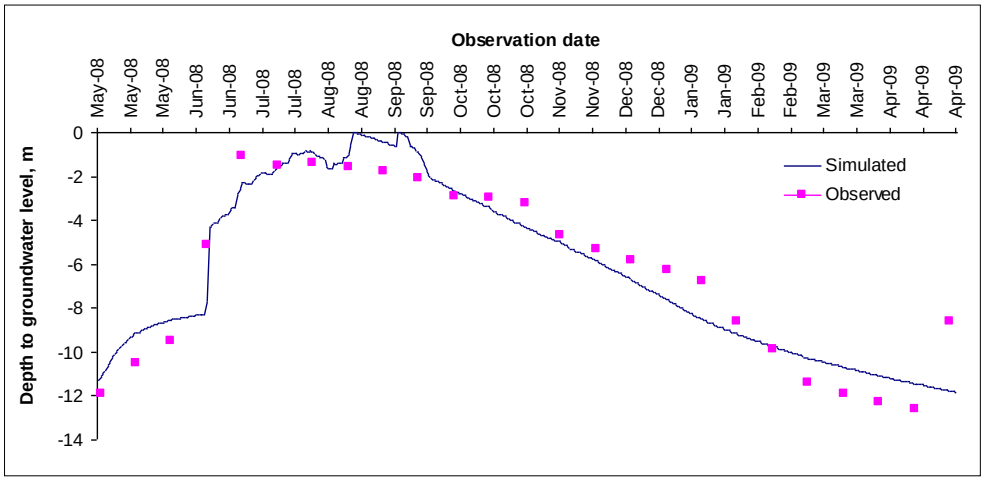

Fig 17: Temporal variation of observed and simulated groundwater levels at well 7

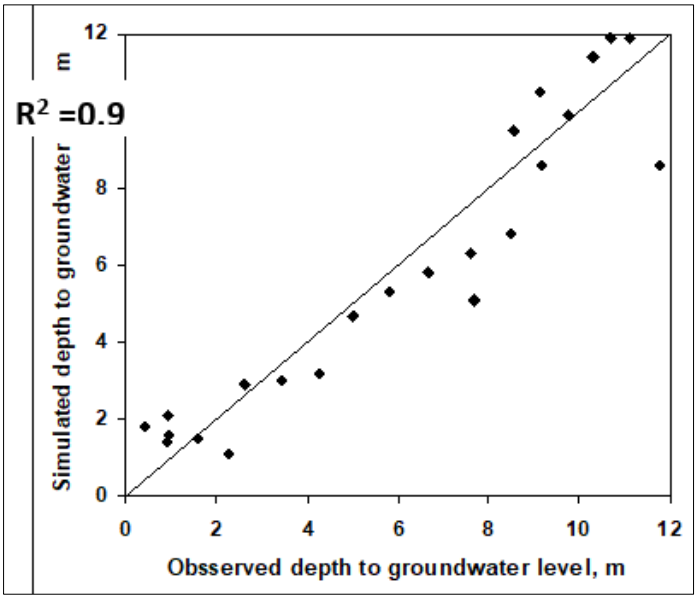

Fig 18: Comparison between observed and simulated groundwater levels at well 7

4. Conclusion

This study successfully applied the MIKE SHE model to the Guptamani Watershed for water balance and groundwater recharge assessment. The model was calibrated and validated with observed groundwater levels and surface runoff data, showing good agreement (Nash-Sutcliffe coefficients of 0.71-0.82 for groundwater levels and 0.73 for surface runoff). Actual evapotranspiration accounted for 72.28% of total

rainfall, surface runoff contributed 7.38%, and saturated zone storage change represented 27.3%. The analysis revealed higher groundwater recharge rates downstream, with upstream areas requiring supplemental irrigation due to lower moisture content. These findings offer critical insights for improving water resource management and developing more efficient water management strategies to support sustainable agriculture amid climate change.

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