Estimating the Spatio-Temporal Variation in the Groundwater Table of Damodar River Basin using Coupled SWAT-MODFLOW Model

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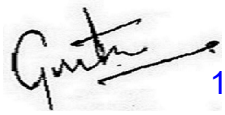

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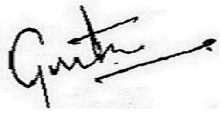

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Abstract

Groundwater plays a crucial part in satisfying the daily water demand. As an element of the hydrological system, subsurface flow investigation must employ a holistic approach. This study aims to develop a regional scale model to study the spatio-temporal characteristics of groundwater dynamics. It uses transient SWAT-MODFLOW model based on MODFLOW-NWT which is applied to Damodar river basin extending over approximately 42000 km^2. Regional model being quite large in extent, requires spatially varied recharge, evaporation, hydraulic conductivity for proper simulation. SWAT model is utilized to generate annual average groundwater recharge and evapotranspiration, amounting to 236.50 mm and 634.1 mm/year, respectively. These parameter were further used in PEST module to calculate the hydraulic conductivity which altogether imparted geographical heterogeneity to the model. A transient MODFLOW model was then developed using above parameter, imitating practical flow condition to some extent. As a result, a maximum deviation of 24.32 m was observed with respect to actual groundwater head based on simulation run between 2018 to 2020. The data generated using SWAT & MODFLOW was incorporated in the model of QSWATMOD. It uses its feature of DHRUs and Grid mapping to simulate exchange between the two integrated model. A transient model was built which used already calibrated hydraulic conductivity ranging from 0.0597 to 35.74 m/s. QSWATMOD model simulation were carried out to generate, evaluate and compare seasonal and annual variation of groundwater table using district-wise abstraction scenarios in aquifer system for observing the utility of the coupled model.

Table of Contents

Abstract 1

List of Tables 5

List of Figures 6

Chapter 1:
Introduction 1
1.1 General 1
1.2 Objectives 5

Chapter 2:
Review of Literature 6
2.1 General 6
2.2 Developing a Coupled Model 6
2.3 Application of Coupled Model 7
2.3.1 Recent research on impacts of climate change 7
2.3.2 Investigating impact due to change in LULC and climate 8
2.4 Watershed Modelling with SWAT-MODFLOW 9
2.5 Multi-Model Approaches 12
2.5.1 SWAT-MODFLOW-MT3DMS 12
2.5.2 SWAT-MODFLOW-RT3D 13
2.5.3 MODFLOW-DSSAT 13
2.5.4 SWAT-MODFLOW and PSO 13
2.5.5 SWAT-MODFLOW and WEAP 14
2.5.6 SWAT-MODFLOW-salt 14
2.5.7 MODFLOW-APEXMOD-RT3D 15
2.6 Studies on groundwater dynamics using machine learning 15

Chapter 3:
Study Area 17
3.1 General 17
3.2 Description of Study Area 17
3.2.1 Location and Extent 17
3.2.2 Physiography 18
3.3 Physical Characteristics 19

3.3.1 Climate and Rainfall . . . 19
3.3.2 Land-Use and Land Cover (LULC) . . . 19
3.3.3 Hydrogeology . . . 20
3.3.4 Soil Map . . . 22
3.4 Data Inputs . . . 23
3.4.1 Digital Elevation Model . . . 24
3.4.2 Groundwater Monitoring Stations . . . 25

Chapter 4:
Methodology . . . 27
4.1 General . . . 27
4.2 SWAT Model Setup . . . 27
4.2.1 Brief Description of SWAT Model Setup . . . 27
4.2.2 Watershed Delineation . . . 28
4.2.3 Creating HRUs . . . 29
4.2.4 Weather Data . . . 30
4.2.5 SWAT Simulation . . . 31
4.3 MODFLOW Setup . . . 31
4.3.1 Brief Description of MODFLOW Setup . . . 31
4.3.2 Delineating Watershed . . . 33
4.3.3 Conceptual Model . . . 33
4.3.4 Defining External Stresses . . . 34
4.3.5 Defining Data in MODFLOW Packages . . . 35
4.3.6 Aquifer Data . . . 37
4.3.7 Starting Head . . . 37
4.3.8 Hydraulic Conductivity . . . 38
4.3.9 MODFLOW Model . . . 38
4.3.10 Numerical Model . . . 38
4.4 SWAT-MODFLOW Model Setup . . . 41
4.4.1 Brief Description of SWAT-MODFLOW Model Setup . . . 41
4.4.2 About QSWATMOD Interface . . . 42
4.4.3 Processing SWAT Files and Creation of MODFLOW Model . . . 43
4.4.4 Formation of DHRU . . . 44
4.4.5 Preparation of Extraction Well Package . . . 45
4.4.6 Simulation Period . . . 45
4.4.7 Calibration and Validation . . . 46

Chapter 5:
Results and Discussion . . . 48
5.1 SWAT Model . . . 48
5.1.1 Groundwater and Evapotranspiration Map . . . 48
5.2 MODFLOW Model . . . 53
5.2.1 Parameter Estimation (PEST) Calibration Outputs . . . 53
5.3 QSWATMOD Model . . . 59

Chapter 6:
Summary and Conclusion 65

Chapter 7:
Future Work 67

References 68

List of Tables

3.1 Input data resolution and sources for SWAT-MODFLOW model preparation 23

4.1 Selected HRU specifications 30
4.2 Weather data input 31
4.3 SWAT-MODFLOW Output Files 46

5.1 Groundwater recharge map 2018 classification 50
5.2 Groundwater recharge map 2019 classification 51
5.3 Groundwater recharge map 2020 classification 52
5.4 Initial and PEST based hydraulic conductivities for different zones of the Damodar river basin 57

List of Figures

3.1 Location map of Damodar river basin 18
3.2 LULC map of Damodar river basin 20
3.3 Soil map of Damodar river basin 22
3.4 Weather data stations taken in/around Damodar river basin 24
3.5 DEM map of Damodar river basin 25
3.6 Groundwater monitoring wells across the Damodar river basin 26

4.1 Delineated watershed of Damodar river basin by SWAT 29
4.2 HRU map of Damodar river basin 30
4.3 Conceptual model of Damodar river basin 32
4.4 Spatial discretization of Damodar river basin 34
4.5 MODFLOW map with packages and top elevaton profile 35
4.6 Hydraulic conductivity zones 37
4.7 QSWATMOD generated MODFLOW model 44
4.8 QSWATMOD generated DHRU and DHRU-grid map 45

5.1 Groundwater recharge map of 2018 49
5.2 Groundwater recharge map of 2019 50
5.3 Groundwater recharge map of 2020 51
5.4 Evapotranspiration map for study period 2018-2020 52
5.5 Computed head v/s observed groundwater heads residuals 54
5.6 Times series map of observed and computed groundwater head (Well 1) 55
5.7 Times series map of observed and computed groundwater head (Well 2) 56
5.8 Times series map of observed and computed groundwater head (Well 3) 57
5.9 Simulated head distribution and residual plot on 21/10/2020 58
5.10 Groundwater level for Pre-Monsoon 2018 59
5.11 Groundwater level for Post-Monsoon 2018 60
5.12 Groundwater level variation in 2018 between Pre and Post Monsoon 60
5.13 Groundwater level for Pre-Monsoon 2019 61
5.14 Groundwater level for Post-Monsoon 2019 61
5.15 Groundwater level variation in 2019 between Pre and Post Monsoon 62
5.16 Groundwater level for Pre-Monsoon 2020 62
5.17 Groundwater level for Post-Monsoon 2020 63
5.18 Groundwater level variation in 2020 between Pre and Post Monsoon 63

Chapter 1

Introduction

1.1 General

This chapter initiates an investigation into the spatial and temporal variability of the groundwater table in river basins around the world. We use a combined SWAT-MODFLOW model, which is well-known for its ability to accurately represent groundwater dynamics. This chapter gives an overview about subsequent brief discussions of different methodologies, models and techniques applied to understand the hydrology of the catchment. Further, We summarise the research objectives, focusing on identifying main drivers of groundwater dynamics and evaluating variation on an annual and seasonal basis.

Groundwater is projected to fulfill approximately half of the global demand for drinking water (Jimenez et al., 2022). The Indian subcontinent accounts for 3.2 percent of the world's land area yet hosts 23.2 percent of the worldwide population (Mukherjee et al., 2015). A concentrated population is equivalent to a localized groundwater overdraft. India's 55% of population is dependent on the agricultural sectors and its burgeoning population is estimated to be 1.6 billion by 2050 (Dhawan, 2017) and relying solely on surface water resources is not enough to guarantee food security anymore. This gap has been fulfilled by groundwater, a backbone to India's upsurging irrigation requirement and meeting the inadequate domestic demands. Studies show that nearly 62 percent of irrigation demands, 85 percent of rural water supply needs and 50 percent of urban water demands are met through the abstraction of groundwater (CGWB, 2022). With the growing reliance on groundwater, the depletion of this vital resource is coming forth as a global concern. Already in many regions, as per research work by (Swain et al., 2022) it is observed that natural replenishment is much lower than GW abstraction. Other adverse effects includes change in supply

and demand (population), anthropogenic activities, stream flow, meteorological patterns and global climate (Yadav et al., 2020) Moreover, having the information about spatial and temporal pattern of groundwater depth will elucidate its availability and also help in understanding the replenishment patterns, emphasizing the crucial importance of prudently managing the groundwater resource.

A hydrological system constitutes an integrated entity that encompasses the cohesive interaction of both surface and sub-surface elements. It is contingent upon sub-surface heterogeneity, as well as climate patterns. The utilization of a basin-scale model holds significant potential for comprehending the parameters related to the watershed, thereby advancing knowledge for improved basin management practices(Maheswaran et al., 2016). Employing distinct models for surface and sub-surface components would not be optimal due to the intricate interdependencies between them. For instance, alterations in land use and meteorological patterns can significantly influence the recharge patterns in groundwater. Consequently, a holistic approach is imperative, given that surface and sub-surface water represent conjunctive elements within the hydrological cycle (Kuffour et al., 2020).

Hydrological models play a crucial role in understanding the intricate dynamics of a watershed by providing insights into variables associated with water movement. For instance, SWAT (Arnold et al., 1998), is a physical based , semi-distributive surface water hydrologic model which simulates surface-water dynamics at continuous time step. SWAT divides a watershed in small segments, sub-basins based on flood accumulation and flow direction calculation . Subsequently, it further separates into Hydrological Response Units (HRUs), lumped together based on soil, landuse and slope data. HRU's respond similar to the hydrological inputs but they don't have spatial attributes (Arnold et al., 2012). It is a widely used hydrological model but has restrictions in GW system simulation. It disregards distributed factors such as storage coefficient, hydraulic conductivity, permeability, specific yield, and base flow recharge into the river system from deep aquifers (Jafari et al., 2021). Therefore limiting its application for simulating shallow aquifers up to the depth of 6m below ground level (Neitsch et al., 2011).

MODFLOW (Harbaugh, 2005), a physical based, fully distributive finite difference approach model which solves the partial differential groundwater equation to simulate GW head. Flow is

associated with external stresses like river,wells,recharge etc which are included with MODFLOW subroutines as packages (Harbaugh, 2005). MODFLOW in past has been used for local as well as regional studies but a known fact i.e. recharge has a high variability depending upon the meteorological pattern, land-cover,etc (Guzman et al., 2015). Recharge cannot be taken as a constant since it will induce error in the model. The discussed deficiencies incorporated by the usage of SWAT & MODFLOW are resolved to a extent by linkage of the two models.

QSWATMOD, a QGIS based GUI to link,simulate and display the coupled data via GIS environment. This interface comprises of a). Processing tab for preparing MODFLOW data and mapping state variables like river stage,recharge,Evapotranspiration to the already prepared SWAT input files b).Simulation Tab to configure and sync the stress period of the two model;c). Graphical visualization tab for mapping, plotting and exporting results (Park et al., 2019).This plugin is based on (Bailey et al., 2016)'s modeling code. It utilizes the groundwater equation solver MODFLOW-NWT (Niswonger et al., 2011) and used as a subroutine in SWAT 2012(Revision 591) code (Park et al., 2019).

Numerous studies related to the development of the SWAT-MODFLOW loosely coupled model and its applications at local, regional, and basin level has been conducted in recent decades.Three pioneer studies were shortlisted based on their high citation counts. (Sophocleous et al., 1999), developed a model SWATMOD for modeling surface-water, groundwater, and stream-aquifer exchanges in a catchment. The model surpasses the lumped nature of SWAT and uses HRUs to represent heterogeneity in each sub-basin.A decade later, (Kim et al., 2008), introduced a new approach of HRU-cell conversion interface which facilitated the simulation of groundwater levels, aquifer-river interactions, spatio-temporal distribution of groundwater recharge rates, and aquifer evapotranspiration.Subsequently, (Bailey et al., 2016) improved upon this idea by proposing a new technique which disaggregate the HRU's further into DHRU's to get the enhanced understanding of SW-GW interaction and their spatial pattern, based on which (Park et al., 2019) developed a QSWATMOD Interface.

Other significant studies includes first coupling of SWAT-MODFLOW with transport model MT3DMS (Zheng, Wang, et al., 1999) used for nitrate fate simulation by (Conan et al., 2003).

Study on groundwater recharge rate distribution by (Chung et al., 2010) in Mihocheion catchment located in South Korea. It proposed a method to simulate delay in infiltrated water in vadose zone by developing a multi-reservoir routing model. (Guzman et al., 2015) developed SWATmf framework to study the human influence on the agroecosystem in Reservoir of Fort Cobb located in USA. (Eshtawi et al., 2016) quantified the SW-GW interaction due to urban area expansion in the Gaza Strip. (Aliyari et al., 2019) further extended its application by updating the SWAT-MODFLOW code which then became applicable to vast agro-urban river watersheds in semi-arid countries. (Jafari et al., 2021) conducted sensitivity analysis on both SWAT as well as MODFLOW parameters to analyze its effect on water table and runoff during simulation. According to the results of the sensitivity analysis, curve number and hydraulic conductivity exhibited most substantial effects.The GW Calibrator (GWCal) was designed as well to improve the efficiency of the calibration process in a watershed situated in Shiraz, Iran, where strong SW-GW interaction was identified. (Frederiksen & Molina-Navarro, 2021) demonstrated how SWAT-MODFLOW simulated the impacts of different sub-surface drainage scenarios on the hydrological system. (Yifru et al., 2021) analyzed the change in GW recharge and water yield due to effect of LULC and change in climate. Based on the findings, increase in average temperature by 8-11% and precipitation by 3-6% reduces the groundwater seepage by 47-53% and water yield by 48% in coming decades. (Aliyari et al., 2021) investigated an agro-urban river basin, uncovering that in the most severe scenario, a 1° increase in annual temperature along with a 1.3% reduction in annual rainfall could lead to a decrease in groundwater reserves by 2-5%, a decline in stream discharge by 8.5%, and a reduction in crop yield by 11%.

The Damodar river basin, a key watershed in eastern India, provides drinking and agricultural water to the people of Jharkhand and West Bengal. Its attentive management becomes necessary as the basin's industrialization and urbanization increases, which has a significant impact on the region's water reserve quality and quantity.

1.2 Objectives

The objectives of the present study are as follows:

- Utilizing the SWAT model to simulate patterns of groundwater recharge and evapotranspiration in the Damodar river basin.
- Modelling the spatio-temporal patterns of groundwater table in the Damodar rive basin.
- Comparing seasonal variations in groundwater water level in recent years of study area.

Chapter 2

Review of Literature

2.1 General

Exploring the Synergy: A Comprehensive Literature Review on coupled SWAT-MODFLOW Model for understanding hydrology of a catchment.

This headline encapsulates a detailed examination of scholarly works focusing on the combined as well as separate use of SWAT and MODFLOW models in river basin studies. The review delves into the integration of these two powerful modeling tools, analyzing their synergistic effects on enhancing understanding and management of river basins. It encompasses an in-depth exploration of methodologies, applications, and advancements in utilization of SWAT and MODFLOW , aiming to provide insights into their potential for addressing complex water resource challenges within river basins. Further reviews about other models like climate models CMIP5, RCP4.5, RCP8.5, Decision Support System (DSSAT), Particle Swarm Optimization (PSO) and some machine learning tools for groundwater depth estimation are discussed.

2.2 Developing a Coupled Model

- **Kim et al., (2008)** developed the idea of integrating MODLFOW as a subroutine of SWAT. Groundwater recharge and evapotranspiration were simulated using HRUs in SWAT that were connected to MODFLOW discretized cells and the RIVER package was linked with HRUs for stream and aquifer interaction. Pumping with numerous wells was used for the draw-down distribution simulation.

- **Yi et al., (2011)** modelled interaction between saturated and unsaturated zone based on modified SWAT and MODFLOW2000. It was concluded that shallow aquifer requires comprehensive assessment of interaction. Calculation of recharge and evapotranspiration between these zones by two way coupling provide a more physically based assessment of the surface and groundwater process.

- **Guzman et al., (2015)**, created an application called 'SWATmf' for simulating the interaction between groundwater and surface water. As it is known that SWAT can only calculate up to 6 m bgl, and MODFLOW is unable to account for differences in recharge rates at different locations due to variations in pumping, land features, and different levels of precipitation. Therefore this application was useful in accounting for spatially varying recharge rates and improving the simulation.

- **Aliyari et al., (2019)** used upgraded version of MODFLOW to model a large urban-agro river basin of about 72,000 km^2. This version included some altering in the code of the solver package. It used MODFLOW-PSB instead of MODFLOW-NWT to manage the wide variety of groundwater sources and sinks occurring in a extremely regulated catchment . It also changed the groundwater and surface water irrigation routines for river basin policy making.

2.3 Application of Coupled Model

2.3.1 Recent research on impacts of climate change

- **Uniyal et al., (2015)** investigated the impact of change in patterns of climate on water balance parameters in the Baitarani catchment. Based on evaluation of 12 scenarios, raising the temperature by 1 to 5°C and rainfall by 2.5 to 15% resulted in reduction of streamflow by 2.5 to 11% and in second case increase by 6.67 to 43.42%. Another 28 Combined Scenarios for area-specific climatic change effect were simulated whose result shows that surface runoff could vary within range of negative 4.55% to 37.53%, groundwater recharge from negative 8.7% to 23.15%, and evapotranspiration within range of 4.05% and 11.88%.

The study concludes that by the end of the 21st century, anticipated climate changes will probably have a significant effect on streamflow in the region.

- **Chunn et al., (2019)** studied climate change by incorporating RCP 8.5 downscaled data in coupled SWAT-MODFLOW at regional scale. It was found that upstream area had more variation in SW-GW exchange amid wet and dry months. Additionally 21 wells with abstraction rate of 4680 m^3/d were added to replicate water usage by energy sectors and it was concluded that abstraction scenario had immediate effect on groundwater levels while climate change exhibited almost negligible immediate effect.

- **Bhatta et al., (2019)** did their research on a basin in Himalayan region to evaluate effect of climate change on. As known, Himalayan region is vulnerable to climate change and due to unavailability of data and complex climate a realistic model is difficult to model. Elevation band was recognised as the main component for a robust hydrological model. Future predictions were simulated for 2030,2060,2080s with CMIP5, RCP4.5 and RCP8.5 scenarios. It was discovered that increase in average maximum/minimum temperature annually by 4°C and 5.5°C decrease precipitation and streamflow by 4.5% and 8.5% by end of 21st century under RCP8.5 scenario. These findings can be significant for policy makers, hydropower development and developing strategies to counter climate change in the region.

- **Aliyari et al., (2021)** coupled SWAT-MODFLOW with climate models to analyze change in crop yield by varying parameters like precipitation, temperature, river discharges and groundwater discharge. Worst modeling case was predicted in which yearly mean temperature was increased by 1°C, and precipitation lowered by 1.3% due to which the basin showed a significant reduction in stream discharge by 8.5% and crop yield by 11%.

2.3.2 Investigating impact due to change in LULC and climate

- **de Oliveira Serr et al., (2022)** performed the effect LULC change on hydro-sedimentological variables in Amazonian basin using the SWAT model. It was noted that sub-basins with a predominant pastureland cover are more prone to increasing surface runoff along with

sediment yield. Conversely, in sub-basins where the land cover is primarily forest, the time series display homogeneity and is trendless. Consequently, it is inferred that the SWAT model offer valuable insights for decision-makers in water and environmental resource management.

- **Abbaszadeh et al., (2023)** researched influence of meteorological change and change in land cover on evapotranspiration and streamflow in coming future. Climate model CMIP6 scenarios were used for 2021–2050 and 2051–2080 and it was observed that climate change would alone cause 12.8% increase in evapotranspiration leaving 2–6% incremental effect to LULC changes. Streamflow was forecasted to decline by 2–11% due to LULC and temporal changes due to climate change were observed with different values throughout the basin.

2.4 Watershed Modelling with SWAT-MODFLOW

- **Bailey et al., (2016)** evaluated the SW-GW interplay along a river system in space-time during a 34-year period utilising the SWAT-MODFLOW model. After analysis, Data was averaged monthly, yearly, and decadal to see the result for seasonal and decadal variation in groundwater discharge rates. The result showed an increase in the GW discharge rate of about 70% rivers.

- **Khadri et al., (2016)** pointed out the importance of groundwater as a substitute with less chance of pollution, needs little treatment before use. A coupled model was thus created for simulation in which residual was reduced by adjusting the transmissivity value of the aquifer. Their research highlighted the potential of coupled modelling for development of groundwater resources.

- **Dowlatabadi et al., (2016)** in their study,they incorporated recharge rate which was an output from SWAT in their MODFLOW model. Sensitivity analysis was performed for hydraulic conductivity and discharge from wells. After validation, model was found to be quite reliable for resource calculation in Firoozabad basin.

- **Maheswaran et., (2016)** modelled the 1 million km^2 Ganga river basin employing visual

MODFLOW to develop a transient numerical model.PEST was used to fine tune parameter for calibration. Time Period was 4.5 years in which interaction between Principal tributaries along river Ganga and aquifer was studied to demarcate water losing and gaining rivers. Further it was discussed how modelling tool can help in simulating various abstraction scenarios and better our understanding of groundwater system aiding in its management and policy making.

- **Semiromi et al., (2019)** conducted the coupled SWAT-MODFLOW study on Ardabil aquifer, Iran achieving an $R^2 \geq 0.5$. The research findings demonstrated that excessive aquifer exploitation led to a consistent decrease in groundwater levels between 1978 and 2012. Moreover based on observation of SW-GW interaction, they concluded that groundwater has very high contribution to river system compared to opposite scenario. Result showed transition of perennial river to ephemeral over the study period and they proposed usage of coupled model to examine different scenarios for improved management as well as restoration of depleted water resources.

- **Gao et., (2019)** applied SWAT along with MODFLOW to calculate the amount of surface water resources available to mitigate the usage of groundwater. It was found that the portion of sub-basins amounted to 21% having water resources > 70 cm in dry years, 35% in mean years and 57% in wet years. It was concluded that surface water can be an alternative for irrigation, thereby giving ample time for groundwater regeneration.

- **Mosase et al., (2019)** estimated groundwater recharge seasonally and annually by SWAT-MODFLOW for Limpopo river basin, Africa. Simulation results was highest for summer with average value of 147 mm/year, 27 mm/year for autumn, 3.2 mm/year for spring and 0.3 mm/year for winter season. As per the evaluation of terrestrial water and groundwater interaction, west rivers infiltrated into the aquifer while east rivers received groundwater discharge. This information will aid in managing water resources and monitoring pollution at interaction sites.

- **Molina-Navarro et al., (2019)** compared abstraction scenarios of groundwater in SWAT and SWAT-MODFLOW. The conclusion was made that for shallow aquifers SWAT gave similar

results as that of SWAT-MODFLOW but in case of deep aquifer, SWAT-MODFLOW gave more accurate results signifying it as a better tool for groundwater analysis.

- **Yifru et al., (2020)** estimated parameters for a gauged watershed and transferred these parameter to an ungauged watershed by physical similarity approach. It was observed that most recharge occurred in between July to September month. Value of yearly areal recharge approaches to approximately 18% of precipitation and remote areas receives substantial amount of groundwater recharge. Model was found flexible to different watersheds with good accuracy and it was concluded that it can used as good management and policy making tool.

- **Loukika et al., (2020)** determined the recharge rates with the help of SWAT-MODFLOW based hydrologic response unit (HRUs). Analysis was done after calibration for seasonal and decadal trends based on which groundwater recharge rates were evaluated.

- **Liu et al., (2020)** compared SWAT and SWAT-MODFLOW model for streamflow response in abstraction scenarios of groundwater. As a result, both model findings showed that abstraction for drinking water reduced streamflow, whereas abstraction for agricultural purpose increased it slightly. SWAT gave rather low values for streamflow decrease due to abstraction. It was found out that SWAT-MODFLOW gave more realistic result relatively and can be a used a management tool for watersheds.

- **Frederiksen et al., (2021)** incorporated for the first time, the impact of sub-surface drainage on the geographical distribution of the hydrological system. They evaluated four models for SWAT and four models for SWAT-MODFLOW, and they came to the conclusion that the latter produced better results because with the addition of MODFLOW, it is now feasible to simulate groundwater flow in locations other than the surface catchment, which is not achievable with SWAT alone.

- **Tolera et al., (2021)** adopted SWAT model to determine recharge rates and MODFLOW to simulate groundwater flow system. Result showed annual recharge in catchment is 179 mm and by increasing the abstraction rate by 50%, 100% and 200% there was reduction

in river baseflow and groundwater level at the outlet which was found to be a huge risk to groundwater sustainability in the basin.

- **Jafari et al., (2021)** stated that combined calibration of integrated SWAT and MODFLOW model poses huge challenge in simulating SW-GW interactions. Based on sensitivity analysis two parameters hydraulic conductivity and curve number (CN2) were found to have most impact in calculating runoff and groundwater level. Additionally, the discussion covers a tool "GW Calibrator" (GWCal) and its application to the study area and how it enhances the results.

2.5 Multi-Model Approaches

2.5.1 SWAT-MODFLOW-MT3DMS

- **Ehtiat et al., (2018)** linked SWAT-MODFLOW along with MT3DMS to forecast groundwater flow and salt concentration for existing and future development scenarios. Moreover change of land cover pattern were accounted for with their respective effect on sub-surface water system.

- **Sundar et al., (2022)** explored the impact of industrialization on quality of water resources. Based on well log data concentration of various pollutants, their fate was simulated along the river flow by using MODFLOW and MT3DMS. Main objective was to provide quality measures to improve the quality of water resources.

- **Eslamian et al., (2023)** simulated nitrate concentration with MT3DMS and vulnerability spots from DRASTIC modelling. Based on model output it was observed that large areas with concentration more than 25 mg/l which signify high agricultural pollution in the region. High potential zones for contamination were also identified and validated. Therefore, it was suggested to develop an efficient plan for crop yield and usage of fertilizer to ensure restoration of groundwater resources.

- **Rajaeian et al., (2024)** evaluated storage decline in Hashtgerd, Iran and used MODFLOW and MT3DMS to develop a aquifer restoration plan. During the period from 2012 to 2016,

mean storage deficiency of 4.08 Mm^3/year was observed with decrease in water quality. They suggested use of licensed agricultural wells instead of unlicensed ones which would increase storage by 7.23 million m^3/year and decrease concentration by 0.06 and 1.14 mg/l/year.

2.5.2 SWAT-MODFLOW-RT3D

- **Wei X et al., (2019)** integrated SWAT–MODFLOW with RT3D, a Solute transport model. The study examined the movement of nitrate between streams and aquifers, focusing on both percolation into the aquifer and movement back to the stream. This was done as a management tool to identify management practices and mitigating contaminant pollution in agricultural watersheds.

2.5.3 MODFLOW-DSSAT

- **Xiang et al., (2020)** in their research linked DSSAT and MODFLOW to evaluate long term impact of management practices and climate change over water use efficiency and farm profitability while maintaining aquifer sustainability. Irrigation rates and deep percolation from DSSAT were used as inputs in MODFLOW model as pumping and recharge rates by python scripts. They discovered that over a decade of irrigation leads to less than 50% decrease in water reserve in wells. Additionally they simulated a scenario without irrigation in which mean water table rose by 2 meters which resulted in a 70% decrease in agricultural yield. Determination of conservation with significant crop yield was not evaluated in this study.

2.5.4 SWAT-MODFLOW and PSO

- **Sabzzadeh et al.,(2020)** in their study coupled SWAT-MODFLOW and Particle Swarm Optimization (PSO), which was employed to determine the best solution among a variety of parameters to maximize crop benefit. It was discovered that the price of crops has a

significant impact on ideal cropping pattern and water consumption of water. On the other hand, increasing irrigation efficiency has near to no effect on the optimal crop net benefit.

2.5.5 SWAT-MODFLOW and WEAP

- **Abbas et al., (2022)** used coupled SWAT-MODFLOW along with tool for assistance in making decisions, WEAP under climate change condition for different abstraction scenarios. Further these tools were used for forecasting future supply and demand rate and to compute the streamflow and unfulfilled demands rates by evaluating abstraction results at maximum licensed rate, 50% withdrawal rate, time-series data for monthly period with increase in water usage by 1%. The model was noted as being applicable for managing supply and demand scenarios in other basins.

- **Asadi et al., (2024)** used IAHRIS (Indices for Hydrological Alteration in Rivers) to analyze alteration in hydrological activities due to dam. Secondly they used SWAT+ and WEAP to estimate streamflow by prioritizing water allocation. The study indicated a rivalry between environmental and agricultural interests, which poses challenges to water management in the Basin. Prioritising environmental requirements improves the reliability of environmental flows by 56 percent and results in an 11% decrease in reliance on agriculture. Further this study provides insights into policy making by balancing the environmental and irrigation demands.

2.5.6 SWAT-MODFLOW-salt

- **Bailey et al., (2023)** simulated fate transport of salts ($SO4^{-2}$, Cl^{-2},etc) with SWAT-MODFLOW paired with salt, an updated variant of SWAT-MODFLOW. Model accounts for salt in soil pores, runoff, lateral flow, recharge and surface water groundwater exchange. Further it is checked for groundwater and surface water salt concentration and than simulated for impact of salinity on crop yield.

2.5.7 MODFLOW-APEXMOD-RT3D

- **Park et al., (2023)** demonstrated the capabilities of APEXMOD, a QGIS based plugin written in python to link (Agricultural Policy / Environmental eXtender) APEX paired MODFLOW with RT3D paired Salt. It incorporates a pre-processor panel for input provision, a simulation tab, and a post-processor tab for output visualization. These functionalities were demonstrated through modeling a river basin and validating its results.

2.6 Studies on groundwater dynamics using machine learning

- **Kumar et al., (2020)** used three AI techniques: Deep Learning , Gaussian Process Regression (GPR) to predict groundwater fluctuations. During the training period, the DL model exhibited minimal residuals when compared to observed values, with RSME of 0.04, correlation coefficient of 0.99, and NSE of 0.98. Furthermore, its performance during the validation period was deemed satisfactory, with RMSE of 0.08, r of 0.95, and NSE of 0.87. The results of this study demonstrate that the model made with utility of deep learning acts as an intelligent tool for effectively predicting groundwater depths..

- **Wu et al., (2021)** stated that solving groundwater flow equation is a computational burden to determine head. In this study, a multi step framework in which wavelet transform (WT) is linked with Multi variate LSTM (Long Short-Term Memory) network. WT disintegrates groundwater time series plot into external and self control term which is evaluated by MLSTM model. Pearson correlation sets relation between river stage and groundwater level. It was determined that the application of the linked WT-MLSTM model diminishes when the groundwater well's complexity increases or as the distance between the groundwater well and river channel increases, both of which may be influenced by additional regulating factors.

- **Sun et al., (2022)** forecasted groundwater level for daily and monthly time period by three data-driven models: BP-ANN, ARIMA, BP-ANN, and LSTM. These models were assessed across 5 sections characterized by distinct aquifer properties with supporting NSE

and RMSE values.The analysis of result from LTSM by using the O2S2 method pinpointed drawdown of greater than 10 m to water source areas. This drawdown was consistently associated with a probability value exceeding 0.7 between 2003 and 2010, gradually decreasing to below 0.3 from 2011 to 2014. Further discussion is done on appropriate method to simulate groundwater level for management purposes.

- **Amiri et al., (2023)** forecasted groundwater variations with the help of ACA-ANN, PSO-ANN hybrid techniques and DL approaches like LSTM, LS-SVM, and ORELM and matching outputs with MODFLOW numerical model. Than most accurate was predicted with Taylor's diagram, ORELM with R=0.977, NSE=0.955, RMSE=0.512 and NRMSE=0.058 respectively during training period. The comparison suggested that numerical models needs extensive data with complexities, more computational time whereas with least data deep learning provide high accuracy.

- **Mahammad et al., (2023)** studied the region of Damodar fan delta to analyse overexploitation due to increasing population and forecasting future scenarios with machine learning. The results indicate that the groundwater level declines during the post-monsoon period in comparison to the pre-monsoon and monsoon periods.Main factors influencing groundwater level was rainfall and abstraction. The best model (extreme gradient boost regressor) showed increasing trends of groundwater in 2025-2026.

Chapter 3

Study Area

3.1 General

This chapter outlines the diverse categories and origins of data employed in crafting the database to build SWAT and MODFLOW model. It delves into the process of obtaining meteorological, hydrological, and remote sensing data and details the methodologies employed for data processing. Additionally, it explores the techniques utilized for generating various thematic layers through GIS.

3.2 Description of Study Area

3.2.1 Location and Extent

Damodar river basin is a watershed with a spatial area of about 41965.49 Sq.km. It is located within the geographical extent of 84° 35' to 88° 20' east longitudes and 21° 44' to 24° 25' north latitudes as shown in Fig. 3.1. It is a part of the Ganga river basin and drains through the states of Jharkhand and West Bengal, occupying approximately 5.19% of the entire Ganga Basin. The Main river is Damodar along with other major tributaries like Barakar, Konar, Guaia, Bokaro, Jamunia, Khadia, Bhera, Ghari, Haharo.

The Damodar River originates from the southeastern hills of the Chota Nagpur Plateau in the Palamau district of Jharkhand, beginning its journey at an elevation of 1,366 meters. The river has a full reach of 592 kilometers eventually merges with the Hugli River, a tributary of the Ganga, on its right bank, east of the Sone River and ultimately reaching the Bay of Bengal through its

confluence with the Hugli.

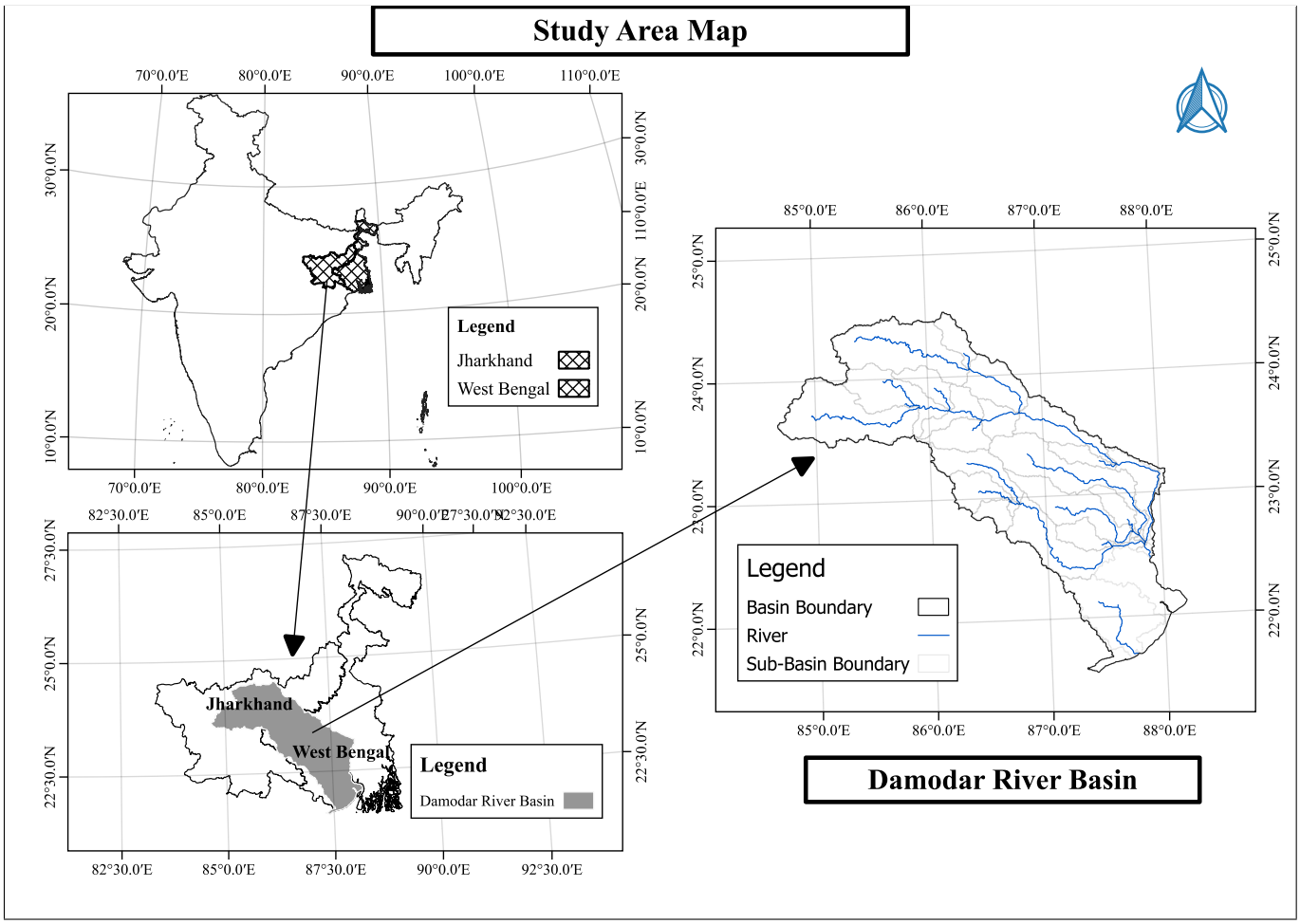

Figure 3.1: Location map of Damodar river basin

3.2.2 Physiography

The Damodar river basin is split into two distinct segments determined by terrain, the upper and lower Damodar Basin, situated in Jharkhand and West Bengal. The upper Damodar Basin encompasses hilly terrains, plateaus, and uplands,namely Chota Nagpur Plateau,Hazaribag plateau, Giridih and Deoghar uplands,etc. where slope varies from 0-68° signifying a very high slope. In the lower Damodar Basin a flatter surface is seen throughout the extent with a slope variation of 0-3°. The altitude range in the river basin have the topography showing variation from 610 m to 11 m in hilly terrains to region close to msl. Due to this topography, the river flowing through high

sloping area contributes to high discharge in the lower Damodar river basin.

3.3 Physical Characteristics

3.3.1 Climate and Rainfall

Damodar river basin accounts for around 1000 mm to 1800 mm of rainfall variation depending upon the distinct topography and the meteorological condition over the basin. Based on the last 60 years of data record, lower Damodar basin covering areas of West Bengal like Hooghly, Howrah, Bardhwan receives rainfall around 1400 mm due to south- west monsoon and sometimes receives rainfall in excess of 1800 mm during past flood years. Comparatively Lower Damodar Basin receives much higher rainfall due to the topography, S-W Monsoon and the cyclonic disturbance occurring in the region of Bay of Bengal.

3.3.2 Land-Use and Land Cover (LULC)

Runoff, Infiltration are essential parameter in a hydrological system needed to define the GW recharge potential of any region. GW recharge varies spatially with to land cover pattern. Therefore, characterisation of the land pattern is important to evaluate the GW table depth. This evaluation is done by employing HRU, feature of the SWAT model.Within the Damodar river basin, around 60% of the land is used for agriculture, 10% is inhabited, 28% is made up of forests and shrubs, and the remaining portion is made up of water bodies, mines, wetlands, etc. as shown in Fig. 3.2. Each region having different soil properties and infiltration capacities.

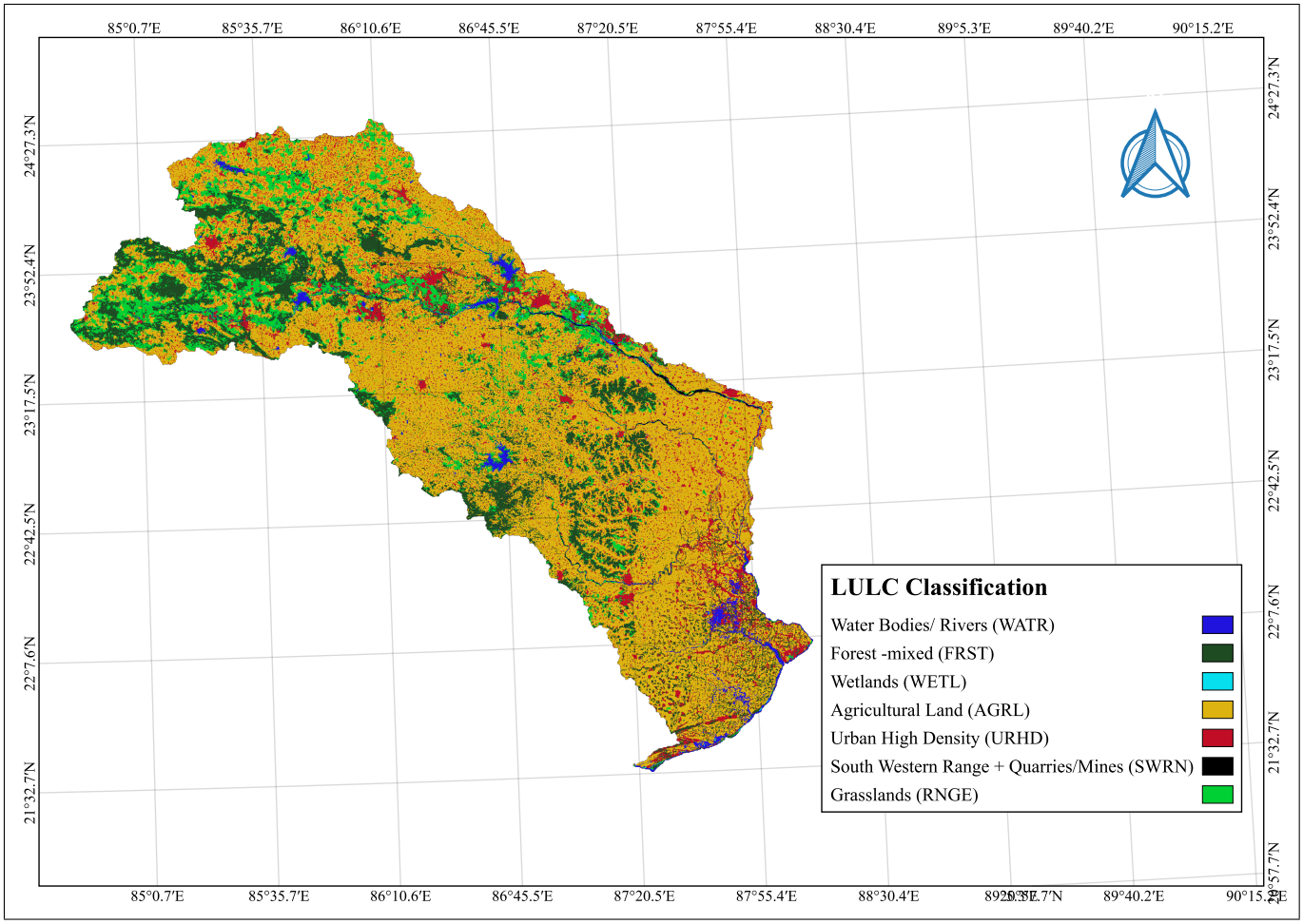

Figure 3.2: LULC map of Damodar river basin

3.3.3 Hydrogeology

The hydrogeological conditions in both the regions is classified on the basis of rock types in three major categories :-

3.3.3.1 Jharkhand Region

1. **Fissured Formations**: Most of the state's area, around 85% is underlain by precambrian gneisses, granites, schists and phyllites in which groundwater is present in weathered or fractured zones. Secondary porosities in the deeper part of the formation are also a good source of groundwater but not availed yet. Almost all abstraction demands are satisfied by

shallow wells. Within 200 m depth, 2-4 fractured zones are available (with maximum of 8) for abstraction purpose. Transmissivity values ranges from 0.9-186 m^2/day.

2. **Semi-Consolidated Formations**: Gondwana sediments where groundwater occurs within inter-granular pore spaces and secondary porosities. These formations are present in the form of patches present in Dhanbad, Giridih, Bokaro, Ranchi, Dumka with thickness of 10-70m and yield from 50-135 m^3/hr. Transmissivity values ranges from 3-4.5 m^2/day.

3. **Porous Formations**: Younger alluvium, laterites formations with thickness of 5 to 40m, generally unconfined with yield of 10 m^3/hr. Parts of East Singhbhum comes under this type of formation. Transmissivity values ranges from 208-570 m^2/day.

3.3.3.2 West Bengal Region

1. **Unconsolidated Formations**: Quaternary sediments of older and recent alluvium made up of clay, silt, sand and gravels covering 2/3rd of the state's area. Alluvium covers the western portion of the state bordering areas of chota nagpur plateau. Water yield ranges from 50-200 ^{m}3/hr, with a thickness of less than 2 m to 10 m bgl.

2. **Coastal Confined Area**: Lies in the Ganga-Brahmaputra river system, groundwater naturally flows towards the Bay of Bengal, characterized by a hydraulic gradient ranging from 1 to 0.3 m/km. Tube wells accessing these freshwater aquifers yield between 100 to 150 m^3/hr, with a maximum drawdown of 17 meters.

3. **Hard Consolidated and Semi-Consolidated Formation**: Archaean crystallines rocks, Gondwana sedimentaries covered in the area of in Purulia and western part of Barddhaman, Bankura, Birbhum and northern part of West Medinipur districts in western and south-western Peninsular region of the State. Weathered region upto the depth of less than 1 to 15 m and secondary porosities tapped by bore wells within 100 m are seen in this formation with yield of 5-30 m^3/day.

3.3.4 Soil Map

Soil classification relies on the Soil Map of the World at scale of 1: 5000000 through a partnership between FAO and UNESCO. Following demarcation, soil was categorized on a band between 3659 to 6690, which were further classified as outlined in the SWAT User Soil Database 2012. These bands primarily consist of three main soil types or their combinations: clay, loam, and sandy soil as depicted in Fig. 3.3.

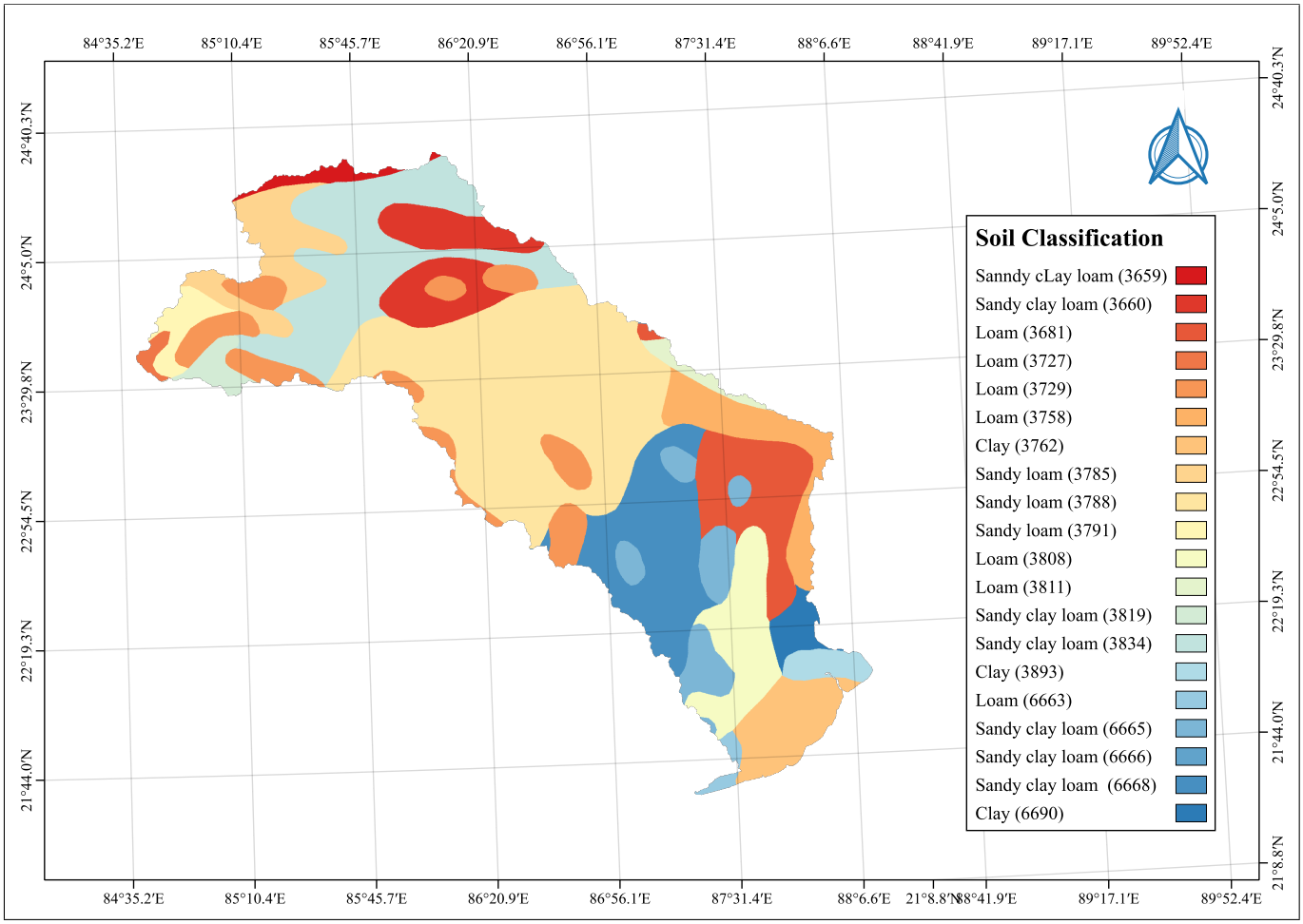

Figure 3.3: Soil map of Damodar river basin

DataType	*Frequency/Resolution*	*Source*	*Model*
Soil map	1000x1000 m	FAO soil database	SWAT
DEM	30x30 m	Shuttle Radar Topography Mission (SRTM)	SWAT-MODFLOW
Landcover map	10x10 m	Sentinel-2 10m LULC data by Esri and Impact Observatory	SWAT
Meteorological dataset			SWAT
Rainfall	.25°x.25°, Daily	India Meteorological Department, Pune	
Temperature	1°x1°,Daily		
Solar radiation	1°x1°, Daily	Nasa Power Data Viewer by NASA Langley Research Center	
Humidity, wind Speed	1/2°x 5/8°, Daily		
GW levels	Monthly	INDIA-Water Resources Information System	SWAT-MODFLOW
Aquifer properties (thickness, specific yield)		Central Ground Water Board, India	SWAT-MODFLOW

Table 3.1: Input data resolution and sources for SWAT-MODFLOW model preparation

3.4 Data Inputs

To apply the SWAT-MODFLOW technique to research, we collected and analysed meteorological, hydrological, and hydro-geological data from various sources (Table 3.1). Rainfall, temperature data was taken from Open Data Access portal of IMD, Pune. A total of 36 data points were taken as weather station as shown in Fig. 3.4 and among which some were outside the study area boundary which were included to ensure comprehensive interpolate of data values, even at the periphery of the study area. For the whole simulation period, from 2015 to 2020, rainfall data was available (IMD, Pune). The INDIA-WRIS portal provided access to GW level data gathered from a well-developed system of groundwater bore well.

Inputs such as Soil map, LULC map are already discussed under section 3.2, Physical Characteristics and their sources are already discussed with all other inputs (Table 3.1). Remaining input such as DEM data and groundwater monitoring stations will be further discussed.

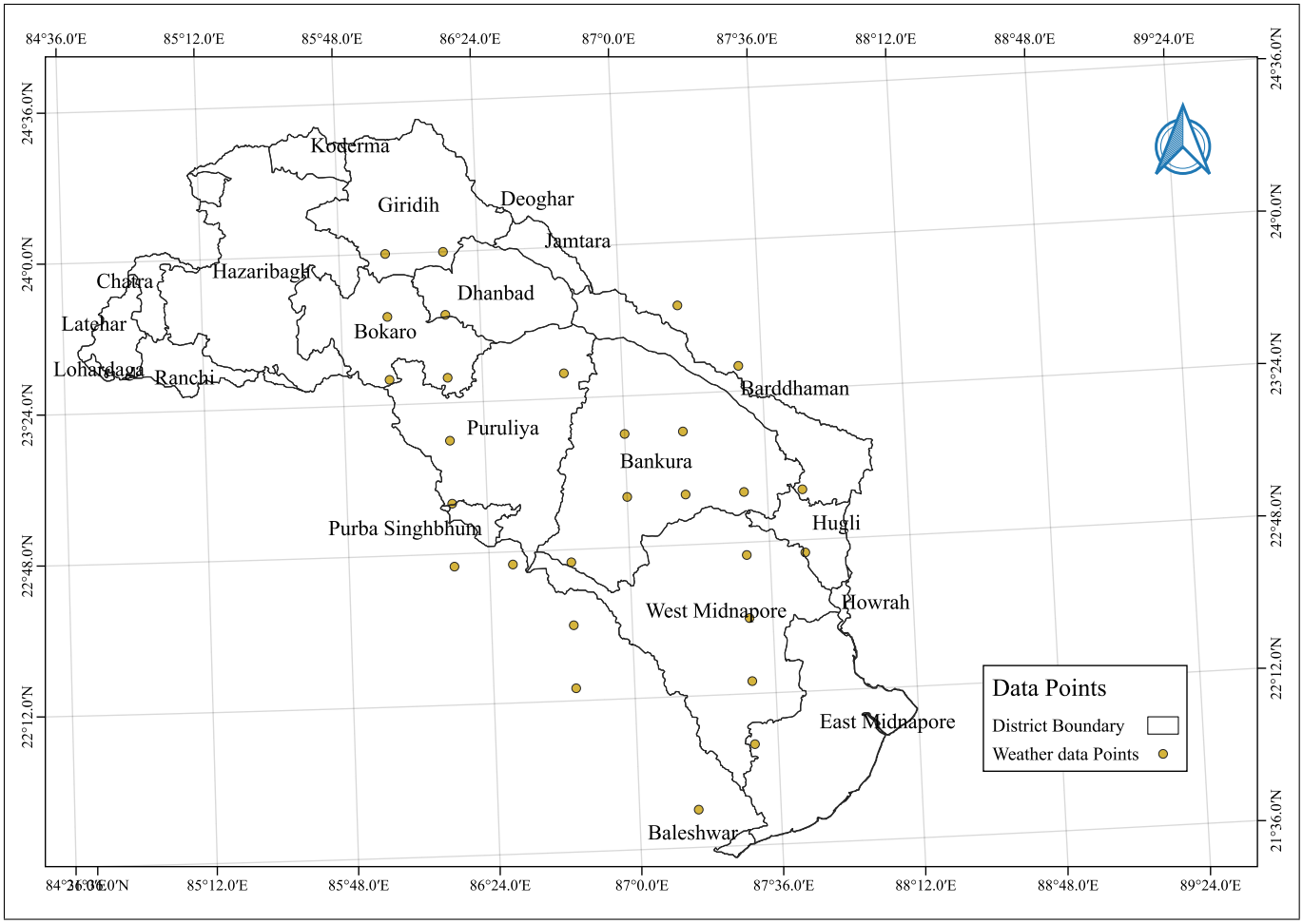

Figure 3.4: Weather data stations taken in/around Damodar river basin

3.4.1 Digital Elevation Model

DEM is used in SWAT model by Terrain Analysis Using Digital Elevation Models (TauDEM) module for river delineation and sub-basin division. Its sources (Table 3.1) and classification based on elevation data is depicted in Fig. 3.5. The sub-basin's topographic characteristics, such as area, slope, and field slope length, are all determined using the DEM. Computational time is dependant on the pixel size of the DEM data, lower the pixel size higher is the computational time.

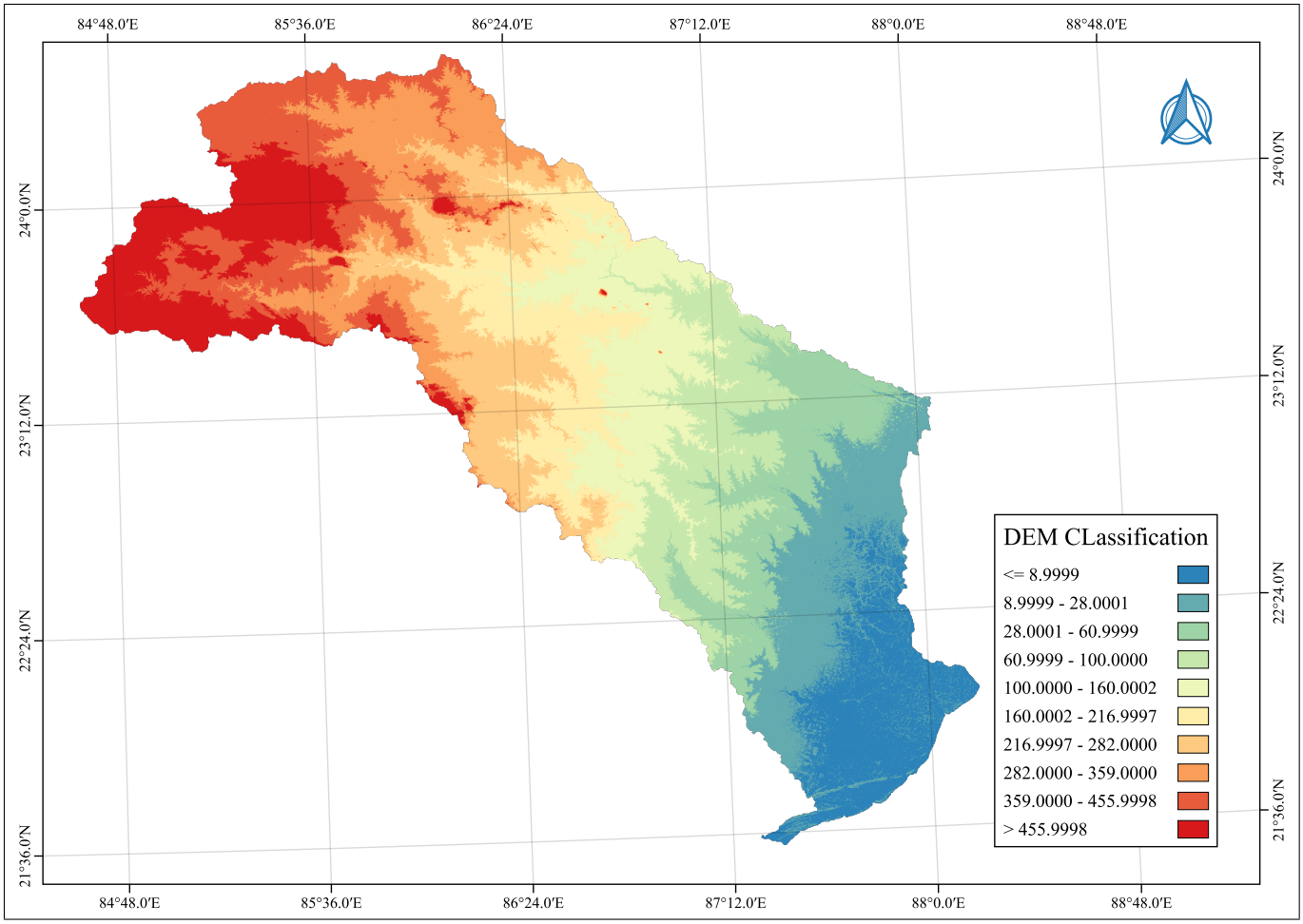

Figure 3.5: DEM map of Damodar river basin

3.4.2 Groundwater Monitoring Stations

Groundwater level data is essential in validating the the accuracy of our result by comparing it to simulated head. This data is used in both MODFLOW and SWAT-MODFLOW model for result validation. Given the extensive study area, this data is taken as secondary sources (Table 3.1). In the research region, 241 data points were collected which were distribute adequately as depicted in Fig. 3.6. In addition to validation, this data is used in Parameter Estimation (PEST) to compute the values of hydraulic conductivity. Among 241 monitoring wells, some lack sufficient data points due to unavailability of data at the source.

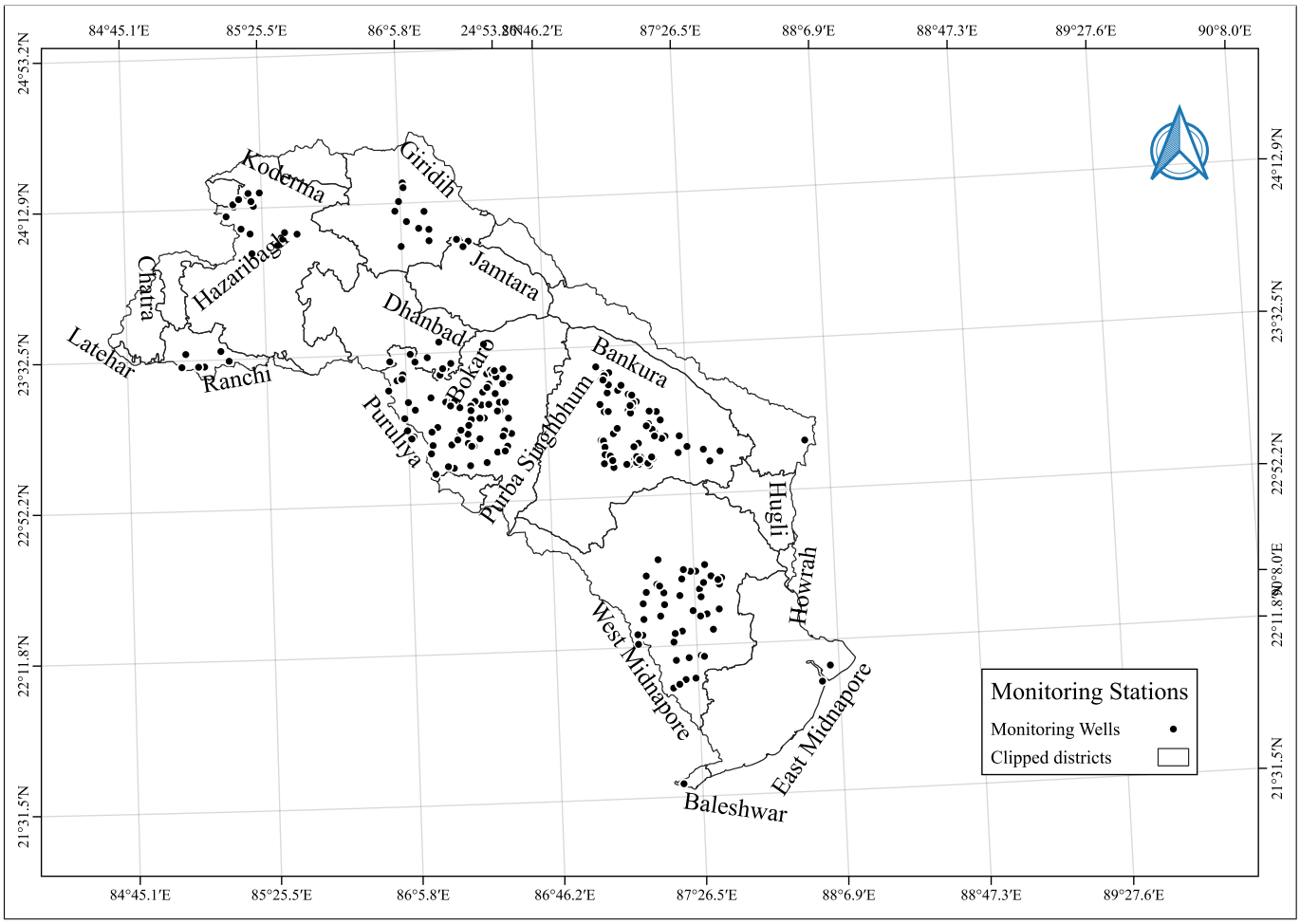

Figure 3.6: Groundwater monitoring wells across the Damodar river basin

Chapter 4

Methodology

4.1 General

This chapter outlines the methodology employed to estimate the spatio-temporal variation in the groundwater table of the Damodar river basin. Groundwater plays a substantial part in maintaining ecosystems and human livelihoods in the basin, but its dynamics are influenced by complicated interactions between hydrological processes, land use changes, and climate variability. To address this, we utilize a coupled SWAT-MODFLOW model, integrating the SWAT for surface water processes and MODFLOW for groundwater dynamics. This coupled approach allows for a holistic model essential for understanding the basin's hydrological system with more accuracy of the surface and groundwater flow dynamics. By applying advanced modeling techniques, we aim to provide valuable insights into the spatio-temporal dynamics of groundwater resources and how this can be further addressed as a tool for groundwater depth estimation and countermeasure can be further discussed to make these resources sustainable.

4.2 SWAT Model Setup

4.2.1 Brief Description of SWAT Model Setup

QSWAT, a QGIS based plugin 2012 was used for the simulation of surface flow dynamics in Damodar river basin. SWAT model was evaluated for the time period ranging from 2015 to 2020. The first three years from 2015 to 2017 was used as warm-up simulation period. Model setup

begins with Watershed delineation which was carried forward based on the WRIS report of Ganga river basin. The report contains all the sub-basin including Damodar River basin, which is one of its sub-basin. Basin demarcation in the report is used to create the Damodar river basin's boundary. Further along with addition of Digital Elevation Model (DEM) and implementation of Terrain Analysis Using Digital Elevation Models (TauDEM) in SWAT module stream networks were created for the study area, while setting the river threshold to 1200km^2(streams with contributing areas greater than or equal to 600km^2 were included in the model).

Based on river network, region was discretized into 27 sub-basins which was sub-divided into HRUs. HRUs encompass distinctive combinations of land cover, soil type, gradient, and altitude that affect hydrological processes such as percolation and surface discharge.

SWAT model use raster file and various shapefiles in building a model. Each raster file should be having identical pixel size to be processed by SWAT .In this study a size of 500 * 500 was used and it was observed that after further lowering of the pixel size there was seen increment of number of HRU's attribute points thereby increasing the computational time. In this study to classify land cover and soil map so that SWAT module can identify the type by referring its database, look up tables was used in which land cover was classified into 7 classes and soil map into 20 classes. This resulted in creation of a total of 793 HRUs.

Meteorological data was organized with the help of weather generator, in total only 36 weather stations were used due to difference in resolution of the different weather data (Table 3.1). Further SWAT model was simulated and evaluated for monthly time step throughout the basin.Rest of the SWAT model setup is discussed in detail as we proceed further.

4.2.2 Watershed Delineation

The purpose of delineation is to partition an area based on stream reaches ensuring that they converge into a single outlet. This outlet serves as the point of calculating SWAT outputs, including water quality, streamflow, sediment transport etc. TauDEM uses flow direction, flow accumulation and lastly threshold value to create stream network based on which sub-basins are created as shown

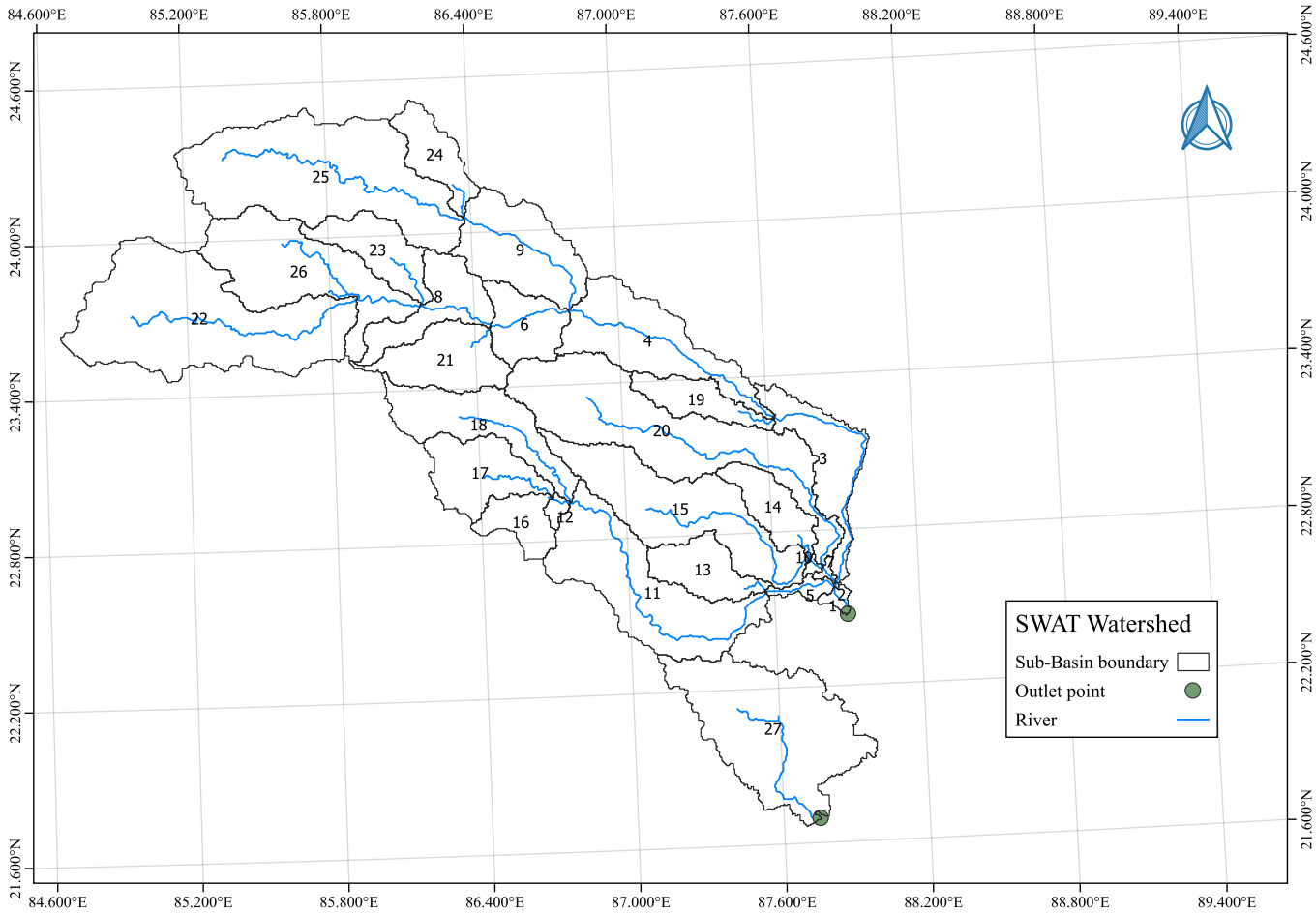

Figure 4.1: Delineated watershed of Damodar river basin by SWAT

in the Fig. 4.1.

4.2.3 Creating HRUs

HRUs are land-based entities characterised by identical landuse, soil and slope which are assumed to respond similarly to the hydrological inputs. Creating HRUs requires 4 GIS layers, namely sub-basin, LULC, soil and slope map. After combining these 4 Attributes we get a HRU map as shown in Fig. 4.2. To show how it is a aggregated form of the selected 4 inputs, one of its attribute is selected (Table 4.1) and highlighted in Fig. 4.2. The SWAT module can generate a single HRU within each sub-basin, which is commonly used when dealing with an excessive amount of sub-basins. However, in this investigation, numerous HRUs were generated inside each sub-basin, as

Subbasin	Landuse	Soil	Slope Band	Area(ha)
20	AGRL	Sandy Clay Loam	0-5.0	140653.10

Table 4.1: Selected HRU specifications

is commonly the case.

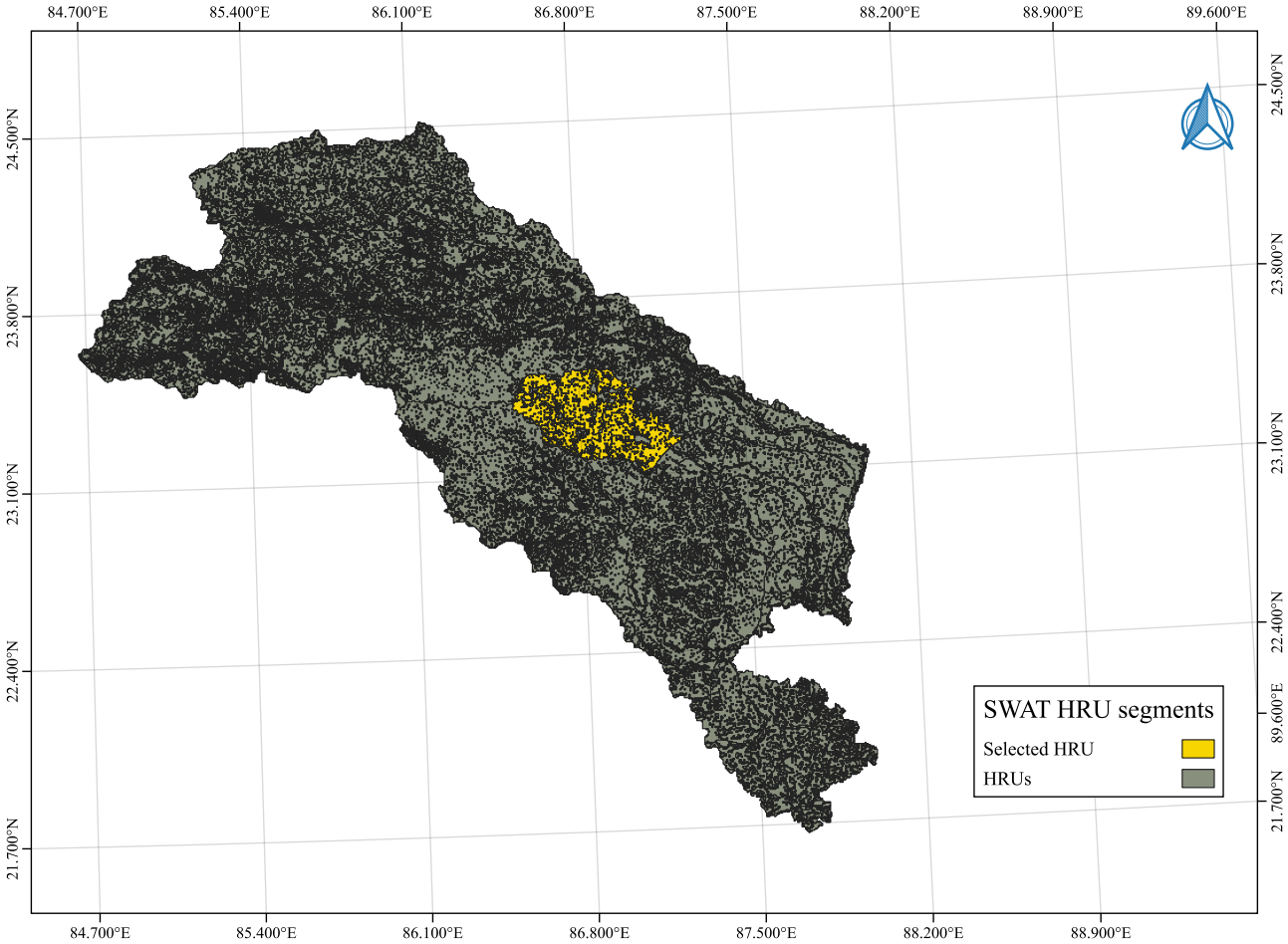

Figure 4.2: HRU map of Damodar river basin

4.2.4 Weather Data

SWAT requires meteorological information to model the hydrological cycle, that involves rainfall, maximum and minimum temperatures, velocity of the wind, relative humidity, and solar radiation. In this study WXGN weather generator model is used as a tool to convert the measured weather data as SWAT inputs. Details regarding the selected weather stations are outlined in Chapter 3

along with Fig. 3.4. The generated parameter based on the 5 input parameter (Table 4.2) which are processed as SWAT inputs for simulation.

Location	Time period	Temperature	Rainfall	Solar Radiation	Wind Velocity	RH
Object ID	Rain yrs	TMPMX	PCPMM	SOLARAV	WNDAV	DEWPT
Station		TMPMN	PCPSTD			
Wlatitude		TMPSTDMX	PCPSKW			
Wlongitude		TMPSTDMN	PCPD			
Welev						

Table 4.2: Weather data input

The full form of the aforementioned terms may be found in SWAT documentation 2009 by (Neitsch et al., 2011).

4.2.5 SWAT Simulation

SWAT run is initiated after providing climate data covering 6 years starting from 2015, the SWAT Editor automatically determines the available date range. The time period for the SWAT run is from 01/01/2018 to 12/28/2020. Monthly time step is chosen and an initial number of years to skip (NYSKIP) is specified as 3. The output which is needed is enabled after which appropriate release version of SWAT.exe based on machine architecture: 64-bit or 32-bit is chosen. Finally, SWAT run is activated by clicking on Setup SWAT Run . This step completes the setup process and activates the SWAT run simulation. After this step output file are created which can be read and output maps such as groundwater recharge can be plotted.

4.3 MODFLOW Setup

4.3.1 Brief Description of MODFLOW Setup

MODFLOW was setup in GMS software (Groundwater Modelling System) 10.7.3 version. Basin boundary and river was created as per SWAT model and divided into 150 row and 150 column grid with 22500 cells of which 8001 were labelled as active cells (Ibound=1). Cells outside the study

area are not included in computation and labelled as Inactive cells (Ibound=0). Two categories of boundary conditions were defined: No flow boundary and another is constant head boundary (specified head boundary), as illustrated in Fig. 4.3. A single-layered MODFLOW model was generated utilizing digital elevation data. DEM data was utilized for topmost layer flow domain and starting head data sourced from monitoring wells in WRIS. The values for Top Elevation and Starting Head for the entire extent is determined using the inverse-distance interpolation method conveniently provided within GMS.

Aquifer depth was taken as 200 m based on MODFLOW model of River Ganga by (Maheswaran et al., 2016) which encompassed the Damodar river basin as a sub-basin within its study area. Recharge rate and evapotranspiration data was obtained through the output file of SWAT (output.std) and incorporated in their respective packages, RCH (m/day) and ET (m/day). Hydraulic Conductivity was obtained through inverse modelling tool PEST, in which observed

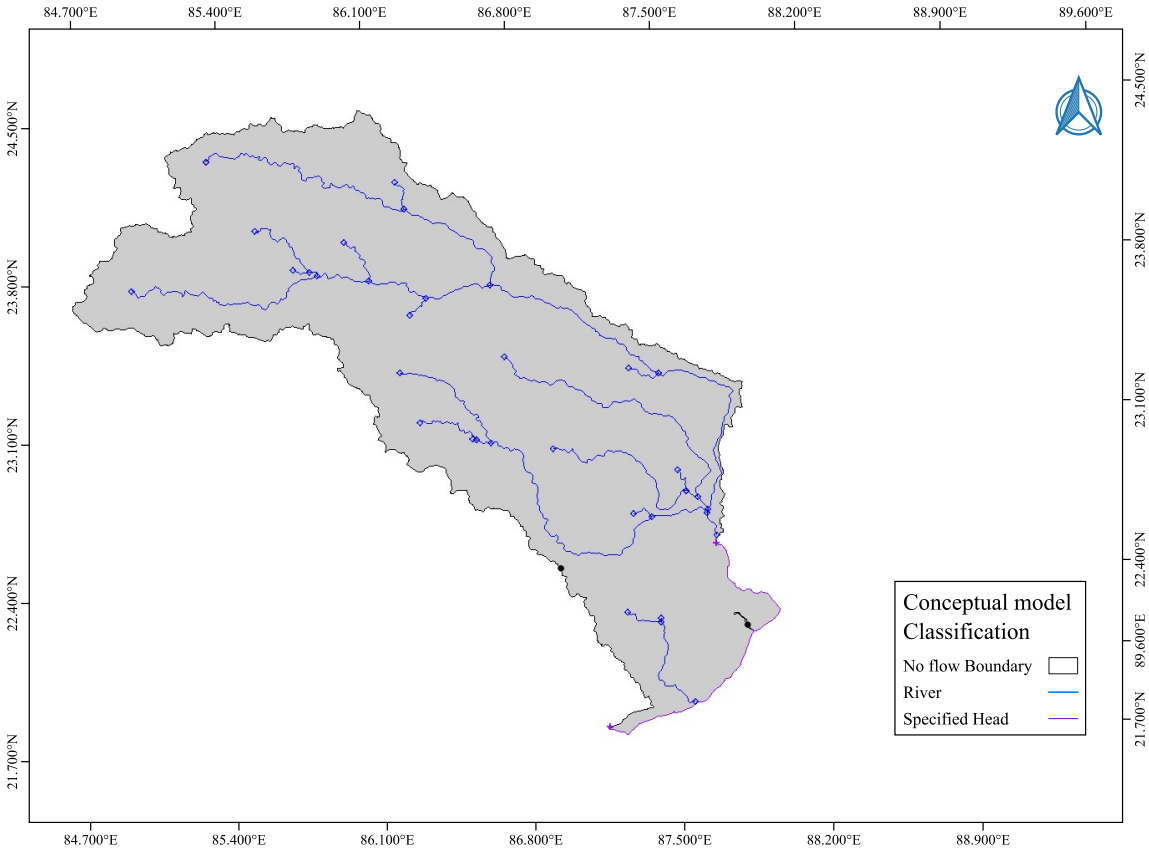

Figure 4.3: Conceptual model of Damodar river basin

head data was used. Head value was obtained through 241 monitoring wells under INDIA-WRIS

which were compared with computer head to minimize the residual. Region was subdivided into 8 hydraulic conductivity zones which were given initial values between 10 to 50 m/s. The number of extraction wells matched the count of active cells, with extraction data sourced from the (CGWB, 2022) report. The base year for the transient model was set as January 2018, and simulations were conducted from 2018 to 2020. The model comprised 12 stress periods, each consisting of four segments per year, with a time step of approximately 10 days. Detailed discussion about model setup is further discussed in the chapter.

4.3.2 Delineating Watershed

A conceptual model is created of the Damodar river basin in GMS interface and then converted to a grid-based model for simulation purposes. The LPF (Layer Property Flow) package is evaluated for groundwater flow and offers the choice of a confined or convertible layer. In this work, a convertible layer is used to determine aquifer parameters for all cells. This can be done directly by the user or using parameters, which distinguishes it from other flow packages. SWAT input shapefiles for basin boundaries and river networks are imported and turned into Feature Objects in the conceptual model. Feature objects are mostly arcs and points, which are further defined as sources/sinks, boundaries like no flow, specified flux, specified head etc as shown in the Fig. 4.3.

4.3.3 Conceptual Model

Conceptual model of the river system is to be converted to a gridded model for the application of numerical model. Once the outer boundary is established, Spatial discretization is done by divided the extent into 150 rows and 150 columns. Within this grid, layers within the basin boundary are designated as active, as depicted in Fig. 4.4.

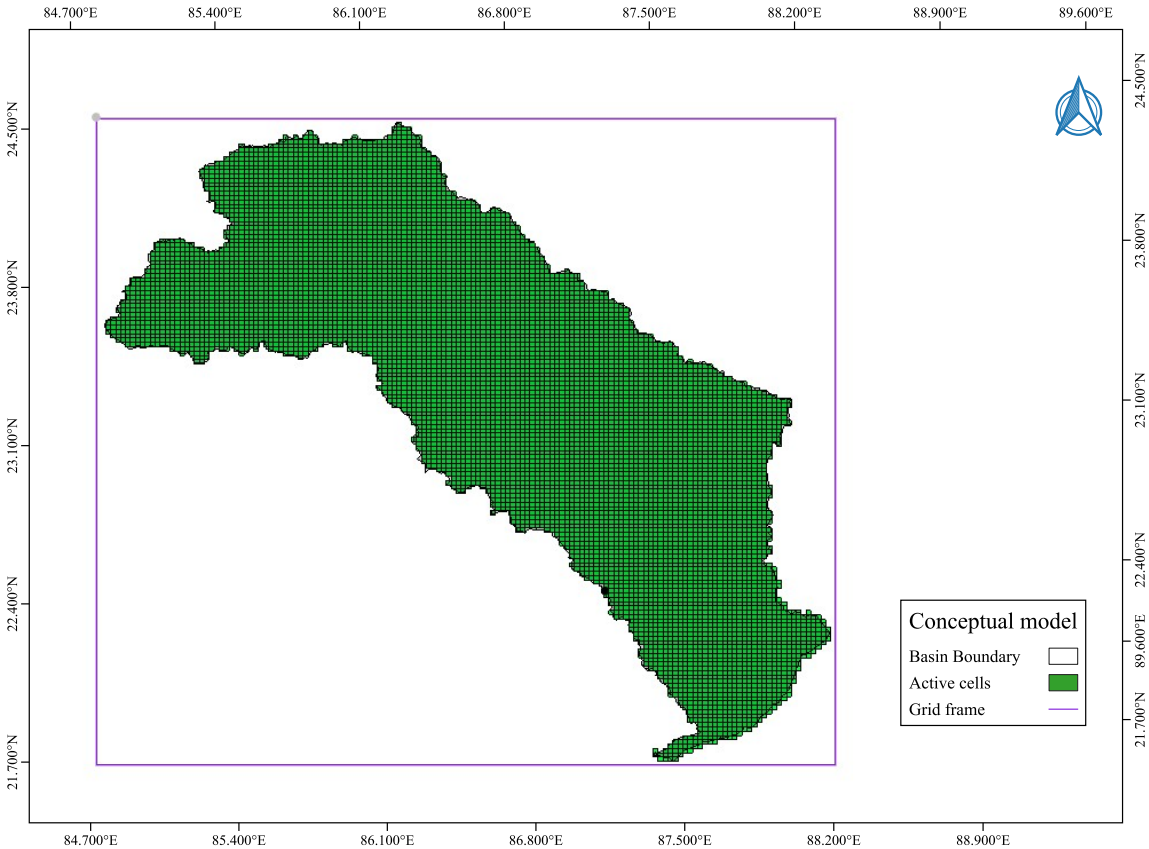

Figure 4.4: Spatial discretization of Damodar river basin

4.3.4 Defining External Stresses

Following the discretization of the spatial domain, external stress packages are incorporated to replicate real world conditions within the model. For this GMS provide coverage setup categorized below:

- Sources/Sinks/Boundary conditions, for well, rivers, specified head, general head,etc.
- Areal Properties, for defining recharge rate, hydraulic conductivity, evapotranspiration, specific yield,etc.
- Observation points such as head, transient head,etc for comparing computed head.

Following application of required coverage we get a model ready to simulate as shown in Fig. 4.5.

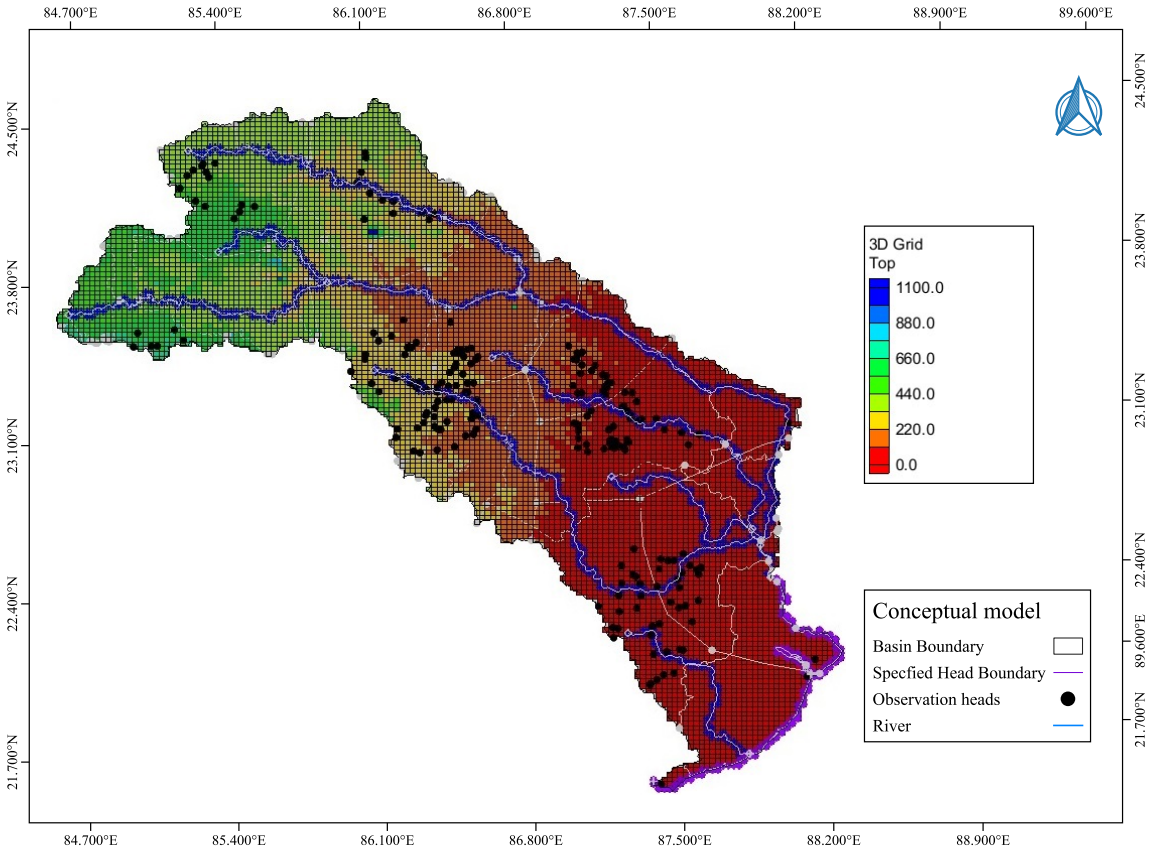

Figure 4.5: MODFLOW map with packages and top elevaton profile

Elevations from the DEM file depicted in Fig. 3.5 are extracted using inverse weighted interpolation to obtain necessary points. Monitoring wells are identified as scattered points using latitude and longitude coordinates, then transformed into a point shapefile. This shapefile is subsequently imported and converted into feature objects within the respective observation head coverage setup, enabling MODFLOW to interpret it.

4.3.5 Defining Data in MODFLOW Packages

For satisfying the convergence criteria, accurate data is required, otherwise model will not converge showing error. Additionally data has significant importance in simulating real field scenarios with the help of various packages offered within MODFLOW model, which are discussed below.

4.3.5.1 River Package

The River (RIV) Package is intended to replicate the effects of flow dynamics among surface water features and groundwater systems. It requires requires river head, river bottom, river conductance acquired from Groundwater dynamics report (CGWB, 2022).

4.3.5.2 Recharge and Evapotranspiration Package

Data for RCH and ET package are available after SWAT simulation in output files. It is implemented as a single value throughout the polygon as per the stress period either manually or through excel csv files.

4.3.5.3 Well Package

The WEL Package was designed to replicate the extraction or injection of water into an aquifer at a steady pace during each stress period. Well package data is implemented to specific districts available in the study area as per the Groundwater dynamics report (CGWB, 2022). In this study, each active grid is allocated an extraction well, and the total extraction value within a specific district is averaged across all wells in that district.

4.3.5.4 Specified Head Package

The values for this package are determined based on the top elevation of the model. These values remain constant throughout the entire time period, and this zone serves as a sink, housing the outlet point of the Damodar river basin.

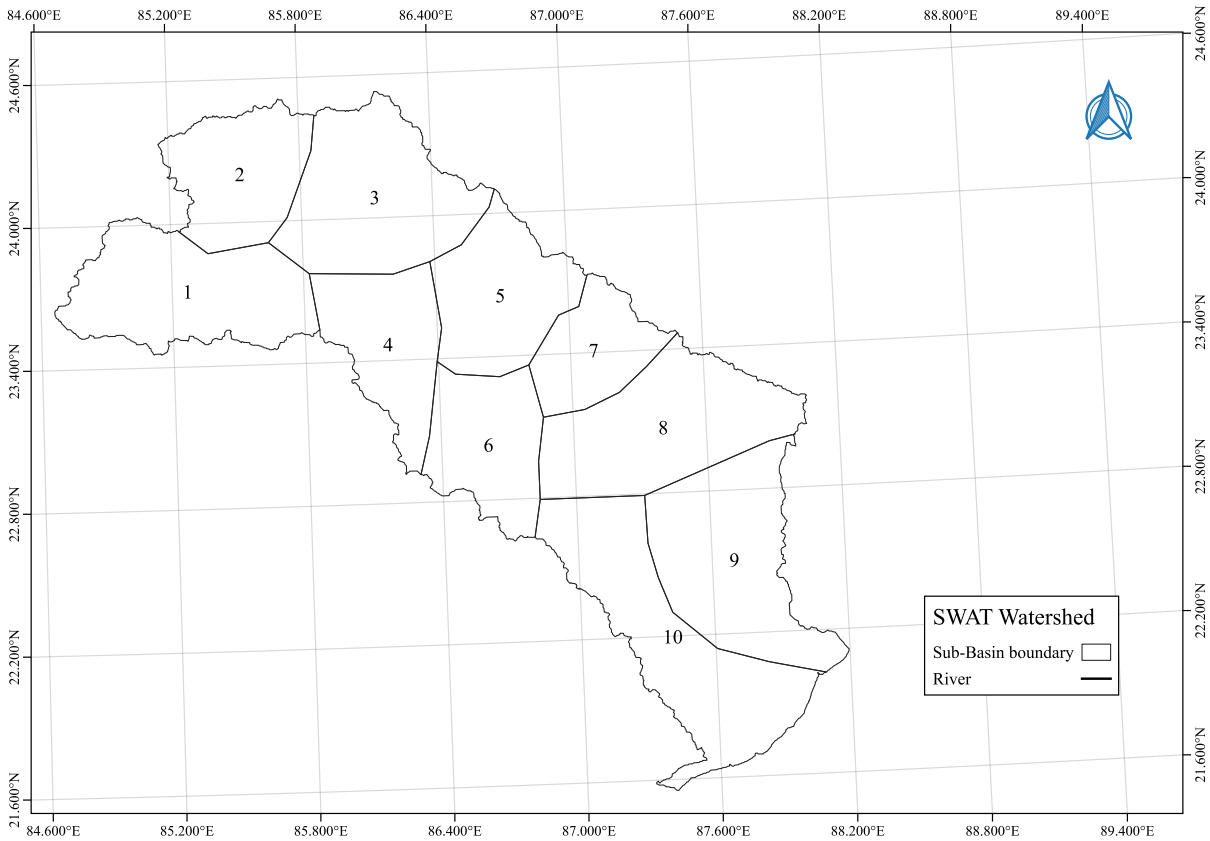

Figure 4.6: Hydraulic conductivity zones

4.3.6 Aquifer Data

The Groundwater Dynamics report (CGWB, 2022) provides information on aquifer characteristic such as specific yield and specific storage. Aquifer depth is as per the research in Ganga river basin (Maheswaran et al., 2016) and hydraulic conductivity was simulated zone-wise from Parameter Estimation tool (PEST). Basin was split into 10 section as depicted in Fig. 4.6 and further values are discussed in Chapter 5.

4.3.7 Starting Head

A transient model requires starting head to calculate the groundwater head, it must be near to the actual head in order to prevent additional computational time. This research acquired starting heads from monitoring wells from INDIA-WRIS Portal.

4.3.8 Hydraulic Conductivity

It is a key element which influence the transient flow of water. Due to unavailability of this parameter, it was obtained with an inverse modelling tool. PEST was used to simulate the hydraulic conductivity after providing groundwater head data from observation wells shown in Fig. 3.6. Zonal analysis was done to procure this parameter as depicted in Fig. 4.6. Further details about its results are discussed in chapter 5.

4.3.9 MODFLOW Model

The MODFLOW model is implemented after discretization and data definition, which means that aquifer flow parameters like top elevation, starting head, porosity, stress periods, etc. must be specified. After that, the model is checked for errors before the simulation is started for the respective time period. This model works on finite difference approach discussed in upcoming subsection.

4.3.10 Numerical Model

The partial-differential equation that governs the movement in the groundwater flow domain having constant density through porous media in 3-D can be represented as:

$$\frac{\partial}{\partial x}(K_x\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(K_y\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(K_z\frac{\partial h}{\partial z})=S_s\frac{\partial s}{\partial t}-W \tag{4.1}$$

For explanation of the symbols in Equation 4.1 refer to book by (Harbaugh, 2005).

The groundwater flow equation is then applied in finite difference form, taking into account the continuity equation. This equation calculates the groundwater head in a transient state at time t+Δt. It states that the sum of fluxes entering and leaving a cell must be equivalent to the rate of alteration in storage within it. Assuming a constant density of ground water, the continuity

equation expresses the equilibrium of flow in a cell as:

$$\sum Q = S_s \Delta V \frac{\Delta h}{\Delta t} \tag{4.2}$$

Explanation of the symbols for equation 4.2 are available in Book by (Harbaugh, 2005).

- Q: Rate of flow (L^3T^{-1}),
- S_s: refers to specific storage,
- ΔV: Change in Volume of water (in litres), and
- Δh: Change in groundwater head over a incease in time periof of Δt.

Mathematically, MODFLOW employs the i, j, k indexing convention to map cells within the model domain. Here, i denotes row, j signifies column, and k represents a layer. This indexing system facilitates the conversion of the partial differential equation governing groundwater flow into simpler equations evaluated at the center of each cell. The flow entering and leaving the cell is computed using Darcy's law as:

$$Q_{i,j-1/2,k} = K_{i,j-1/2,k} \Delta c_i \Delta v_k \frac{(h_{i,j-1/2,k} - h_{i,j,k})}{\Delta r_{j-1/2}} \tag{4.3}$$

In 4.3 equation:

- $h_{i,j,k}$ stands for groundwater head at cell centre (i, j, k),
- $Q_{i,j-1/2,k}$ stands for the flow rate between adjacent cells with dimensions (L^3T^{-1}),
- $K_{i,j-1/2,k}$ stands for the hydraulic conductivity,
- $\Delta c_i \Delta v_k$ represents the area of cell perpendicular to flow direction, and
- $\Delta r_{j-1/2}$ represents the distance between two cell centre, with dimensions (L).

When considering external stresses such as wells or river seepage into an aquifer, the flow is determined differently. For wells, flow is calculated based solely on the flow rate, irrespective of the head as shown in equation 4.4 . However, for river seepage, the flow is dependent on the head, as illustrated by the following equation 4.5.

For well,

$$a_{i,j,k} = q_{i,j,k} \tag{4.4}$$

- $a_{i,j,k}$: Flow from well (external source), L^3T^{-1} unit, and
- $q_{i,j,k,1}$: Extraction rate of well.

For river seepage,

$$a_{i,j,k} = C_{i,j,k}(R_{i,j,k} - h_{i,j,k}) \tag{4.5}$$

- $a_{i,j,k,n}$: Flow from river (external source), with dimensions of L^3T^{-1},
- $R_{i,j,k}$: River head,(L) unit,
- $C_{\mathrm{RIV},i,j,k}$: River bed conductance,L^2T^{-1} unit, and
- $h_{i,j,k}$: Head in the cell i, j, k.

These equation are written as per equation 4.2 and computed to calculate head at $t + \Delta t$ time step. It is carried out with backward-difference approach to avoid numerical instability. MODFLOW employs various solvers for iteration, such as the Strongly Implicit Procedure Package, Preconditioned Conjugate-Gradient Package, and Direct Solver Package. Each solver employs distinct criteria to address inner and outer equations, ensuring convergence toward a close-to-accurate solution.

Various computational packages have been utilized to model external stresses within the groundwater system, including the Recharge, River, Evapotranspiration, and Well packages. These packages have been integrated into the study to address the groundwater head equation effectively.

Moreover, the temporal domain for calculating the groundwater head is segmented into discrete intervals, stress periods. As already known, during each stress period, external stresses remain constant. Subsequently, each stress period is split into time steps, wherein the governing equations are iteratively solved until convergence criteria are met.

In present study, the temporal framework spans from 2018 to 2020, comprising twelve defined stress periods. Within each stress period, a time step of ten days is employed to advance the numerical solution of the groundwater head equation.

4.4 SWAT-MODFLOW Model Setup

4.4.1 Brief Description of SWAT-MODFLOW Model Setup

SWAT gives satisfactory result for shallow aquifer but in case of deep aquifer its groundwater subroutine is not much effective (Molina-Navarro et al., 2019) instead MODFLOW has to be used. Following the inverse calibration of the MODFLOW model, it was observed that the estimates of recharge and evapotranspiration derived from the SWAT model gave good result at some region, with the highest residual reaching approximately 30 meters. This discrepancy was of higher magnitude as compared to study by (Maheswaran et al., 2016), primarily stemmed from the steep decline in slope within the hilly terrain of Jharkhand region. Additionally, the two outputs from SWAT were used as a constant value in the whole study area. As both parameters are dependent on soil property, a constant value will introduce computational error. To mitigate these challenges, an innovative approach utilizing the coupled SWAT-MODFLOW model, as proposed by (Park et al., 2019), has been implemented. This integrated model runs on a daily time scale and accounts for the regional heterogeneity of recharge and evapotranspiration, improving the accuracy and reliability of groundwater computations inside discretized grid cells.

To properly couple the SWAT-MODFLOW model, the parameters must be transferred ("mapped") among the two models. The variables below are transmitted among SWAT and MODFLOW:

- Recharge into groundwater: with interaction between HRUs and MODFLOW cells,
- Difference between potential ET and actual ET*: shared between HRUs and MODFLOW cells,
- Channel stage: between sub-basin channels to MODFLOW gridded river, and
- Stream-Groundwater interaction rates: between MODFLOW gridded rive to sub-basin channels in SWAT.

To initiate SWAT-MODFLOW needs, Input/Output (TxtInOut) folder, HRU, Sub-basin, River. This model needs a Steady state model to operate, which was built separately in QGIS without dependency on other platform with the help of SWAT-MODFLOW plugin. In MODFLOW, a grid size of 150 $\times$ 150 was chosen to achieve finer resolution for enhanced accuracy. However, for the SWAT-MODFLOW simulation, maintaining the same grid size was not feasible due to the computational burden it imposed. Consequently, a grid size of 31 $\times$ 35 was adopted instead after several hit and trial.

Using QGIS interface, a MODFLOW model was created after providing DEM, River hydraulic conductivity, Boundary and aquifer properties acquired from the transient MODFLOW model in GMS. A discretized base is needed to link the Outputs of SWAT to MODFLOW model which is carried out by breaking the linking parameter grid-wise leading to its transfer from grid to grid, providing it a spatial variability. Other required packages were created with the help of 'Notepad+' as per the required format of the module. After linking process, Simulation period is read by the module from SWAT file 'file.cio' which is from 1 January, 2015 of about 1035 days.

QSWATMOD is divided into three tab which are discussed in the following section.

4.4.2 About QSWATMOD Interface

QSWATMOD facilitates model preparation along with viewing results. It has 3 tabs whose brief details are given below.

1. Pre-Processing tab: It is used to process and create database of SWAT and MODFLOW input files and later create linkage files. After exporting SWAT model files, there is an option to create a new MODFLOW model or provide input files for pre-existing MODFLOW model. In this study, new MODFLOW model was created and similar data provided to MODFLOW model in GMS is imported and provided in coupled model. This tab also provide option to create MODFLOW observation points in the study area for validation purpose.

2. Simulation tab: It comprises three sections: the first handles the simulation period, sourced from 'file.cio' within the SWAT model. The second encompasses configuration settings, facilitating the inclusion of irrigation pumping, drains, and activation of RT3D for transport modeling. The third section is optional, defining model outputs such as HRU aquifer recharge, MODFLOW recharge, sub-basin channel stage, MODFLOW river stage, SWAT sub-basin water exchange, and MODFLOW river cell exchange. Finally, it has two options: choose the "Create'swatmf link.txt' file" button to export the configuration parameters to the project folder, and then click the "Run Simulation" button to launch the SWAT-MODFLOW executable and begin the simulation.

3. Post-Processing tab: It offers three modules for visualizing output data graphically: plotting, mapping, and exporting results. It has following options: Hydrographs depicting and comparing streamflow and hydraulic head, mapping hydraulic head and recharge, visualizing surface and groundwater interaction, water balance chart .

In the next section, step by step application of QSWATMOD to Damodar river basin are discussed.

4.4.3 Processing SWAT Files and Creation of MODFLOW Model

SWAT input/output files are stored in new directory, addition to which SWAT basin file discretized for mapping of data between HRUs and MODFLOW grid cells. Data required is similar to MODFLOW model based on which a spatial discretized model as shown in Fig. 4.7 is made.

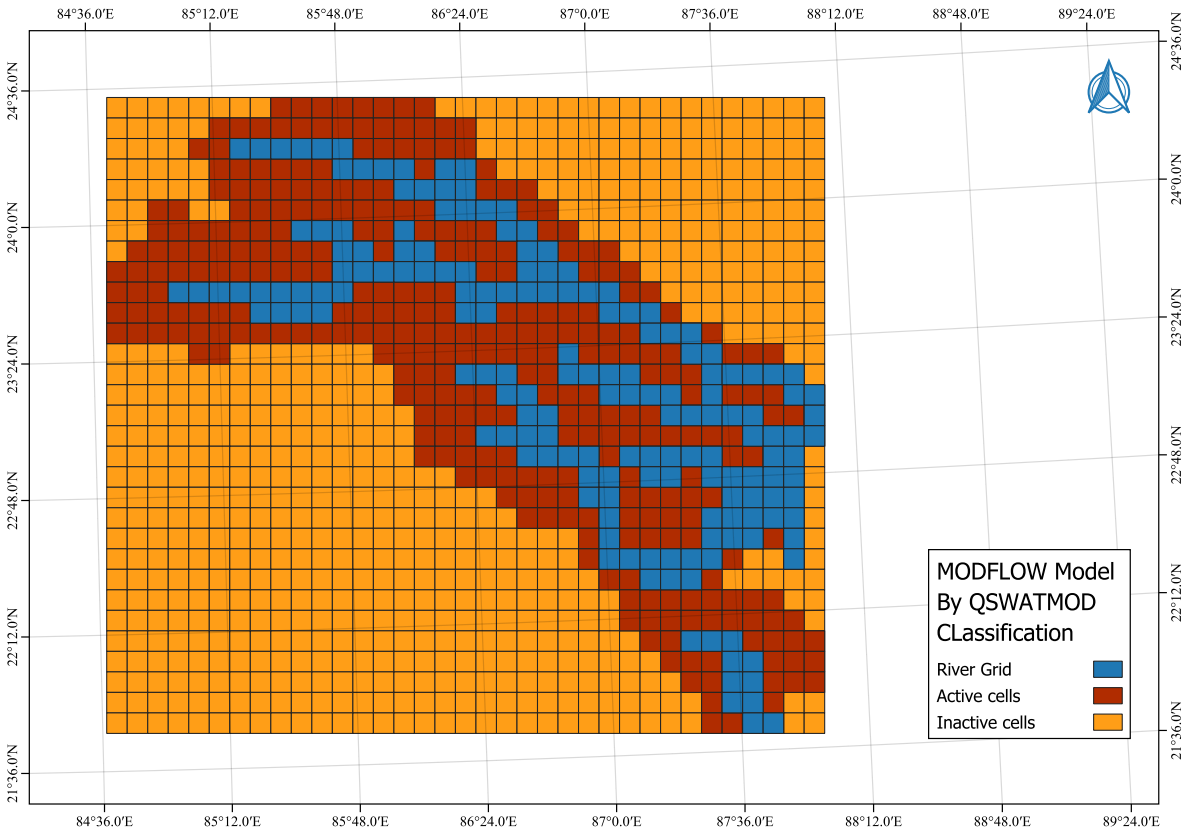

Figure 4.7: QSWATMOD generated MODFLOW model

4.4.4 Formation of DHRU

Hydrologic response unit are further segmented into DHRUs (Disaggregated Hydrologic Response Units) thereby providing more finer mapping of variables like deep percolation to MODFLOW grid cells. QSWATMOD splits area of each HRU into required number of polygons having spatial attribute. In this study, a total of 783 HRUs divided into 30226 DHRUs which is shown in Fig. 4.8. Following refinement of HRUs, they are intersected with grids to facilitate the linking of data from SWAT DHRUs to MODFLOW grid or river cells and vice-versa as shown in Fig. 4.8. Linkage files are created using the module which are used to generate groundwater recharge, evapotranspiration,etc to be used in simulation.

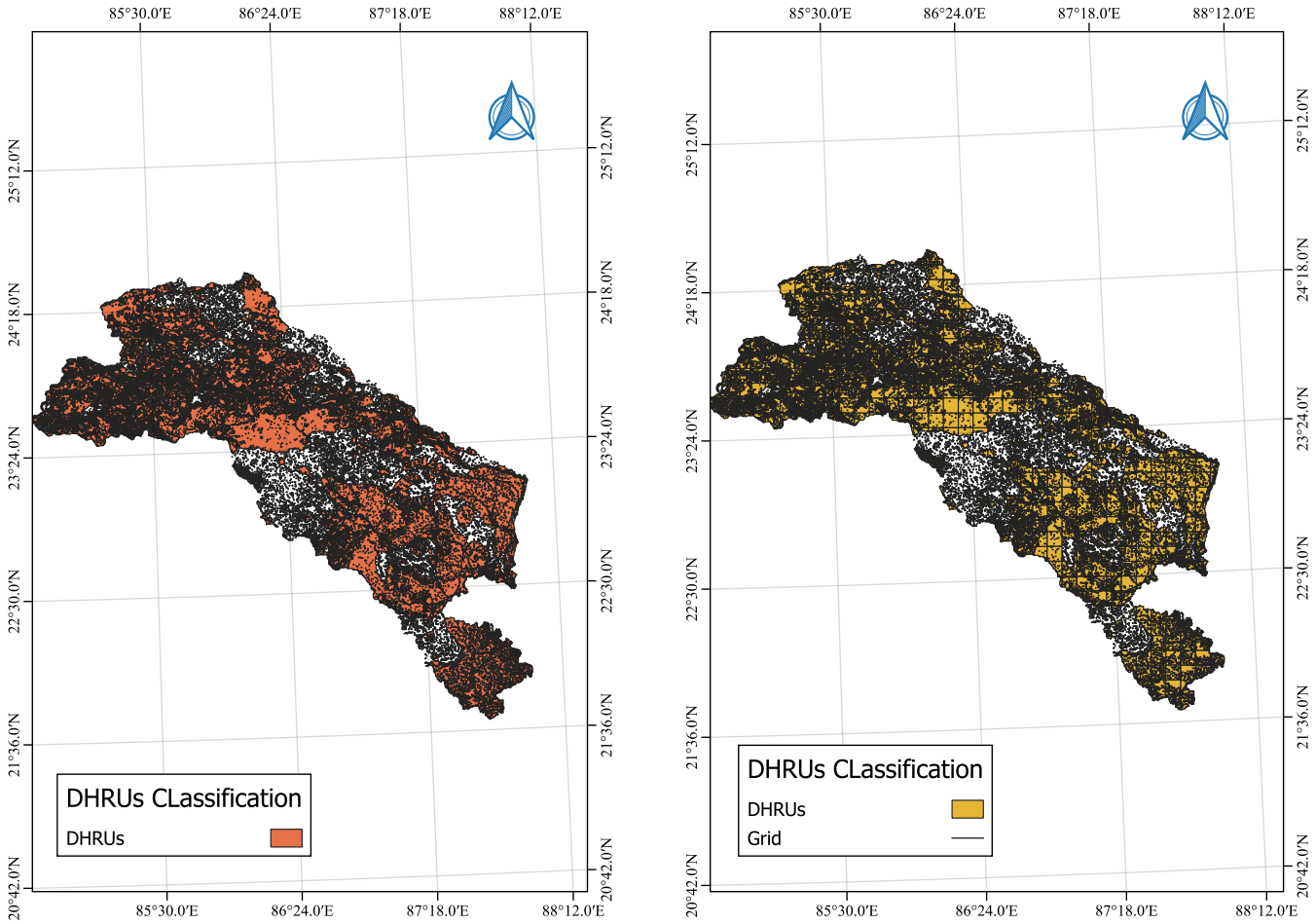

Figure 4.8: QSWATMOD generated DHRU and DHRU-grid map

4.4.5 Preparation of Extraction Well Package

This package needs to be created manually with similar data from groundwater dynamics report by (CGWB, 2022) which was used in the Transient MODLFOW model. 'Notepad+' was used to create WEL package as per the required format.

4.4.6 Simulation Period

The six-year time period, which spans 2189 days from 2015 to 2020, was divided into three warm-up years and three simulation years, from 2018 to 2020. Throughout the simulation period, MODFLOW operates at a daily time step interval after gathering daily data from the SWAT

model. After simulation we get output in form of groundwater head, recharge, surface water and groundwater interaction, etc (Table 4.3).

System	Output File	Frequency	Units	Remarks
MODFLOW	swatmf_out_MF_head	Monthly, Yearly	L	Groundwater head for each cell
	swatmf_out_MF_recharge	Monthly, Yearly	L^3/T	Recharge rate for each grid cell
	swatmf_out_MF_riverstage		L	River stage for every river grid cell
SWAT	swatmf_out_SWAT_recharge	Monthly, Yearly	mm	Depth of recharge from each HRU
	swatmf _out_SWAT_channel		m	Channel depth for each SWAT basin

Table 4.3: SWAT-MODFLOW Output Files

4.4.7 Calibration and Validation

4.4.7.1 SWAT

Calibration is a technique for better guess for parameters used in modelling. Though there are a different methods for calibrating SWAT including manual calibration, the most used one is SWAT-CUP (SWAT-Calibration and Uncertainty Programming). IT contains SUFI-2 algorithm (Sequential Uncertainty Fitting) used for calibration, Sensitivity and Uncertainty analysis. It provide interface for adjusting parameters and its ranges between auto calibration runs.Parameter values should be bound in realistic realm of actual knowledge of watershed otherwise even if model results are good, this model does not simulate realistic conditions.

Validation is done with running the model and comparing the outputs. SWAT model is basically used in this study for data input in MODFLOW model which requires recharge and evapotranspiration. Post-simulation, the annual recharge value is determined to be 236.50 mm.

This value is compared to the findings of a previous study conducted by (Bhanja et al., 2019), where a recharge rate ranging from 143 to 264 mm per year was tabulated based on the Water Dynamics report by CGWB. Evaporation parameter is also validated by referring to research article (Jung et al., 2010) where it was found out that global average precipitation is ranging between 558 and 650 mm/year. In out study it was about 634.1 mm/year which comes within the range of global evaporation scenario. Further it was matched with Book (Rakhecha & Singh, 2009) which accounts for around 51% is lost to transpiration and evaporation in India out of precipitation. Our study shows precipitation of 1253.7 mm in Damodar river Basin which accounts for about 50.5% evapotranspiration in this region. As per comparison results holds good integrity for use in MODFLOW model.

4.4.7.2 MODFLOW

Calibration in MODFLOW is done using inverse calibration, PEST (Parameter Estimation) tool. Parameter values to be estimated was of hydraulic conductivity which was found to be most sensitive parameter, similar to study done by (Frederiksen & Molina-Navarro, 2021). Parameter results are further discussed in the next chapter along with validation by comparing the values of PEST with observed values as shown in Fig. 5.8, 5.6 and 5.7 in chapter 5.

Chapter 5

Results and Discussion

In this chapter, we show and discuss the outputs from the SWAT-MODFLOW coupled model. We follow the findings of SWAT, which are groundwater and evapotranspiration maps, and examine how different soil and landuse classes influence their variability using HRUs. Further MODFLOW and SWAT-MODFLOW model results are provided for calculating groundwater levels. The simulated groundwater levels are then compared to observed readings to determine how well the model replicates real-world hydrological conditions.

5.1 SWAT Model

In this section we will SWAT model was used in this study for computation of groundwater recharge and evapotranspiration. SWAT simulates interaction of precipitation with land-cover, soil, slope,etc by using HRUs which resulted in formation of required parameters. A total of 783 HRUs were formulated in this basin which is equivalent to that many values for the desired two parameters.

5.1.1 Groundwater and Evapotranspiration Map

Variability in groundwater recharge was observed in connection to LULC and soil changes, as depicted in the accompanying maps and tables. The associated tables are arranged area-wise as per the availability of landuse cover. After examining groundwater recharge, it demonstrated that locations with forest cover have the highest recharge rate. Region's soil type is clay, which inhibits

groundwater percolation due to its high moisture-holding capacity (Table 5.1).However, because it is a forest cover, roots can penetrate to a certain depth into the soil, producing voids for water to percolate. Furthermore, data from INDIA-WRIS shows that the water table is observed at a depth of 5 to 10 meters, which is relatively close to the surface, allowing for this high rate of recharge. The area around the region is classified as URHD, which are densely populated areas with low percolation due to the presence of impermeable constructions like as houses, apartments, and highways.

Earlier it was discussed in Chapter 3 under sub heading of LULC that 60% of the area is agricultural area. Subsequently, HRU having agriculture cover has the maximum area among other 5 LULC classes (Table 5.1).

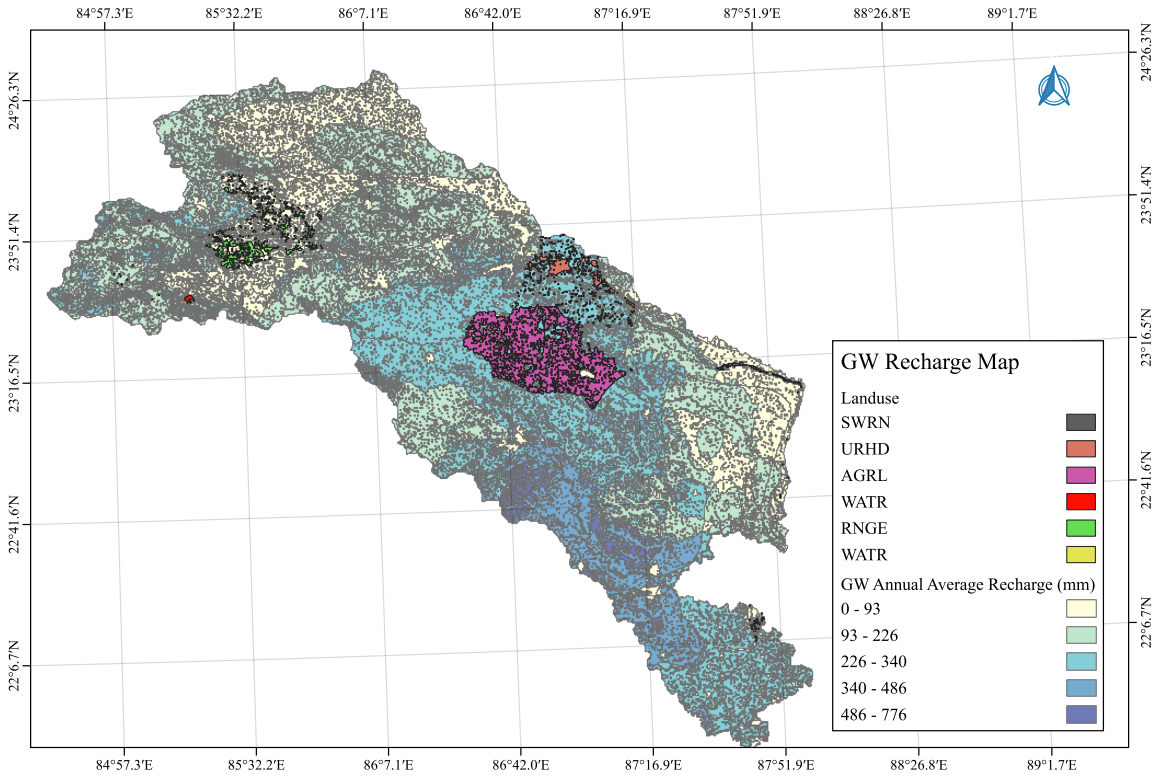

Figure 5.1: Groundwater recharge map of 2018

Agricultural cover is a favorable zone for seepage leading to groundwater recharge (Table 5.1). This is owing to soil tilling and the availability of sandy loam soil which has a good permeability of

water. The value for groundwater recharge is 239.241 mm which is close to the averaged recharge of the basin.

GW Map	Landuse	Soil	Area (km^2)	GW Rch (mm)
2018 Map	AGRL	Sandy Loam	1406	239.251
	RNGE	Sandy Clay Loam	251	39.475
	UHRD	Sandy Loam	200	46.70
	SWRN	Loam	27	119.13
	WATR	Loam	11	0
	FRST	Clay	10	776.36

Table 5.1: Groundwater recharge map 2018 classification

Zones of low groundwater recharge on land covered by RNGE (grasses) and URHD (residential, high density) are illustrated (Table 5.1, Table 5.2, and Table 5.3). This reaction is mostly caused by the high grass cover density in RNGE and the extremely impermeable layers that are found in urban areas, UHRD, on buildings, roads, and other impermeable structures.

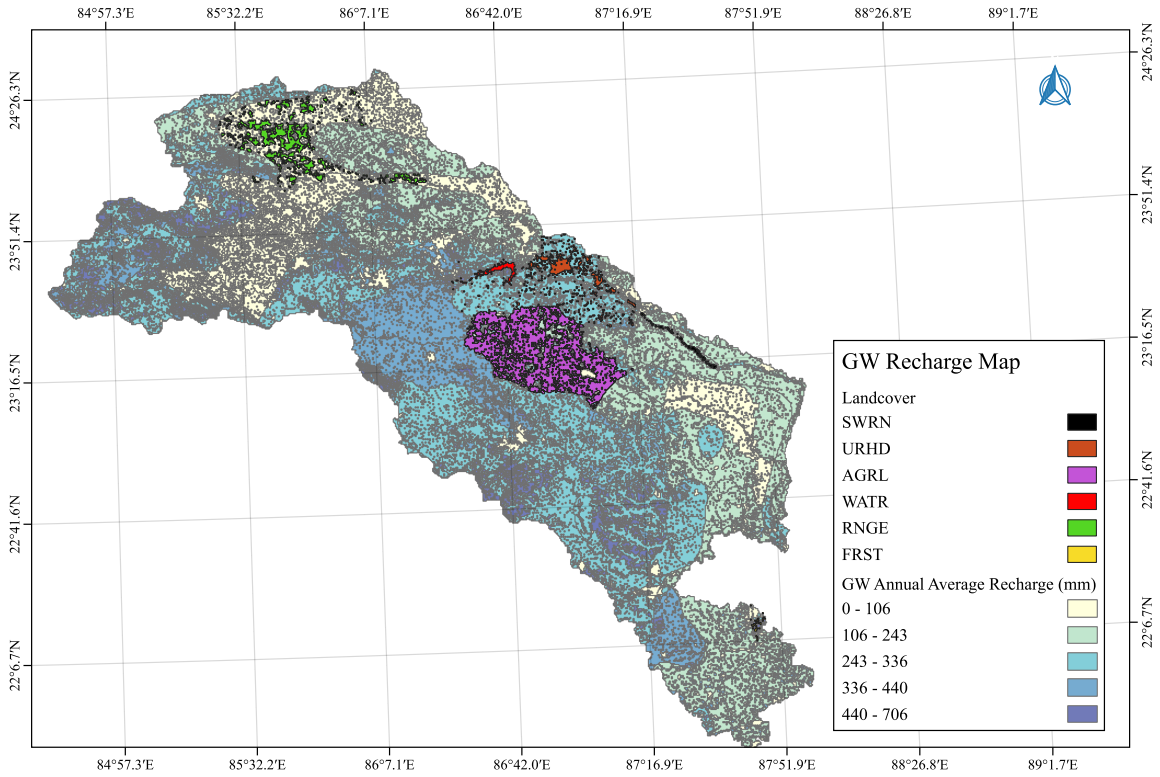

Figure 5.2: Groundwater recharge map of 2019

Landuse cover for water bodies was taken as SWRN, which represent unconsolidated shore. It includes channel and rivers in estuarine river system, system of rivers flowing out to the ocean.

GW Map	Landuse	Soil	Area (km^2)	GW Rch (mm)
2019 Map	AGRL	Sandy Loam	1406	203.72
	RNGE	Sandy Clay Loam	433	32.57
	UHRD	Sandy Loam	200	38.17
	SWRN	Loam	31	321.74
	WATR	Loam	54	0
	FRST	Clay	10	705.6

Table 5.2: Groundwater recharge map 2019 classification

Based on soil map classification, the river bed is considered loam soil; hence, these are appropriate zones for groundwater recharge. It is evident by comparing the research period's recharge maps that groundwater in 2018 and 2019 exhibits closer values.

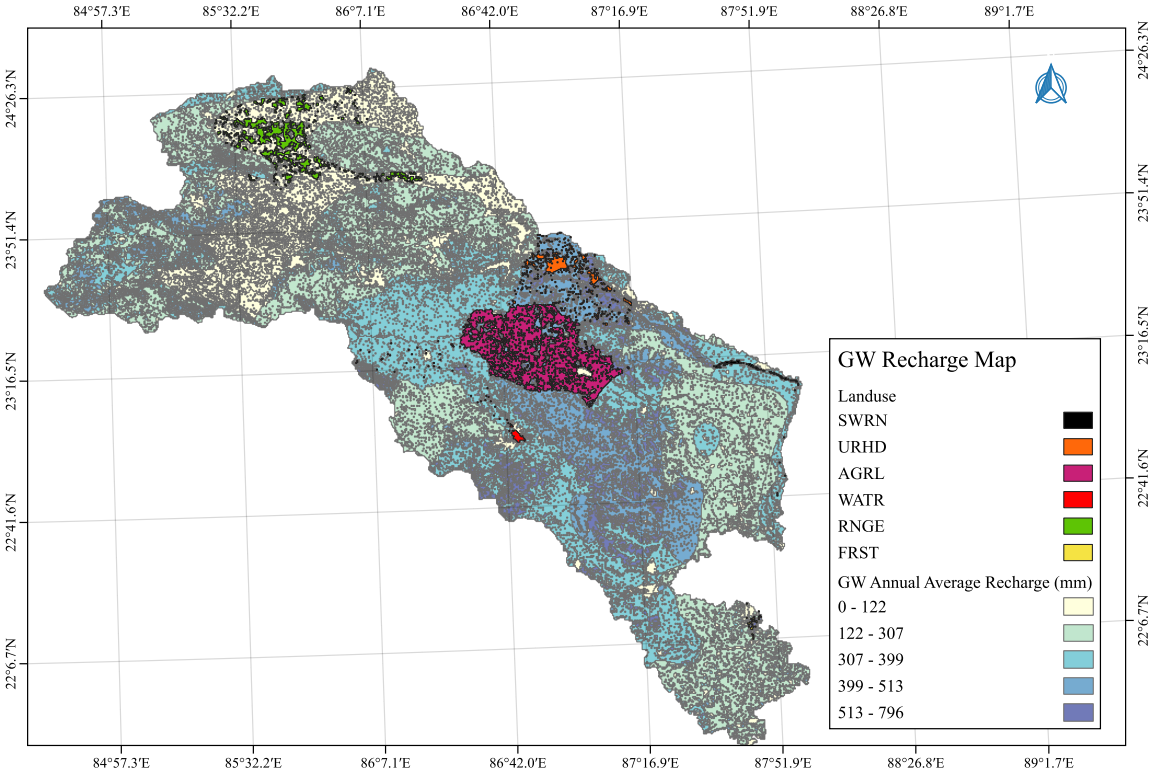

Figure 5.3: Groundwater recharge map of 2020

The readings for 2020 are 1.8 times higher than those for 2018, most likely because of a 310.3 mm rise in precipitation in 2020 as per SWAT output file.

GW Map	Landuse	Soil	Area (km^2)	GW Rch (mm)
2020 Map	AGRL	Sandy Loam	1406	366.60
	RNGE	Sandy Clay Loam	433	47.13
	UHRD	Sandy Loam	200	122.14
	SWRN	Loam	27	456.43
	WATR	Loam	31	0
	FRST	Clay	10	796.08

Table 5.3: Groundwater recharge map 2020 classification

By examining the SWRN (groundwater seepage from rivers) value in 2020. The majority of the nation was shut down in 2020 as a result of the COVID outbreak. The majority of the water needed for agriculture and industry was put on hold.

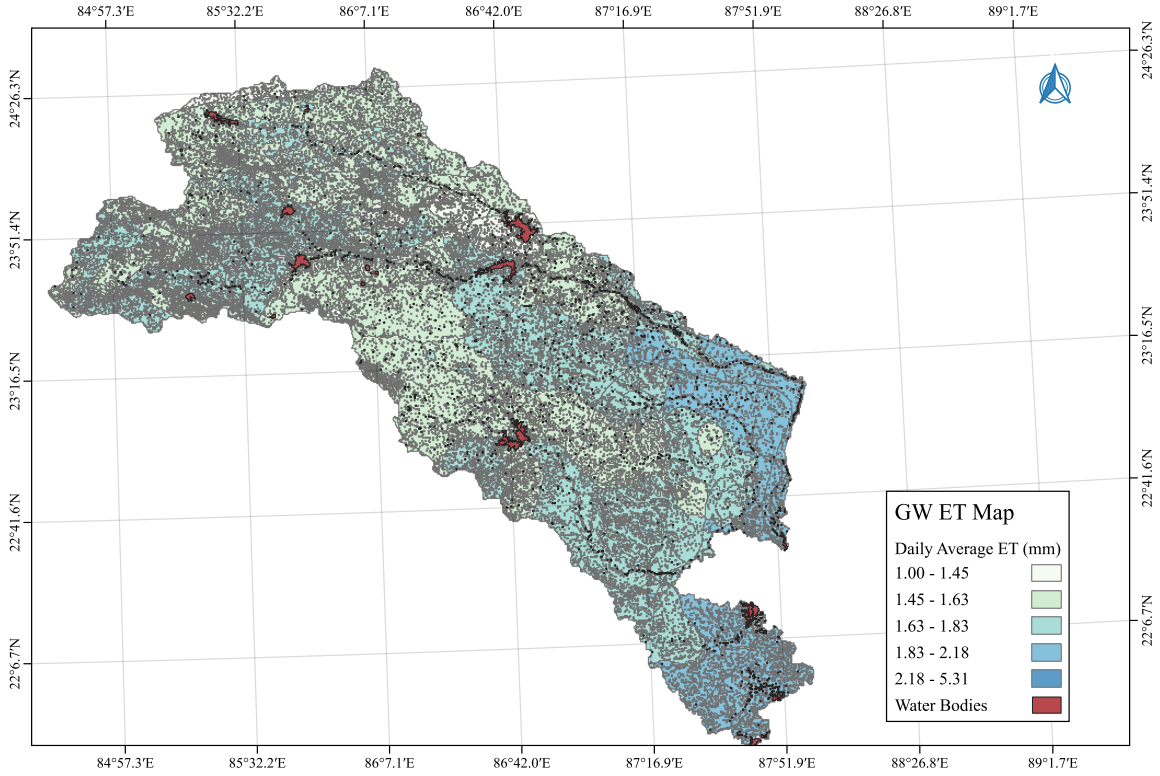

Figure 5.4: Evapotranspiration map for study period 2018-2020

As a result, less river water was diverted to these sectors, which increased the volume of water in the river. More percolation therefore occurred as a result of the river system's increased water supply.

The Evapotranspiration map, which is displayed in Fig. 5.4, is another output of SWAT that can be assessed. The maximum magnitude, which is mostly for bodies of water like rivers, lakes, ponds, etc., is around 5.31 mm. It was discovered after analyzing the attribute table that evapotranspiration larger than 5 mm is limited to water bodies. About 70% of the region is made up of agricultural and urban areas, where daily ET ranges from 1 to 2 mm. The remaining portion is split among the other land use classes.

Examining the results for both output parameters highlights the significance of having a river modeling system that can represent the regional variability of evapotranspiration and groundwater recharge. The SWAT model combined all land features, such as soil and land use, into a single characteristic within a sub-basin by using the Hydrologic Response Unit (HRU).By looking at the previously described maps and tables, it is clear that HRUs are crucial for figuring out the needed parameter and solving the water balance equation more accurately.

5.2 MODFLOW Model

5.2.1 Parameter Estimation (PEST) Calibration Outputs

To simulate better results, the PEST module in MODFLOW is used to calibrate the Groundwater model. The goal here is to minimize the discrepancy between the simulated and observed heads. Hydraulic conductivity is the desired parameter for the entire river basin, similar to the parameter used in (Frederiksen & Molina-Navarro, 2021) study that follows sensitivity analysis. The PEST run outcomes are provided (Table 5.4). Fig. 5.5 depicts the scatter plot of observed and simulated water levels (relative to mean sea level). The simulation period is taken as for 1094 days, from 2018 to 2020.

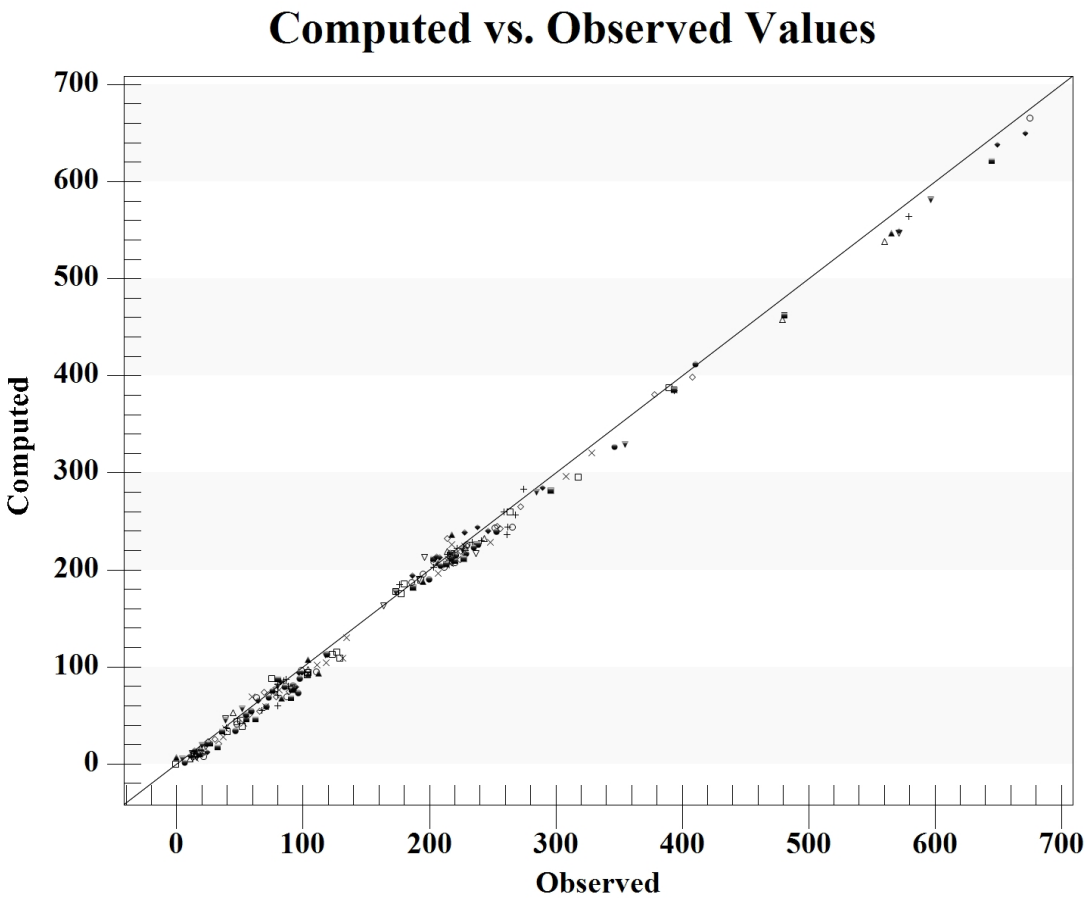

Figure 5.5: Computed head v/s observed groundwater heads residuals

The plot in fig 5.5 shows most points in the local region of the 45° bisector line, with minor exceptions. The biggest deviation is 24.32 m. This disparity was of bigger size as compared to the study done by (Maheswaran et al., 2016) . This deviation was noticed in the hilly terrain of Jharkhand area, and it mostly came from the rapid decline in slope. It was determined that the drop in elevation is close to 500 meters in half-span of roughly 1700 kilometers in the study area. As a result, the starting point head was impacted. Fig. 3.6 shows how the starting head was plotted based on the available data from monitoring wells. Because the wells are not evenly distributed throughout the basin, the starting head was determined at each cell using an inverse weighted technique. Our research area's starting head is consistent with actual groundwater table values at several places. When comparing two points, topographical variations cause rise and decline of starting head between the two points. Despite this variation, starting head exhibits linear behaviour causing higher magnitude error at some points. This behaviour in hilly areas may be resolved by

reducing the grid size. Starting heads need to be manually inputted but for that groundwater data is needed at each which is not yet available.

Furthermore, manually segregating groundwater recharge output based on HRUs in SWAT is challenging due to geographical irregularities in HRUs (see Fig. 4.2). It is tough to construct a polygon in the conceptual model. The two variables, recharge and evapotranspiration, were averaged and given as constant values across the entire extent. As described earlier in Chapter 3, these two parameters are dependent on land, soil, slope, etc., so every area within a specific stress period will receive the same recharge, which is not the case. As a result, deviations may be seen in Fig.s 5.5, 5.6, 5.8, and 5.7.

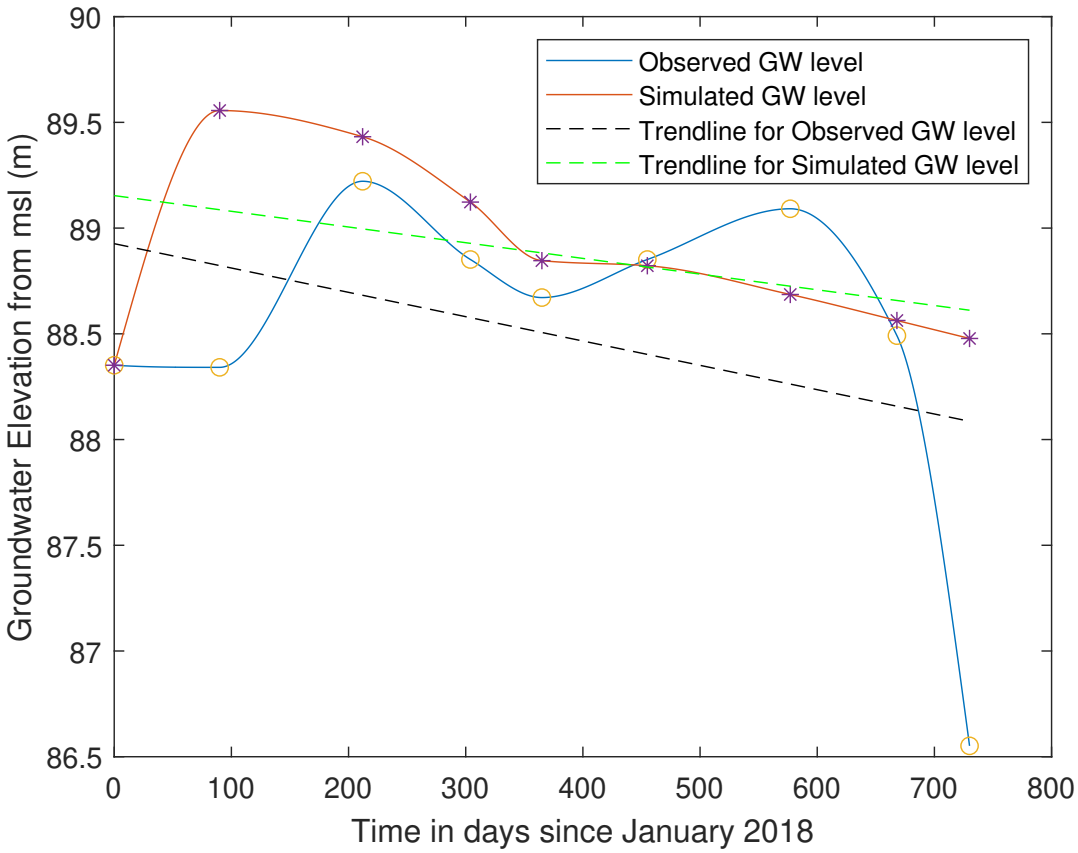

Figure 5.6: Times series map of observed and computed groundwater head (Well 1)

To better understand the deviation described in Fig. 5.5, model results corresponding to three wells are given in Fig. 5.6, 5.8, and 5.7 with the aid of time series plot of observed and simulated

groundwater heads.

Furthermore, based on the trend analysis in the corresponding graphs, it is clear that the change in groundwater head as displayed is either decreasing or increasing, indicating that this model can reasonably describe the hydrogeological system of the Damodar river basin.

Groundwater head observations at these wells reveal residuals, which could be attributed to assumptions used while model setup . The flow domain is treated as a single homogeneous layer, resulting in an omission of vertical heterogeneity in aquifer properties.

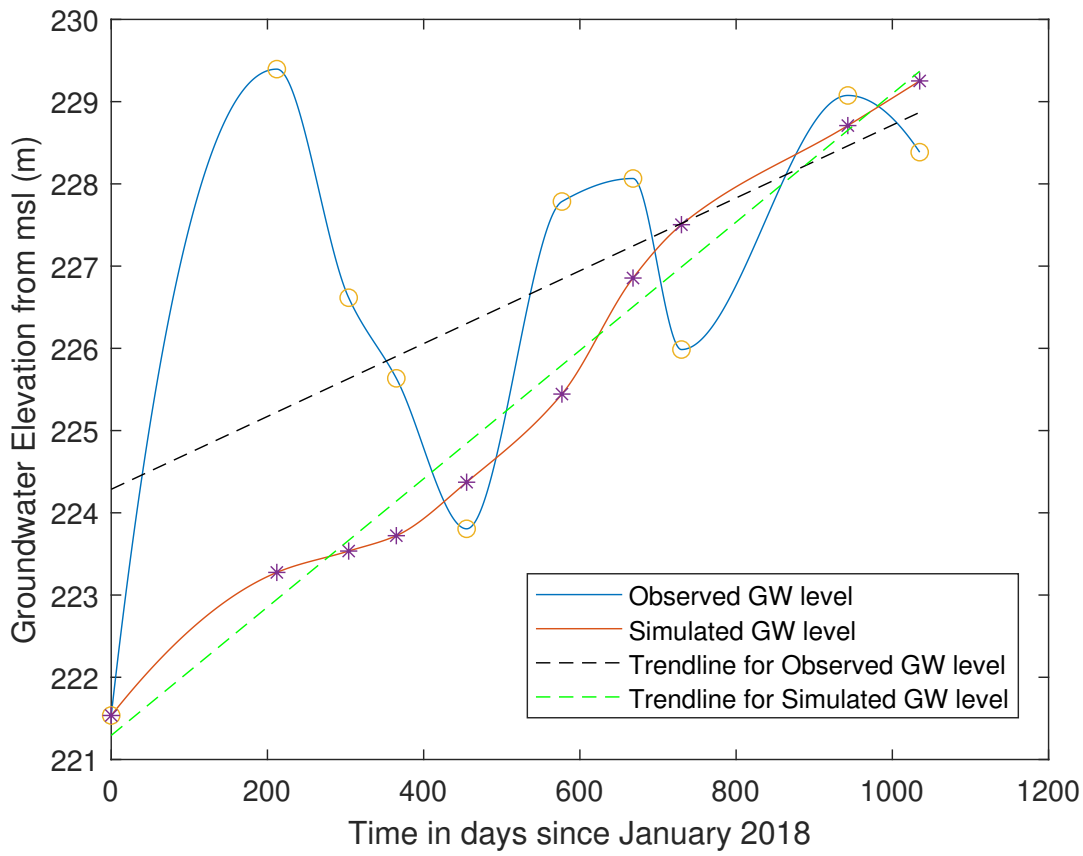

Figure 5.7: Times series map of observed and computed groundwater head (Well 2)

The second possible explanation for the mismatch is that the well is positioned in the cell's center. MODFLOW calculates groundwater using a grid-based technique. External forces like well are assumed to be at the cell's centre, causing disparities in well location.

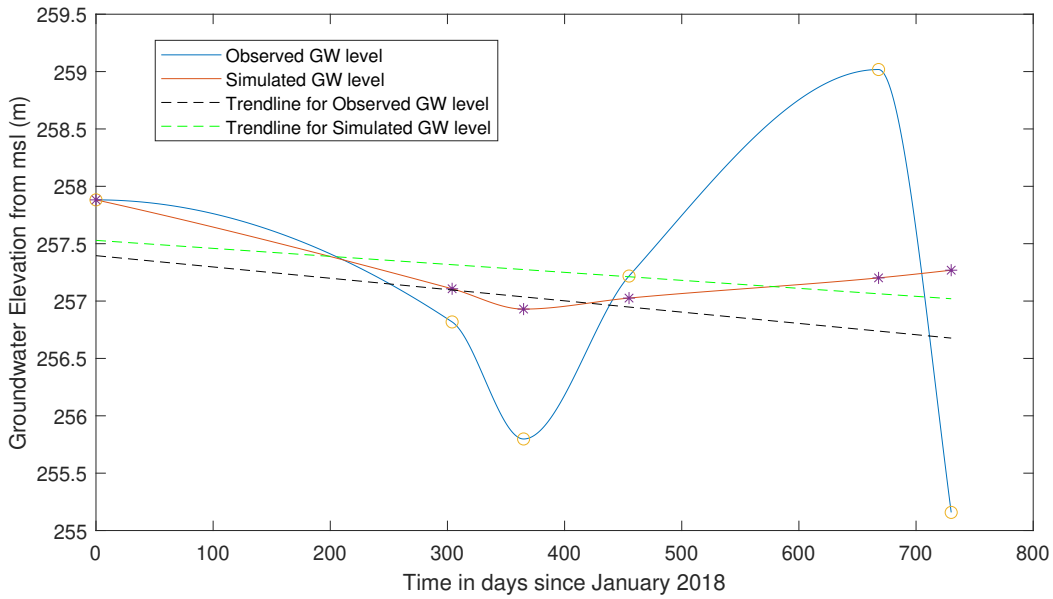

Figure 5.8: Times series map of observed and computed groundwater head (Well 3)

Fig. 5.8 shows that simulated groundwater head follows the trend of fluctuation in the water table. However, it is unable to precisely compute the gradient, owing to the assumption of using well in each grid. As a result of averaging the well data, the model is unable to duplicate the extraction rate.

	Initial Conductivity		PEST Calibrated Conductivity	
Conductivity Zone	K_x (m/d)	K_y (m/d)	K_x (m/d)	K_y (m/d)]
1	5	5	.0597	0.0597
2	8	8	0.11	0.11
3	10	10	0.246	0.246
4	15	15	2.22	2.22
5	8	8	0.54	0.54
6	19	19	0.61	0.61
7	20	20	0.298	0.298
8	18	18	2.5	2.5
9	10	10	35.74	35.74
10	11	11	2.49	2.49

Table 5.4: Initial and PEST based hydraulic conductivities for different zones of the Damodar river basin

After PEST calibration run, MODFLOW was simulated with updated hydraulic conductivity

thorough in which result discussed were formed. It was observed while simulating that hydraulic conductivity value even goes till 2 place after decimal. This was observed in the model in region with hilly terrain since model need to maintain that much water level at high elevation. Based on this finding, it was speculated that this water level is maintained by external base flow from outside of the basin.

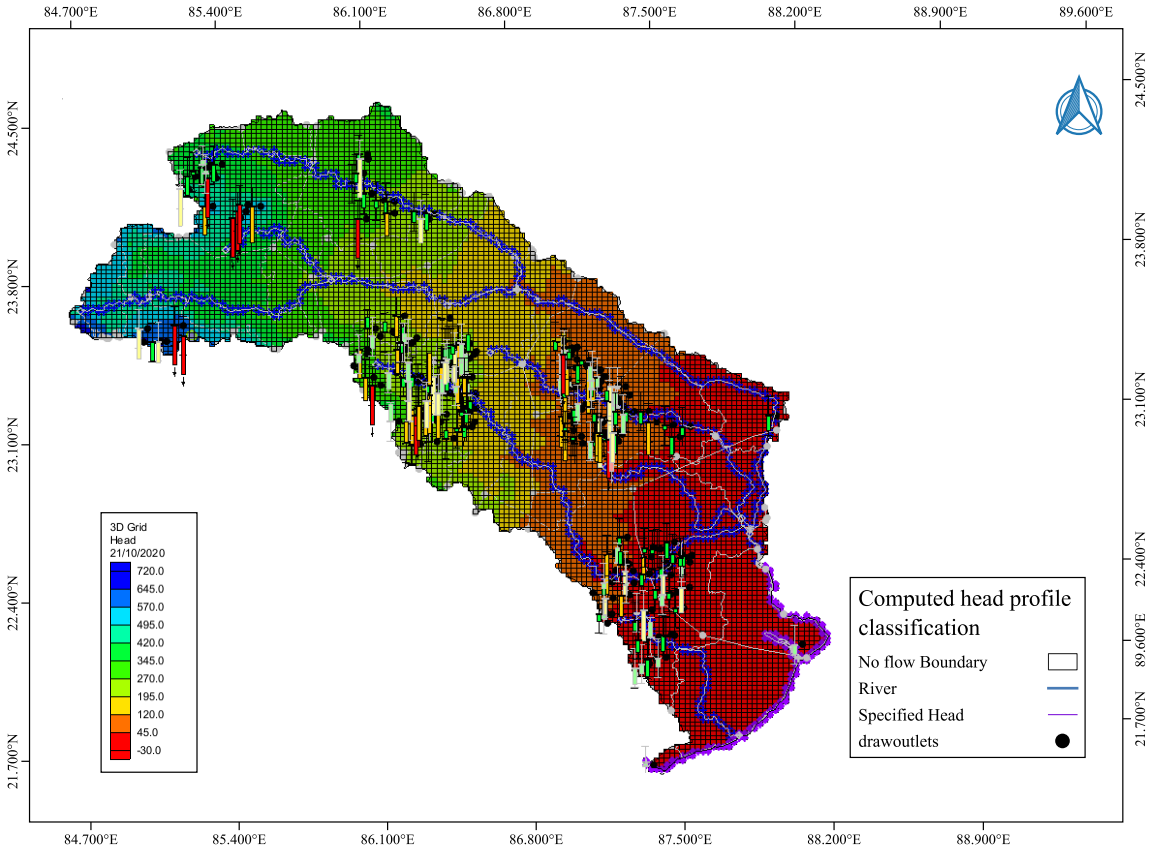

Figure 5.9: Simulated head distribution and residual plot on 21/10/2020

Overall result from these hydraulic conductivity provide good results in area with lesser elevation as depicted in Fig. 5.9. Bars represent the amount of deviation, red represent high deviation in the region which can be observed in areas with high elevation. Green and yellow representing deviation less than 10 m, can be seen throughout the rest of the extent.

5.3 QSWATMOD Model

QSWATMOD created maps depicting seasonal and annual variations in groundwater depth patterns in the Damodar river basin. Figures below indicate significant seasonal fluctuation between pre-monsoon and post-monsoon shows sign of decreasing water table. Seasonal analysis can be seen to be replicated by QSWATMOD based on exchange of parameter between SWAT and MODFLOW.

The following groundwater level maps and their fluctuations are discussed below. It was observed that increase in post monsoon level mostly in regions of West Bengal. Pixel wise variation were tough to differentiate from one another, therefore variation maps were created using QGIS.

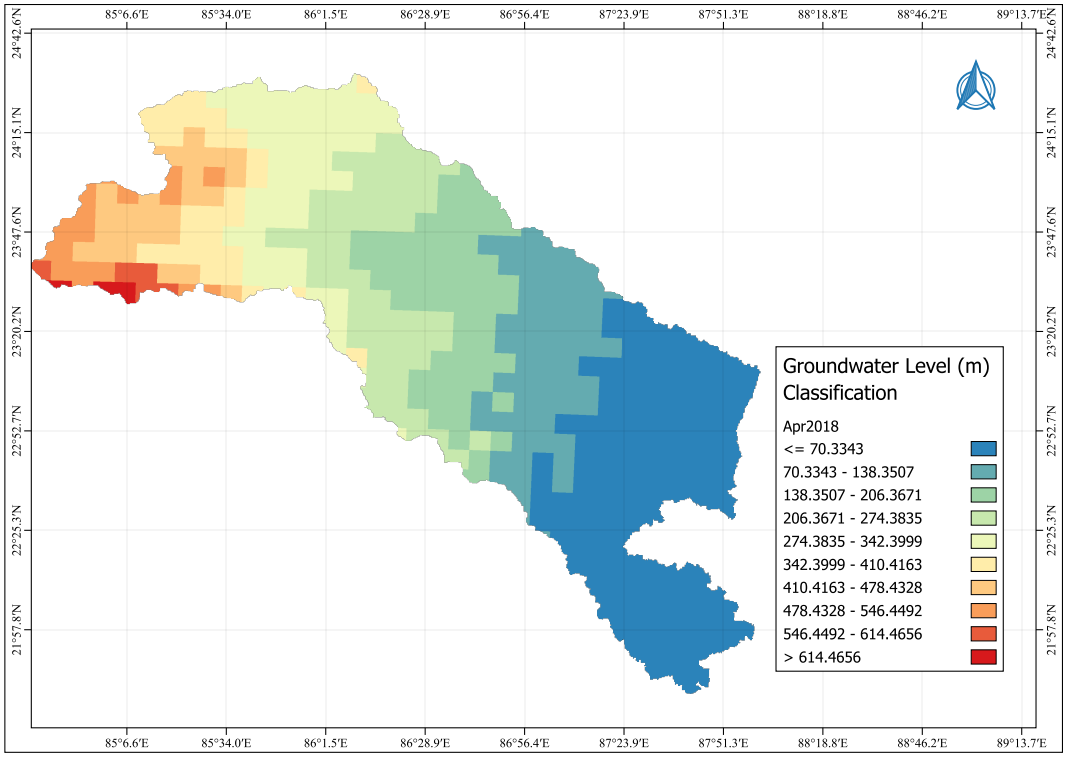

Figure 5.10: Groundwater level for Pre-Monsoon 2018

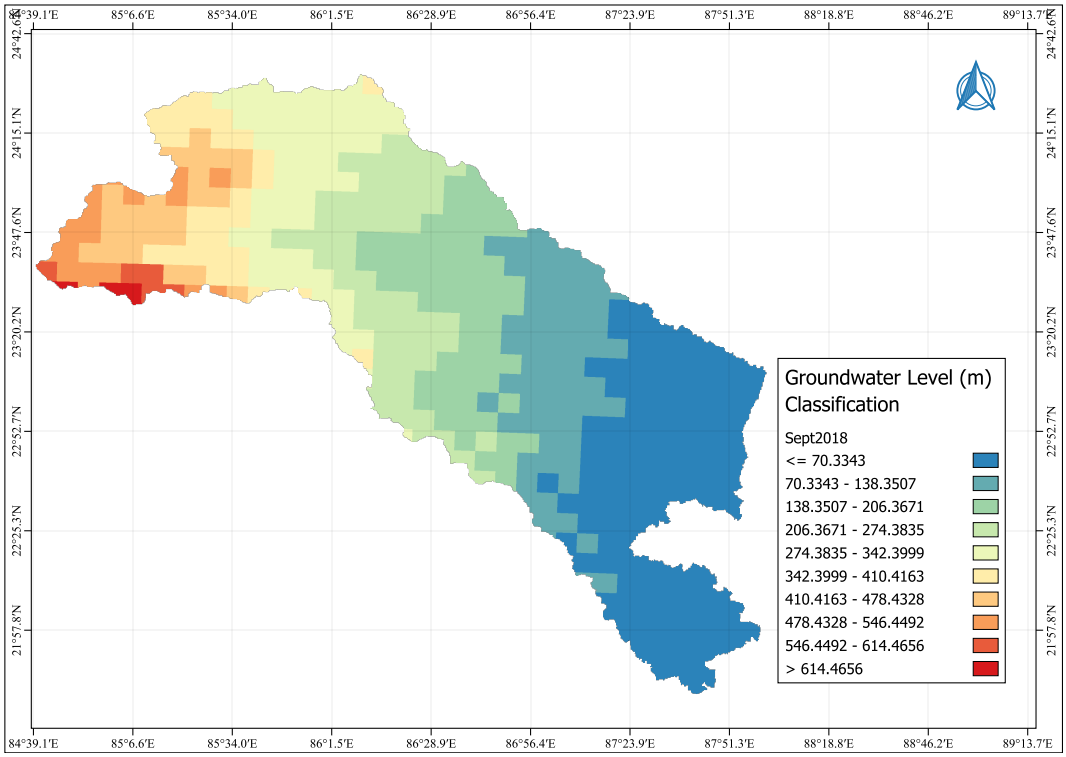

Figure 5.11: Groundwater level for Post-Monsoon 2018

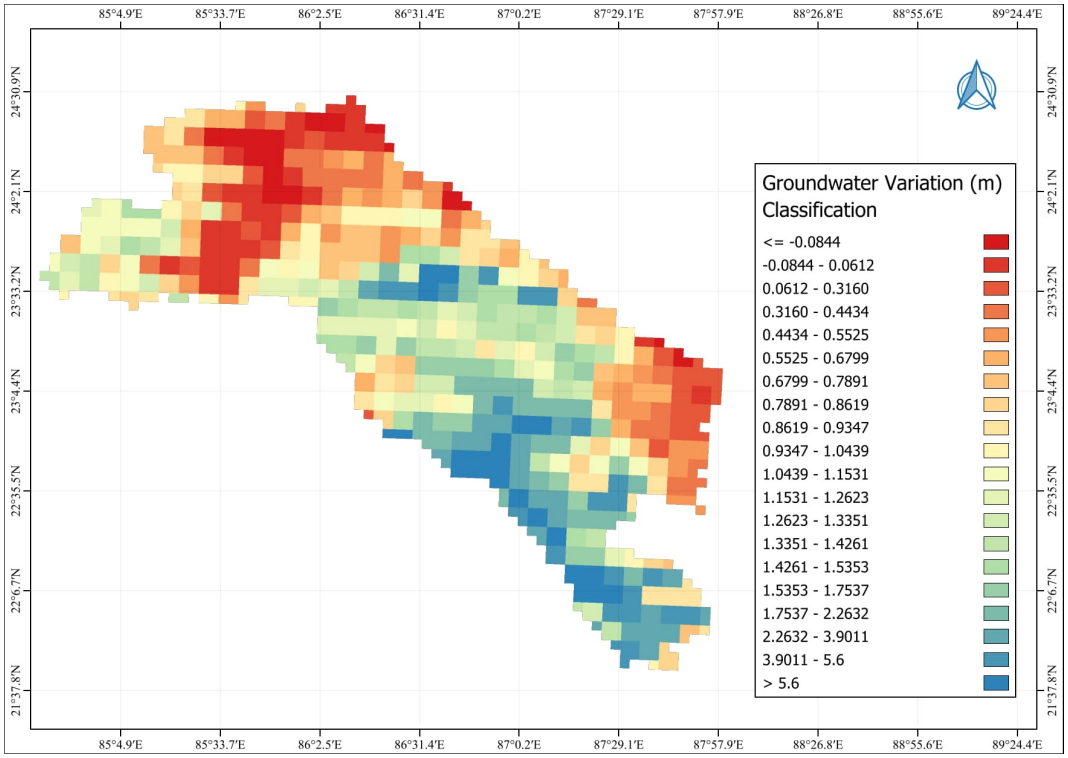

Figure 5.12: Groundwater level variation in 2018 between Pre and Post Monsoon

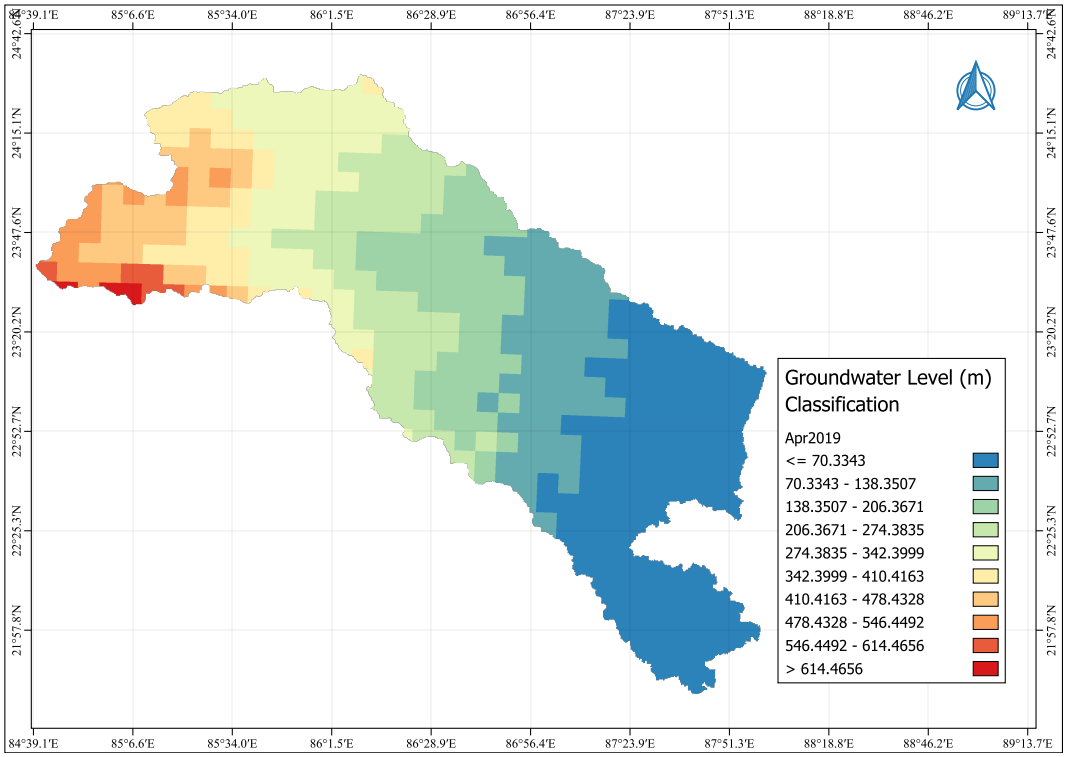

Figure 5.13: Groundwater level for Pre-Monsoon 2019

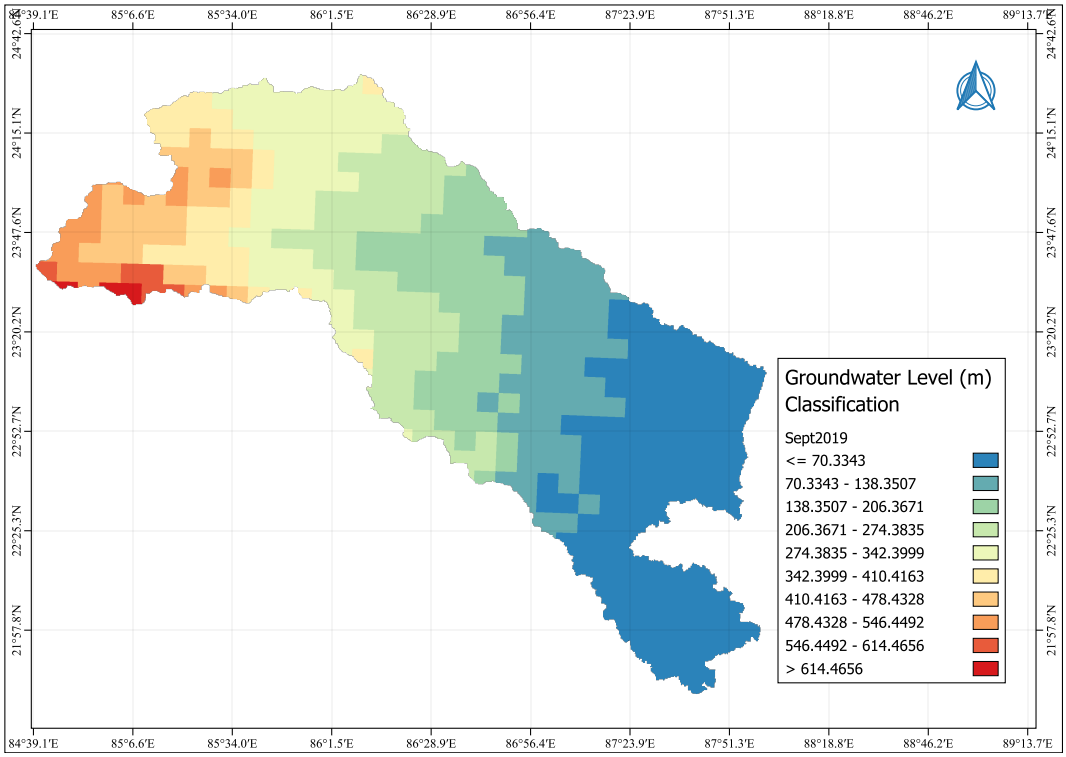

Figure 5.14: Groundwater level for Post-Monsoon 2019

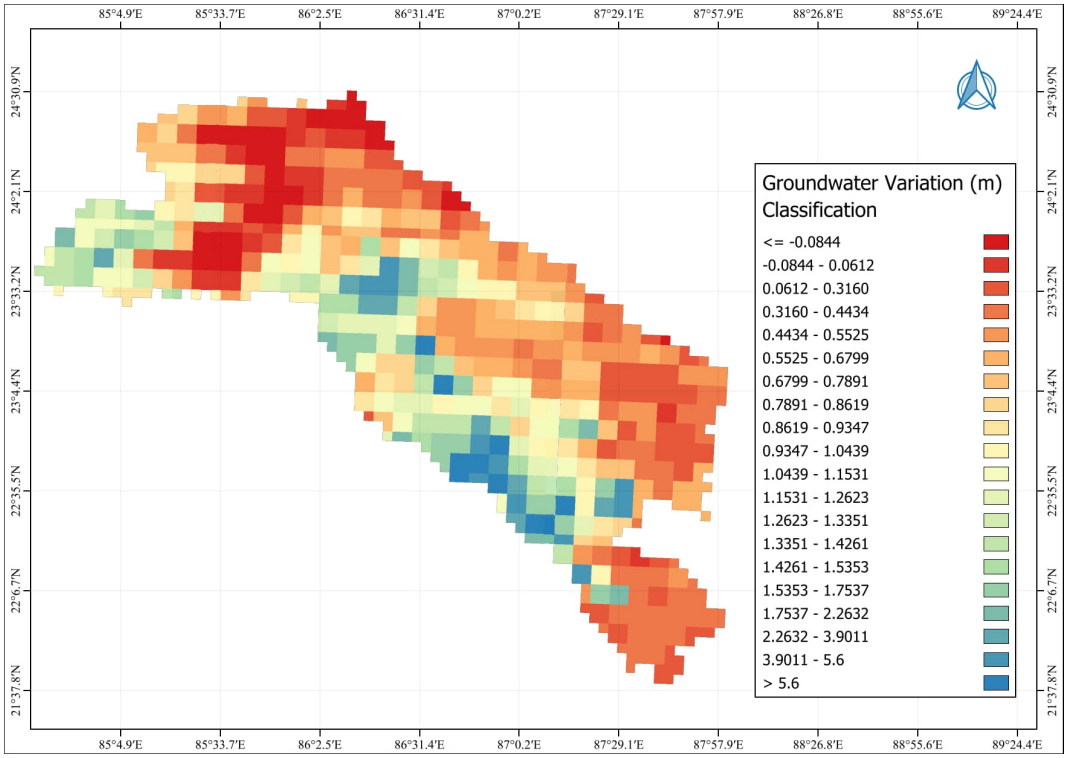

Figure 5.15: Groundwater level variation in 2019 between Pre and Post Monsoon

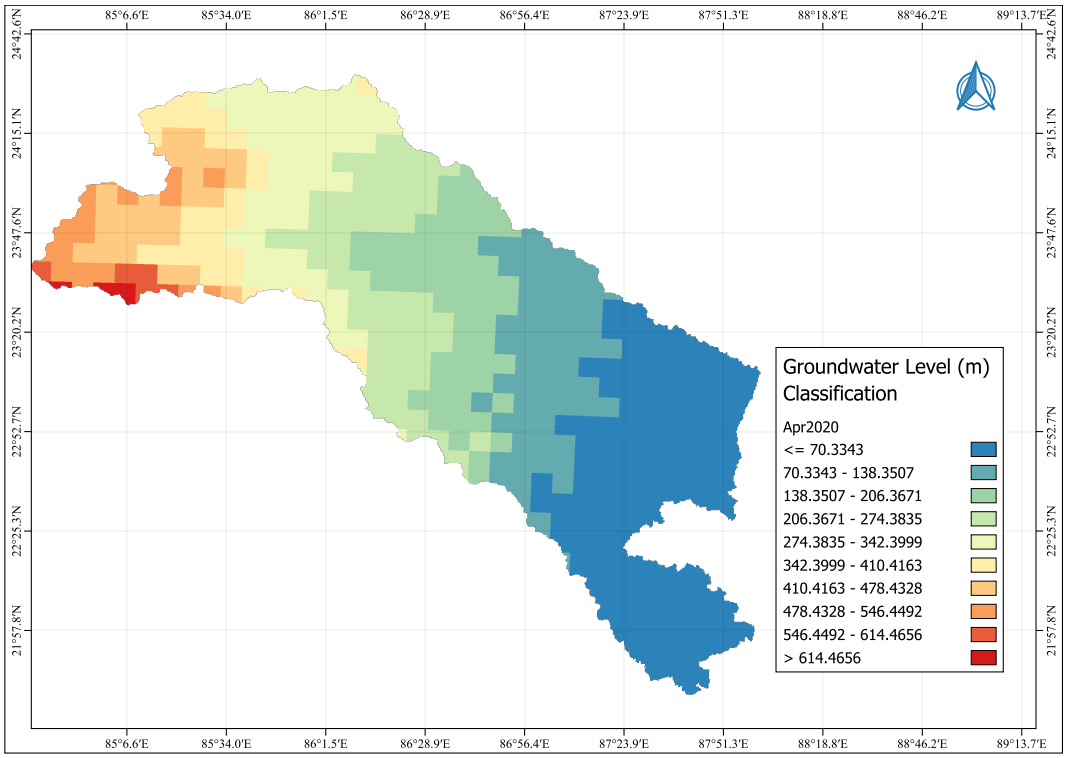

Figure 5.16: Groundwater level for Pre-Monsoon 2020

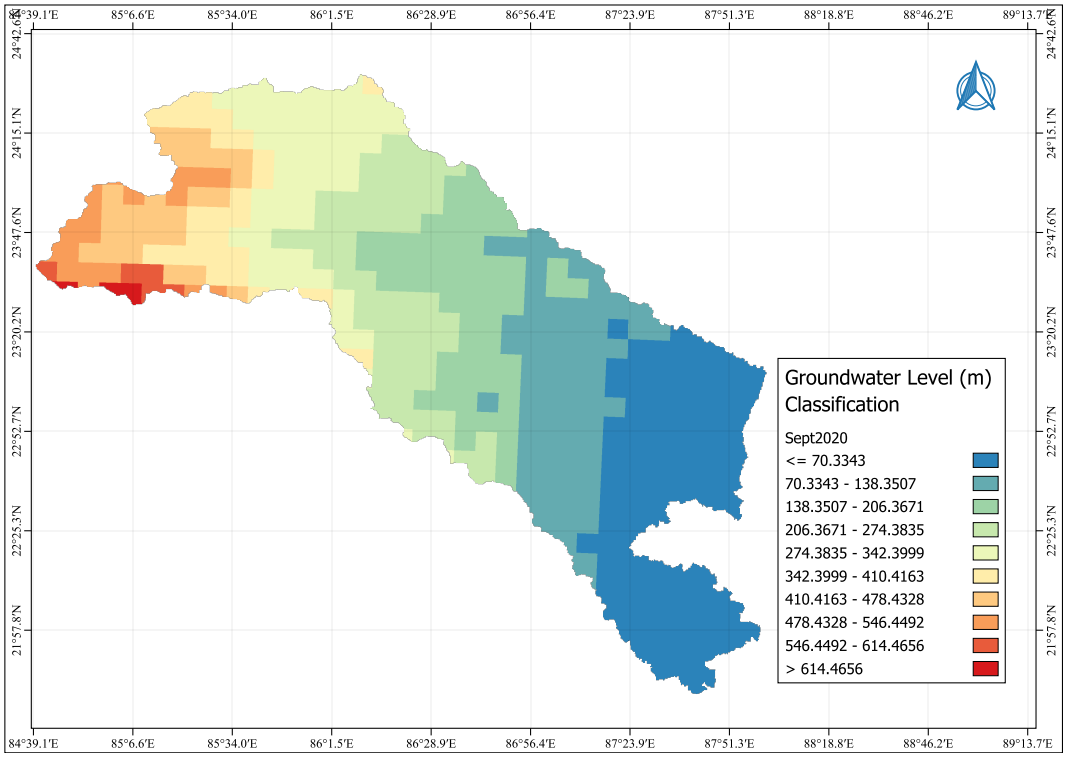

Figure 5.17: Groundwater level for Post-Monsoon 2020

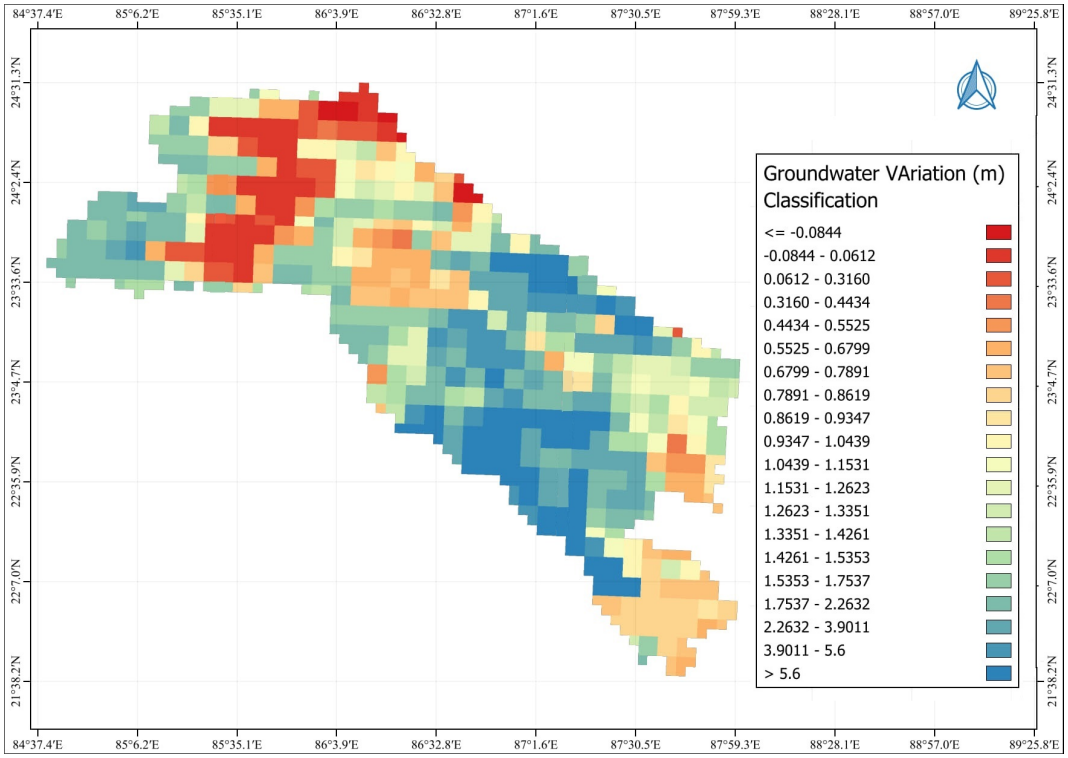

Figure 5.18: Groundwater level variation in 2020 between Pre and Post Monsoon

Variation between Pre and Post Monsoon shows decline in most of the catchment's area. The regions demonstrating decrease in water table are in the districts of Hazaribagh, with some regions in Giridih and Dhanbad.

Most of other areas shows increase in groundwater table with maximum increase as seen in Fig. 5.17 in region of West & East Midnapore.

After evaluating variation in 2020 as per fig. 5.18, in comparison to variation map of 2018 and 2019. It can be seen that groundwater level increases more in 2020. Mostly in region of Bankura and West Midnapore, groundwater rose. This can be inferred to lockdown in 2020 due to COVID pandemic. Most of the irrigation, industrial work was on hold leading to less extraction of groundwater.

Chapter 6

Summary and Conclusion

The present study utilizes SWAT & MODFLOW to understand the spatio-temporal change in the catchment of Damodar river. Following parameter were modelled and evaluated for the period of 2018 to 2020 to understand the hydro-geological nature of the basin:

- An annual average groundwater recharge of 236.50 mm was simulated. The recharge showed substantial spatial variability, with values between 0 and 796 mm, clearly demonstrated in Fig. (5.3). Maximum recharge of 796 mm was seen in East Medinapur district, while districts with least recharge were Giridih, Hazaribagh and Hugli. River seepage is also examined (Table 5.3), with an annual value of 456.43 mm.

- Evapotranspiration was averaged for the study period with average yearly value of 634.1 mm. Value for average daily evapotranspiration ranges from 1 to 5.31 mm with highest patches in West Midnapore , followed by regions in district of East Midnapore, Bankura, Hugli and rest of the region highlighted in Fig. 5.4.

- Groundwater head profile is clearly depicted in Fig. 5.9, with shallow aquifer depth available in eastern region, West Bengal and Wells in Fig. 5.6,5.7,5.8, showed maximum residual of 1.93 m, -6 m, 2.11 m, respectively. These residuals were produced after PEST calibration with overall maximum residual of 24.32 m in entire study area.

- The seasonal variations of the groundwater table demonstrated a significant increase in in groundwater depth in the regions of East Midnapore, Bankura, West Midnapore. Regions of Dhanbad, Giridih, and Hazaribagh has shown loss in groundwater with Dhanbad being among the most populous districts after Ranchi.

The findings of this work provide essential insights into understanding groundwater dynamics utilizing a coupled model technique. Spatial attributes were effectively incorporated into groundwater recharge and evapotranspiration, which were ultimately used by QSWATMOD to simulate the seasonal and annual changes in the groundwater table. Mitigation techniques and management practices can be implemented in the East Midnapore, Dhanbad and Hazaribagh region to combat groundwater head loss. Overall, the implementation of SWAT and MODFLOW in the Damodar River Basin yielded positive results . Within some years, after the completion of CGWB's effort for detailed, national aquifer mapping, more data on aquifers will be available. Instead of relying on inverse modelling, real field parameters will be applied in constructing the model. The model can be broadened to incorporate several levels, allowing for the incorporation of vertical heterogeneity.

Chapter 7

Future Work

Further following work can be carried out based on the data obtained with the coupled model:

- QSWATMOD data in section 5.3 can be further matched with real field data.
- Future prediction can be made based on current validated model.
- Contaminant transport can be employed in the already constructed MODFLOW model for fate transport of pollutant in Damodar rive basin.

References

Abbas, S. A., Xuan, Y., & Bailey, R. T. (2022). Assessing climate change impact on water resources in water demand scenarios using SWAT-MODFLOW-WEAP. *Hydrology*, *9*(10), 164.

Abbaszadeh, M., Bazrafshan, O., Mahdavi, R., Sardooi, E. R., & Jamshidi, S. (2023). Modeling future hydrological characteristics based on land use/land cover and climate changes using the SWAT model. *Water Resources Management*, *37*(10), 4177–4194.

Aliyari, F., Bailey, R. T., & Arabi, M. (2021). Appraising climate change impacts on future water resources and agricultural productivity in agro-urban river basins. *Science of the Total Environment*, *788*, 147717.

Aliyari, F., Bailey, R. T., Tasdighi, A., Dozier, A., Arabi, M., & Zeiler, K. (2019). Coupled SWAT-MODFLOW model for large-scale mixed agro-urban river basins. *Environmental Modelling & Software*, *115*, 200–210.

Amiri, S., Rajabi, A., Shabanlou, S., Yosefvand, F., & Izadbakhsh, M. A. (2023). Prediction of groundwater level variations using deep learning methods and GMS numerical model. *Earth Science Informatics*, *16*(4), 3227–3241.

Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., Santhi, C., Harmel, R., Van Griensven, A., Van Liew, M. W., et al. (2012). SWAT: Model use, calibration, and validation. *Transactions of the ASABE*, *55*(4), 1491–1508.

Asadi, S., Mousavi, S. J., López-Ballesteros, A., & Senent-Aparicio, J. (2024). Analyzing hydrological alteration and environmental flows in a highly anthropized agricultural river basin system using SWAT+, WEAP and IAHRIS. *Journal of Hydrology: Regional Studies*, *52*, 101738.

Bailey, R. T., & Hosseini, P. (2023). Comprehensive simulation of salinity transport in irrigated watersheds using an updated version of SWAT-MODFLOW. *Environmental Modelling & Software*, *159*, 105566.

Bailey, R. T., Wible, T. C., Arabi, M., Records, R. M., & Ditty, J. (2016). Assessing regional-scale spatio-temporal patterns of groundwater–surface water interactions using a coupled SWAT-MODFLOW model. *Hydrological processes*, *30*(23), 4420–4433.

Bhanja, S. N., Mukherjee, A., Rangarajan, R., Scanlon, B. R., Malakar, P., & Verma, S. (2019). Long-term groundwater recharge rates across india by in situ measurements. *Hydrology and Earth System Sciences*, *23*(2), 711–722.

Bhatta, B., Shrestha, S., Shrestha, P. K., & Talchabhadel, R. (2019). Evaluation and application of a SWAT model to assess the climate change impact on the hydrology of the himalayan river basin. *Catena*, *181*, 104082.

CGWB. (2022). Central ground water board (2022) dynamic ground water resources of india. department of water resources, RD & GR, ministry of jal shakti, govt. of india. *Dynamic Ground Water Resources of India*, *2*, 135539.

Chung, I.-M., Kim, N.-W., Lee, J., & Sophocleous, M. (2010). Assessing distributed groundwater recharge rate using integrated surface water-groundwater modelling: Application to mihocheon watershed, south korea. *Hydrogeology Journal*, *18*(5), 1253.

Conan, C., Bouraoui, F., Turpin, N., de Marsily, G., & Bidoglio, G. (2003). Modeling flow and nitrate fate at catchment scale in brittany (france). *Journal of Environmental Quality*, *32*(6), 2026–2032.

de Oliveira Serrão, E. A., Silva, M. T., Ferreira, T. R., de Ataide, L. C. P., dos Santos, C. A., de Lima, A. M. M., da Silva, V. d. P. R., de Sousa, F. d. A. S., & Gomes, D. J. C. (2022). Impacts of land use and land cover changes on hydrological processes and sediment yield determined using the SWAT model. *International Journal of Sediment Research*, *37*(1), 54–69.

Dhawan, V. (2017). Water and agriculture in india. *Background paper for the South Asia expert panel during the Global Forum for Food and Agriculture*, *28*, 80–85.

Dowlatabadi, S., & Ali Zomorodian, S. (2016). Conjunctive simulation of surface water and groundwater using SWAT and MODFLOW in firoozabad watershed. *KSCE Journal of Civil Engineering*, *20*, 485–496.

Ehtiat, M., Jamshid Mousavi, S., & Srinivasan, R. (2018). Groundwater modeling under variable operating conditions using SWAT, MODFLOW and MT3DMS: A catchment scale approach to water resources management. *Water resources management*, *32*, 1631–1649.

Eshtawi, T., Evers, M., & Tischbein, B. (2016). Quantifying the impact of urban area expansion on groundwater recharge and surface runoff. *Hydrological Sciences Journal*, *61*(5), 826–843.

Eslamian, S., Harooni, Y., & Sabzevari, Y. (2023). Simulation of nitrate pollution and vulnerability of groundwater resources using MODFLOW and DRASTIC models. *Scientific reports*, *13*(1), 8211.

Frederiksen, R. R., & Molina-Navarro, E. (2021). The importance of subsurface drainage on model performance and water balance in an agricultural catchment using SWAT and SWAT-MODFLOW. *Agricultural Water Management*, *255*, 107058.

Gao, F., Feng, G., Han, M., Dash, P., Jenkins, J., & Liu, C. (2019). Assessment of surface water resources in the big sunflower river watershed using coupled SWAT–MODFLOW model. *Water*, *11*(3), 528.

Guzman, J. A., Moriasi, D., Gowda, P. H., Steiner, J. L., Starks, P., Arnold, J. G., & Srinivasan, R. (2015). A model integration framework for linking SWAT and MODFLOW. *Environmental Modelling & Software*, *73*, 103–116.

Harbaugh, A. W. (2005). *Modflow-2005, the us geological survey modular ground-water model: The ground-water flow process* (Vol. 6). US Department of the Interior, US Geological Survey Reston, VA, USA.

Jafari, T., Kiem, A. S., Javadi, S., Nakamura, T., & Nishida, K. (2021). Fully integrated numerical simulation of surface water-groundwater interactions using SWAT-MODFLOW with an improved calibration tool. *Journal of Hydrology: Regional Studies*, *35*, 100822.

Jimenez, M., Velsquez, N., Jimenez, J. E., Barco, J., Blessent, D., Lopez-Sanchez, J., Castrilln, S. C., Valenzuela, C., Therrien, R., Boico, V. F., et al. (2022). Sequential surface and subsurface flow modeling in a tropical aquifer under different rainfall scenarios. *Environmental Modelling & Software*, *149*, 105328.

Jung, M., Reichstein, M., Ciais, P., Seneviratne, S. I., Sheffield, J., Goulden, M. L., Bonan, G., Cescatti, A., Chen, J., De Jeu, R., et al. (2010). Recent decline in the global land evapotranspiration trend due to limited moisture supply. *Nature*, *467*(7318), 951–954.

Kim, N. W., Chung, I. M., Won, Y. S., & Arnold, J. G. (2008). Development and application of the integrated SWAT–MODFLOW model. *Journal of Hydrology*, *356*(1-2), 1–16.

Kuffour, B. N., Engdahl, N. B., Woodward, C. S., Condon, L. E., Kollet, S., & Maxwell, R. M. (2020). Simulating coupled surface–subsurface flows with parflow v3. 5.0: Capabilities, applications, and ongoing development of an open-source, massively parallel, integrated hydrologic model. *Geoscientific Model Development*, *13*(3), 1373–1397.

Kumar, D., Roshni, T., Singh, A., Jha, M. K., & Samui, P. (2020). Predicting groundwater depth fluctuations using deep learning, extreme learning machine and gaussian process: A comparative study. *Earth Science Informatics*, *13*(4), 1237–1250.

Liu, W., Park, S., Bailey, R. T., Molina-Navarro, E., Andersen, H. E., Thodsen, H., Nielsen, A., Jeppesen, E., Jensen, J. S., Jensen, J. B., et al. (2020). Quantifying the streamflow response to groundwater abstractions for irrigation or drinking water at catchment scale using SWAT and SWAT–MODFLOW. *Environmental Sciences Europe*, *32*, 1–25.

Loukika, K., Venkata Reddy, K., Durga Rao, K., & Singh, A. (2020). Estimation of groundwater recharge rate using SWAT MODFLOW model. *Applications of Geomatics in Civil Engineering: Select Proceedings of ICGCE 2018*, 143–154.

Mahammad, S., Islam, A., Shit, P. K., Islam, A. R. M. T., & Alam, E. (2023). Groundwater level dynamics in a subtropical fan delta region and its future prediction using machine learning tools: Sustainable groundwater restoration. *Journal of Hydrology: Regional Studies*, *47*, 101385.

Maheswaran, R., Khosa, R., Gosain, A., Lahari, S., Sinha, S., Chahar, B., & Dhanya, C. (2016). Regional scale groundwater modelling study for ganga river basin. *Journal of Hydrology*, *541*, 727–741. https://doi.org/https://doi.org/10.1016/j.jhydrol.2016.07.029

Molina-Navarro, E., Bailey, R. T., Andersen, H. E., Thodsen, H., Nielsen, A., Park, S., Jensen, J. S., Jensen, J. B., & Trolle, D. (2019). Comparison of abstraction scenarios simulated by SWAT and SWAT-MODFLOW. *Hydrological Sciences Journal*, *64*(4), 434–454.

Mosase, E., Ahiablame, L., Park, S., & Bailey, R. (2019). Modelling potential groundwater recharge in the limpopo river basin with SWAT-MODFLOW. *Groundwater for sustainable development*, *9*, 100260.

Mukherjee, A., Saha, D., Harvey, C. F., Taylor, R. G., Ahmed, K. M., & Bhanja, S. N. (2015). Groundwater systems of the indian sub-continent. *Journal of Hydrology: Regional Studies*, *4*, 1–14.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., & Williams, J. R. (2011). *Soil and water assessment tool theoretical documentation version 2009* (tech. rep.). Texas Water Resources Institute.

Niswonger, R. G., Panday, S., & Ibaraki, M. (2011). Modflow-nwt, a newton formulation for MODFLOW-2005. *US Geological Survey Techniques and Methods*, *6*(A37), 44.

Park, S., Jeong, J., Motter, E., Bailey, R. T., & Green, C. H. (2023). Introducing APEXMOD-A QGIS plugin for developing coupled surface-subsurface hydrologic modeling framework of APEX, MODFLOW, and RT3D-Salt. *Environmental Modelling & Software*, *165*, 105723.

Park, S., Nielsen, A., Bailey, R. T., Trolle, D., & Bieger, K. (2019). A qgis-based graphical user interface for application and evaluation of SWAT-MODFLOW models. *Environmental modelling & software*, *111*, 493–497.

Rajaeian, S., Ketabchi, H., & Ebadi, T. (2024). Investigation on quantitative and qualitative changes of groundwater resources using MODFLOW and MT3DMS: A case study of hashtgerd aquifer, iran. *Environment, Development and Sustainability*, *26*(2), 4679–4704.

Rakhecha, P. R., & Singh, V. P. (2009). Evaporation. In *Applied hydrometeorology* (pp. 300–318). Springer Netherlands. https://doi.org/10.1007/978-1-4020-9844-4_13

Sophocleous, M., Koelliker, J., Govindaraju, R., Birdie, T., Ramireddygari, S., & Perkins, S. (1999). Integrated numerical modeling for basin-wide water management: The case of the rattlesnake creek basin in south-central kansas. *Journal of Hydrology*, *214*(1-4), 179–196.

Sun, J., Hu, L., Li, D., Sun, K., & Yang, Z. (2022). Data-driven models for accurate groundwater level prediction and their practical significance in groundwater management. *Journal of Hydrology*, *608*, 127630.

Sundar, M. L., Ragunath, S., Hemalatha, J., Vivek, S., Mohanraj, M., Sampathkumar, V., Ansari, A. M. S., Parthiban, V., & Manoj, S. (2022). Simulation of ground water quality for noyyal river basin of coimbatore city, tamilnadu using modflow. *Chemosphere*, *306*, 135649.

Swain, S., Sahoo, S., Taloor, A. K., Mishra, S., & Pandey, A. (2022). Exploring recent groundwater level changes using innovative trend analysis (ita) technique over three districts of jharkhand, india. *Groundwater for Sustainable Development*, *18*, 100783.

Taie Semiromi, M., & Koch, M. (2019). Analysis of spatio-temporal variability of surface–groundwater interactions in the gharehsoo river basin, iran, using a coupled swat-modflow model. *Environmental Earth Sciences*, *78*(6), 201.

Tolera, M. B., & Chung, I.-M. (2021). Integrated hydrological analysis of little akaki watershed using SWAT-MODFLOW, ethiopia. *Applied Sciences*, *11*(13), 6011.

Uniyal, B., Jha, M. K., & Verma, A. K. (2015). Assessing climate change impact on water balance components of a river basin using SWAT model. *Water resources management*, *29*, 4767–4785.

Wu, C., Zhang, X., Wang, W., Lu, C., Zhang, Y., Qin, W., Tick, G. R., Liu, B., & Shu, L. (2021). Groundwater level modeling framework by combining the wavelet transform with a long short-term memory data-driven model. *Science of The Total Environment*, *783*, 146948.

Xiang, Z., Bailey, R. T., Nozari, S., Husain, Z., Kisekka, I., Sharda, V., & Gowda, P. (2020). DSSAT-MODFLOW: A new modeling framework for exploring groundwater conservation strategies in irrigated areas. *Agricultural Water Management*, *232*, 106033.

Yadav, B., Gupta, P. K., Patidar, N., & Himanshu, S. K. (2020). Ensemble modelling framework for groundwater level prediction in urban areas of india. *Science of the Total Environment*, *712*, 135539.

Yi, L., & Sophocleous, M. (2011). Two-way coupling of unsaturated-saturated flow by integrating the SWAT and MODFLOW models with application in an irrigation district in arid region of west china., *3*(3), 164–173.

Yifru, B. A., Chung, I.-M., Kim, M.-G., & Chang, S. W. (2020). Assessment of groundwater recharge in agro-urban watersheds using integrated SWAT-MODFLOW model. *Sustainability*, *12*(16), 6593.

Yifru, B. A., Chung, I.-M., Kim, M.-G., & Chang, S. W. (2021). Assessing the effect of land/use land cover and climate change on water yield and groundwater recharge in east african rift valley using integrated model. *Journal of Hydrology: Regional Studies*, *37*, 100926.

Zheng, C., Wang, P. P., et al. (1999). MT3DMS: A modular three-dimensional multispecies transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems; documentation and user's guide.

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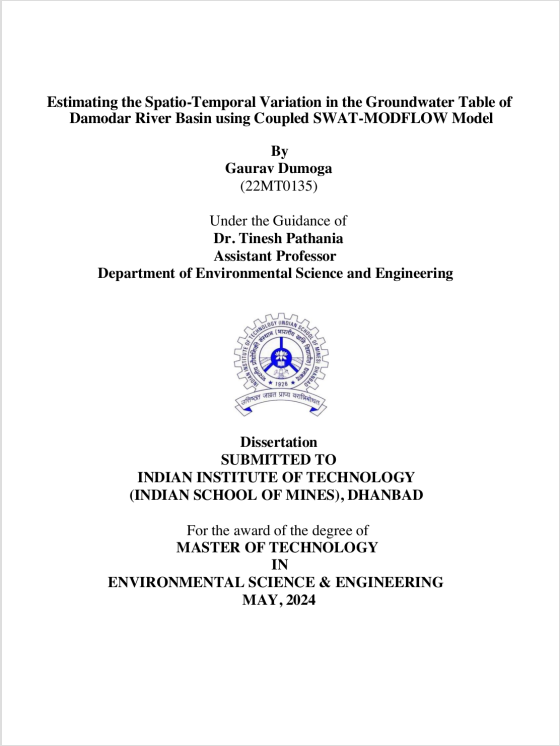

Estimating the Spatio-Temporal Variation in the Groundwater Table of Damodar River Basin using Coupled SWAT-MODFLOW Model

By
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Under the Guidance of
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