1 Materials and Methods

1.1 Study Area

For study purposes, an area of 130.6 km^2 is taken instead of the whole Mirsharai and Sitakunda upazila, which is 966.85 km^2. The model boundary was taken from the HydroBASINS dataset, which represents a vectorized polygon layer that depicts the sub basin boundary (Lehner & Grill, 2013). The study area is located between the latitude of 22˚37’0.3612” to 22˚49’2.0136” and the longitude of 91˚39’54.594” to 91˚41’42.929” in tropical monsoon and coastal climatic condition. The area contains both hilly and plain land topography. The eastern hilly area has an elevation between 50 and more than 250m with a very scarce population. The transition from plain land to hills is abrupt and marked by a regional fault line (Khan et al., 2022). The Mirsharai Economic Zone marks the northeastern boundary of the study area. A coastal zone exists along the western boundary. In the study area, the total percentage of groundwater usage is 95.5% (Bangladesh Bureau of Statistics, 2011). The study area receives an average of 3000 mm of rainfall per year. The driest month is January receiving an average of 6mm of rainfall, and the wettest month is July receiving an average of 761 mm. The average temperature of the area is 25.7˚C.

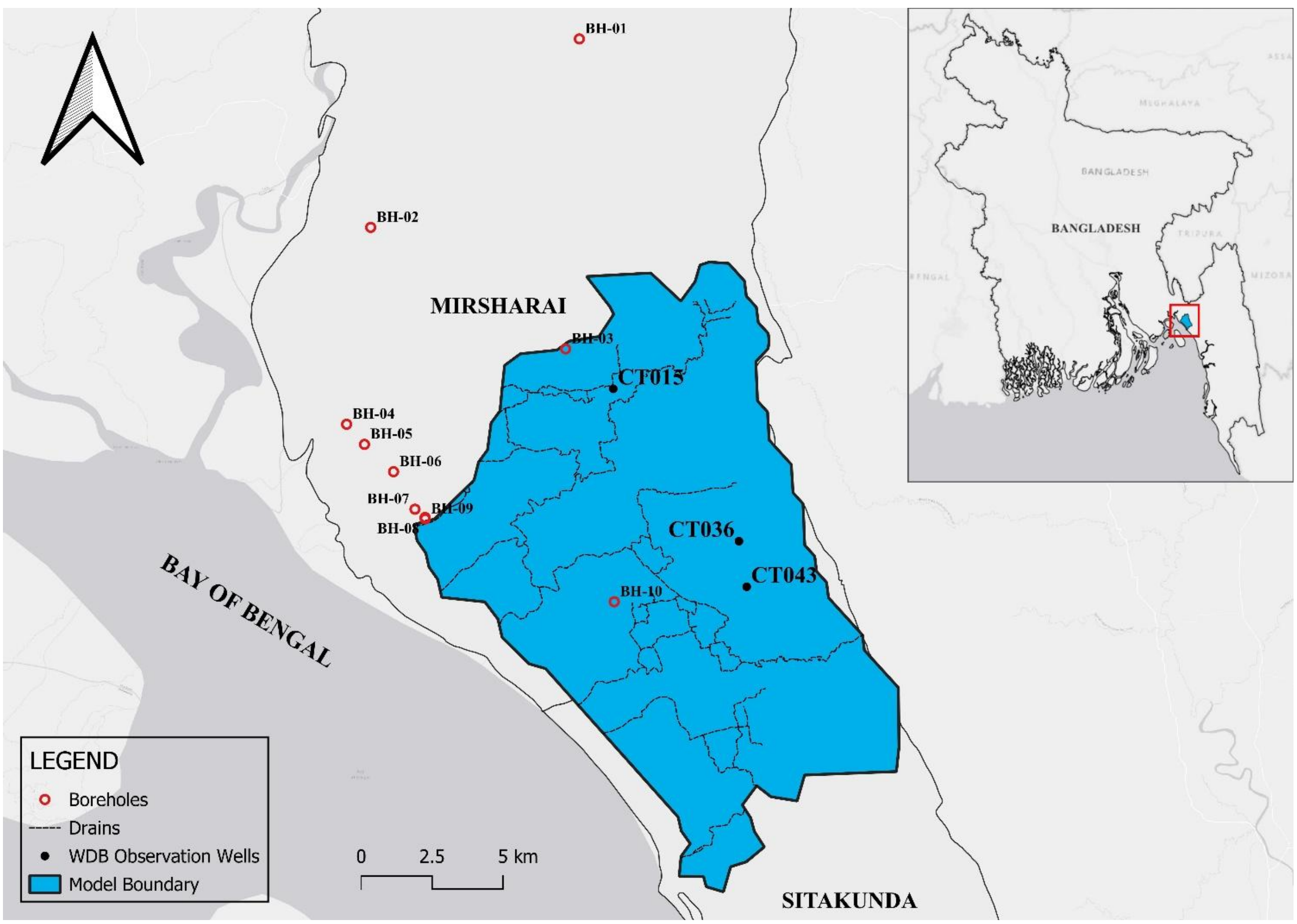

Figure 1.1: Location Map of the Model Boundary

1.2 Methodology

The groundwater modeling procedure (*Figure 1.2*) was carried out in two major phases: steady-state model setup and transient model setup, followed by model application, scenario analysis and sensitivity analysis. Data sources like HydroSHED, HydroBASIN, Bangladesh Water Development Board (BWDB) dataset, CHIRPS 2.0, Google Earth Pro, etc. support the various model development and refinement stages. For this study MODFLOW model Aquaveo™ GMS (Groundwater Modeling System) version 10.8 GUI is used to develop and simulate our model.

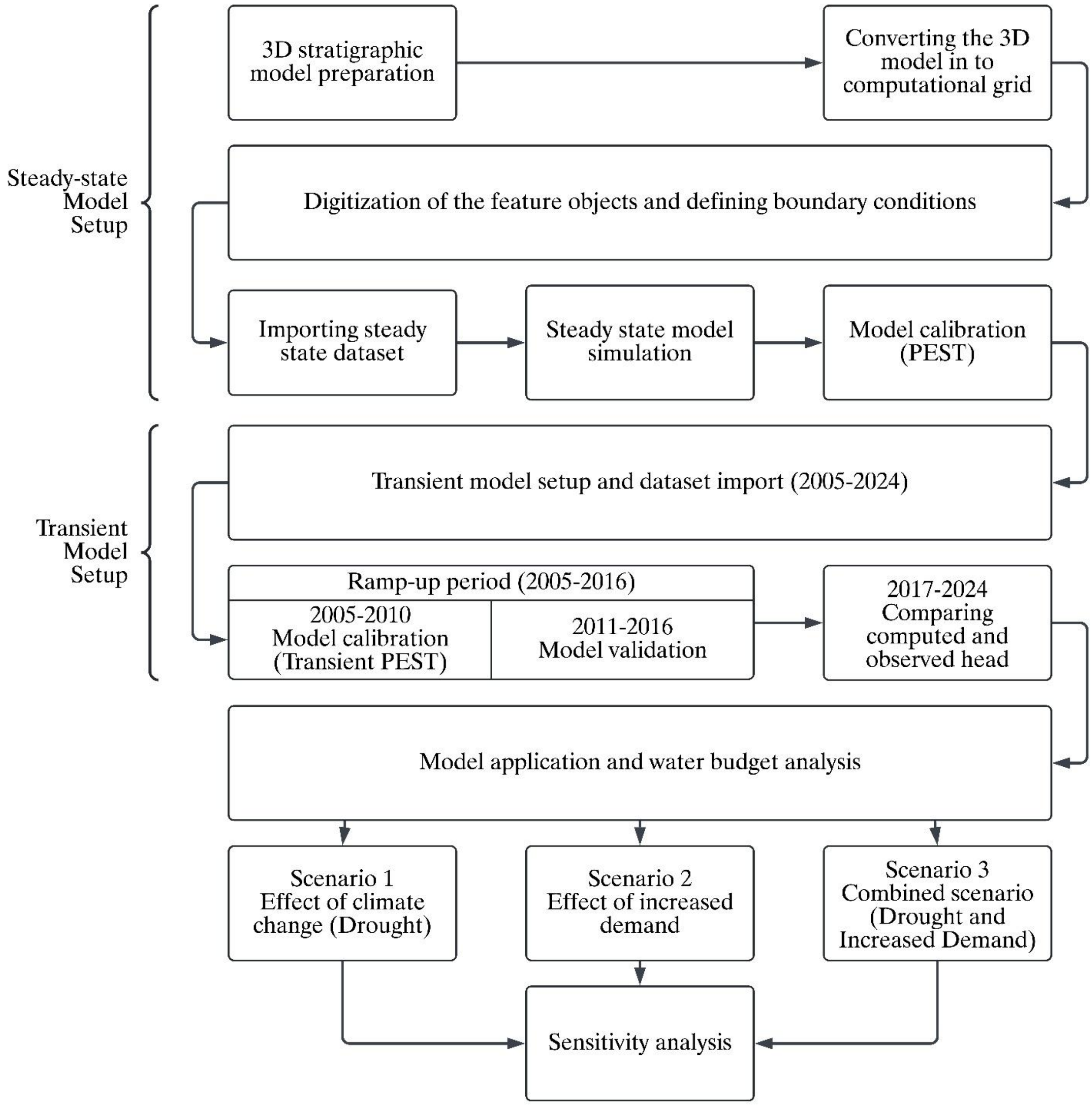

Figure 1.2: Methodology of the Study

1.3 Steady State Model Development

1.3.1 3D Stratigraphic Model Preparation and Converting the Model into Computational Grid

The foundation of any groundwater model lies in a robust representation of the subsurface stratigraphy. For this purpose, available geological, lithological, and borehole data from Center for Geoservices and Research, (2018); Ghosh & Rahman, (2015); Woobaidullah et al., (2020) were compiled and analyzed to construct a three-dimensional stratigraphic model of the study area through IDW interpolation. Lithological logs from the boreholes (*Figure 1.1*) were interpreted to delineate aquifer and aquitard layers, while additional geophysical and hydrogeological information was incorporated where available (Table 1.1; Table 1.2).

Table 1.1: Porosity values and ranges for the soil types

Lithology	**Porosity (%)**	**Reference**
Sandy Clay (1st layer)	0.35	(Chatrayi et al., 2023)
Fine to Medium Sand (2nd & 4th Layer)	0.40	(Shalahuddin et al., 2023)
Clay (3rd Layer)	0.30	(Esselburn et al., 2011)

Table 1.2: Hydraulic conductivity values & ranges for the soil types

Lithology	**Hydraulic Conductivity (K) (m/d)**	**Reference**
Sandy Clay (1st layer)	0.0864	(Fetter, 2000)
Fine to Medium Sand (2nd & 4th Layer)	0.44	(Zahid et al., 2021)
Clay (3rd Layer)	0.000864	(Fetter, 2000)

The resulting stratigraphic model represented the vertical and lateral distribution of hydro stratigraphic units such as sandy aquifers and clay aquitards. This model provided the basis for assigning hydraulic properties, including hydraulic conductivity and storage parameters, to each hydro stratigraphic unit.

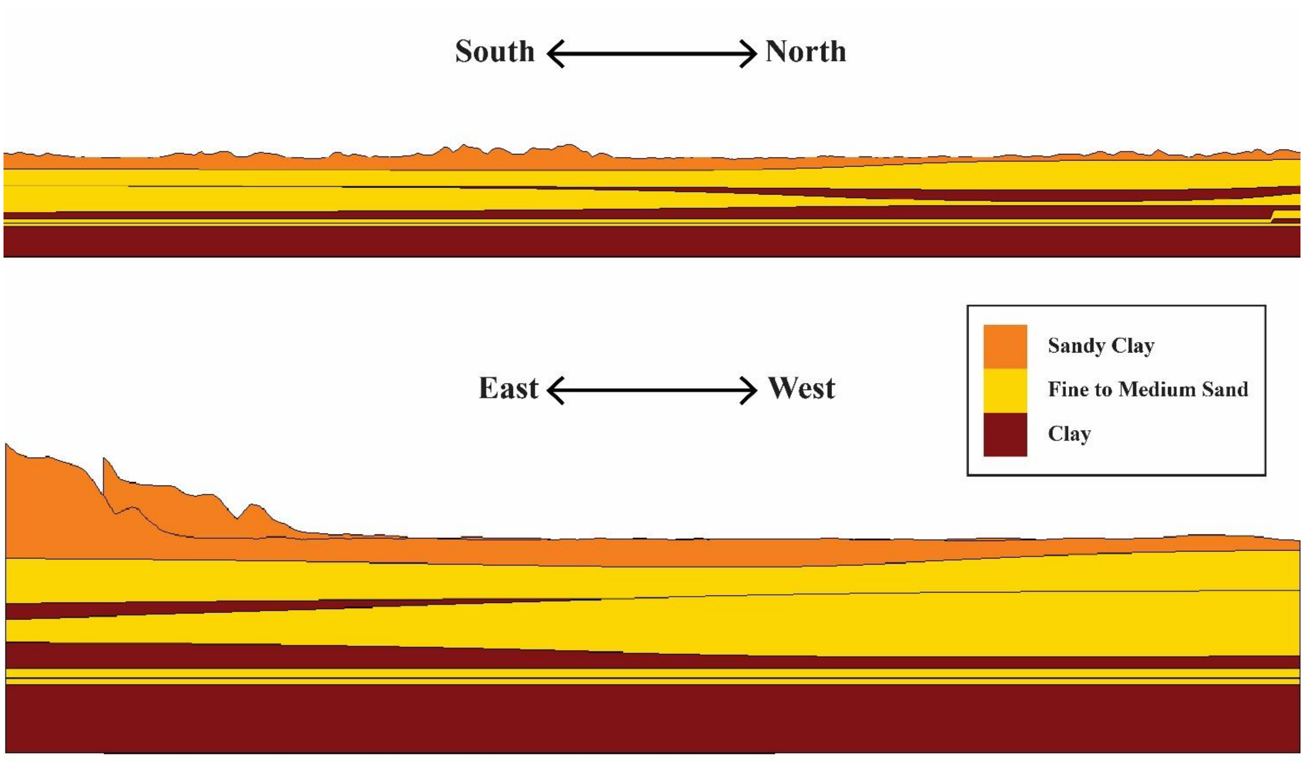

Figure 1.3: Stratigraphic Cross Section of the Study Area (IDW interpolation)

Then, the model was converted into a numerical grid suitable for MODFLOW simulations. The computational grid was discretized both horizontally and vertically, with careful attention to selecting an appropriate cell size that captured hydrogeological heterogeneity while maintaining computational efficiency. The vertical discretization ensured that aquifers and aquitards were represented as distinct model layers. The conversion also included defining the topography of the land surface, the thickness of aquifer units, and the elevation of aquifer bottoms. This process ensured that the numerical model adequately replicated the physical hydrogeological framework of the study area.

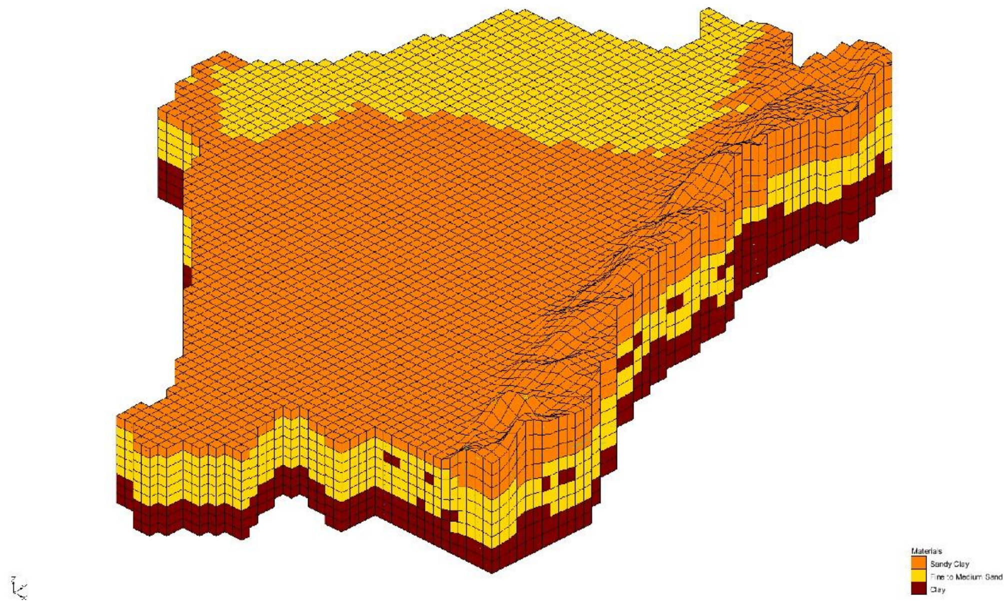

Figure 1.4: 3D Grid after Conversion from Stratigraphic Model

The results of the numerical groundwater model depend on the size of the computational grids (Aghlmand & Abbasi, 2019). The smaller the grid size, the more accurate the model will be. In this study, as shown in **Error! Reference source not found.**, the grid cell size is 250×250 m in horizontal plane and the depth of the whole model is 350 m uniformly and divided into 9 layers of identical depth (*Figure 1.5*). The computational grid consists of 29010 active cells (all cells inside the aquifer).

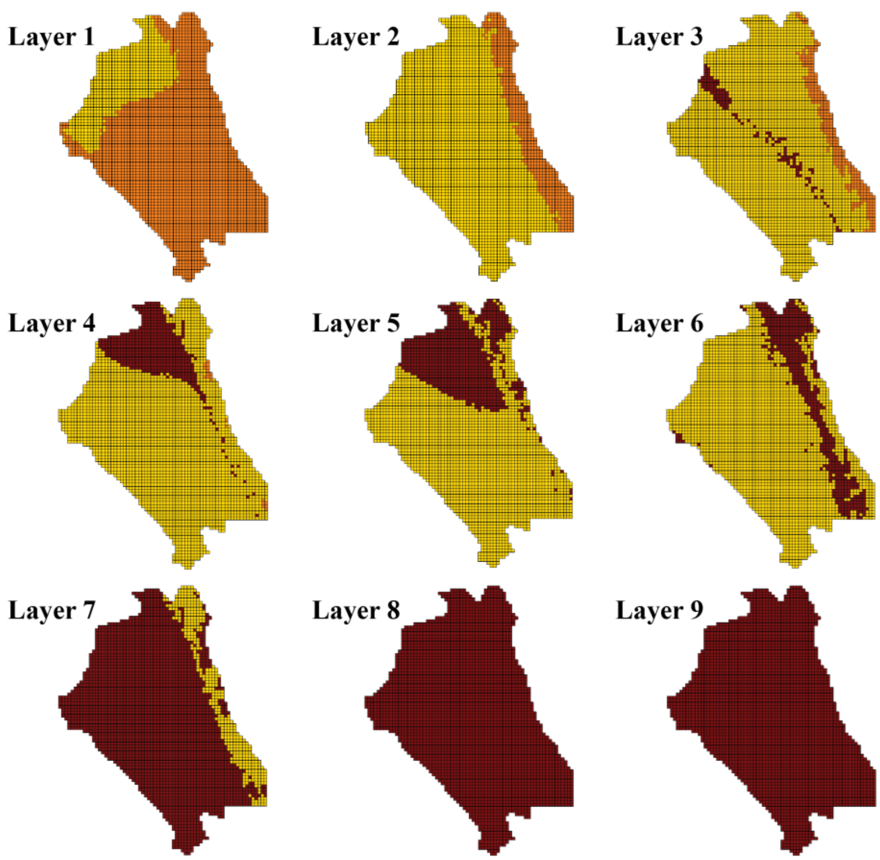

Figure 1.5: Layer Wise Distribution of Lithologic Attributes of the Model

1.3.2 Digitization of the Feature Objects and Defining Boundary Conditions

After building the initial computational grid, it is essential to introduce other hydrological features like sea, drains, wells, ponds, etc. to emulate as close to natural hydrological characteristics as possible into the model. Due to an extensive number of ponds in the study area, hardware limitations, and maintaining a simplistic nature of the model, the ponds are excluded from the model. The digitized shapefile of all the feature objects were prepared using Google Earth Pro and QGIS and then imported into the model.

The necessary values regarding the wells were also imported while importing the digitized shapefiles of the pumping well and observation well. Pumping wells are wells equipped with pumps to draw water from the aquifer, often leading to significant drawdown effects in the subsurface water level (Baalousha, 2016). They require data like surface elevation, flow rate (m^3/d), and screen length. On the other hand, observation wells do not extract water rather they are used to measure water level and monitor groundwater changes (Székely, 2013). They include surface elevation, screen length, and observed water level data. The flow rate of the pumping wells was collected through a sociological survey and the water level of the observation wells was collected from Bangladesh Water Development Board, (2024). The exact location of the wells was verified from Google Earth Pro and the location was taken from the site. GMS measures the water level considering mean sea level (MSL) as the datum. So, the following formula is used to calculate the water level.

$$H(m) = RL\ Parapet(m) - Parapet\ Height(m) - Water\ Table(m)$$

Here, H is the total head value of water in the observation well considering mean sea level as the datum.

Other sociological data such as the number of households, number of pumping wells (household and irrigation) and season-wise daily water usage are also collected during the sociological survey and from Bangladesh Bureau of Statistics, (2022, 2023, 2024). From, our calculation there are 1751 household pumping wells and 200 pumping wells are used for irrigation purposes.

In the model under sources/sinks/boundary coverage, sea, all wells, drains, and specific heads were defined. The sea side of the model boundary was considered as General Head Boundary as there is active fluid movement between the aquifers and the sea, and the rest of the boundary was defined as a No Flow Boundary because there is no visible connection between the subsurface aquifers and surface water bodies. The drains were defined as Drain, and the pumping wells were defined as Well. But the observation wells weren’t considered as Wells, because they were observation points for measuring the water level of the model.

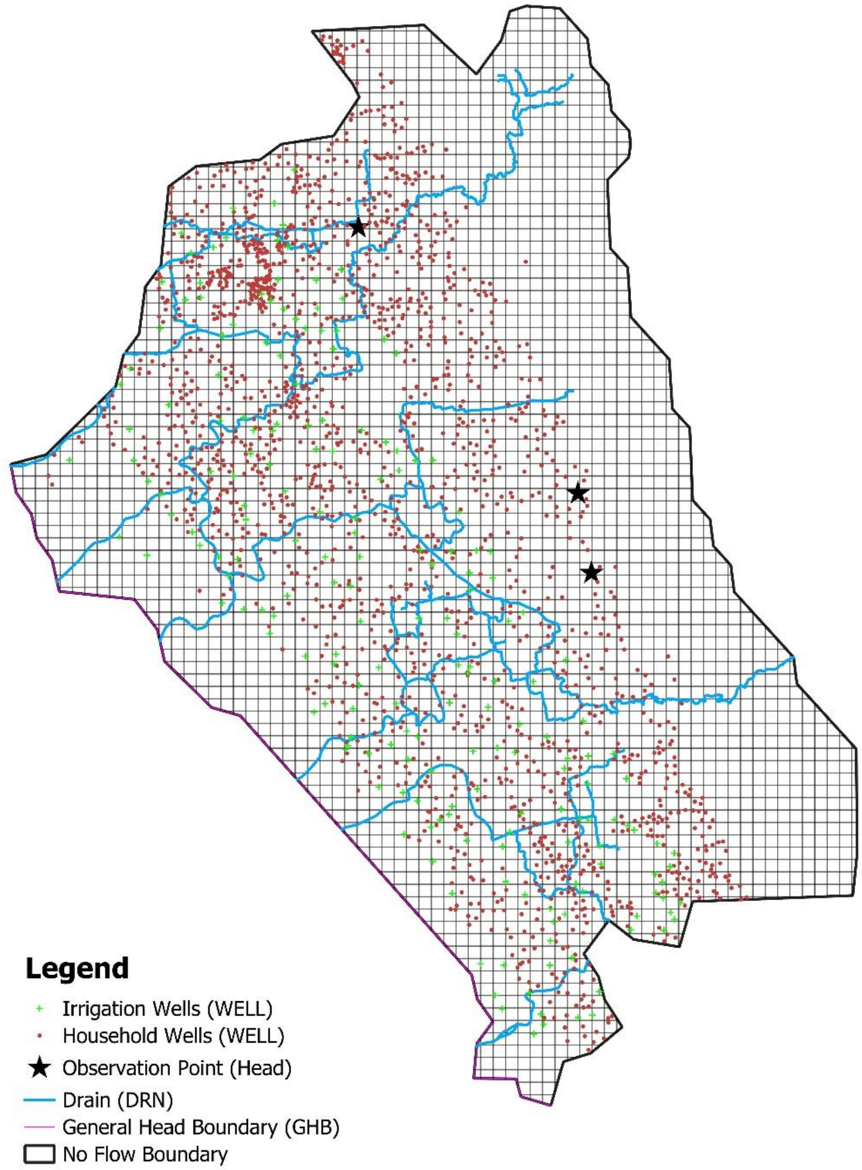

Figure 1.6: Boundary Conditions of the Model

1.3.3 Importing Dataset

Critical hydrological parameters like hydraulic conductivity, potential evapotranspiration (PET) rate, ET extinction depth, recharge rate, drain depth, drain conductance, and seawater level are required to simulate groundwater flow dynamics. In the case of Mirsharai and Sitakunda Upazila, the main lithological constituents were sandy clay, fine to medium sand, and clay. For the type of formation, hydraulic conductivity and porosity value were required to develop the numerical model, and they were imported during the preparation of the three-dimensional stratigraphic model. In this model, the hydraulic conductivity and porosity were assumed to be the same for a particular layer throughout the boundary of the study area.

The PET rate and ET extinction depth were 0.002637584 m/d and 1 m respectively (Climate Engine, 2017; Huntington et al., 2017; Shah et al., 2007). The recharge rate was calculated from the precipitation dataset of Funk et al., (2015) (CHIRPS 2.0) using the formula 3.2 from PR, (1970).

$$RE_{mm} = 0.35 \times (RF_{mm} - 600)$$

Here, RE_{mm} = annual total recharge due to precipitation, and RF_{mm} = annual total rainfall.

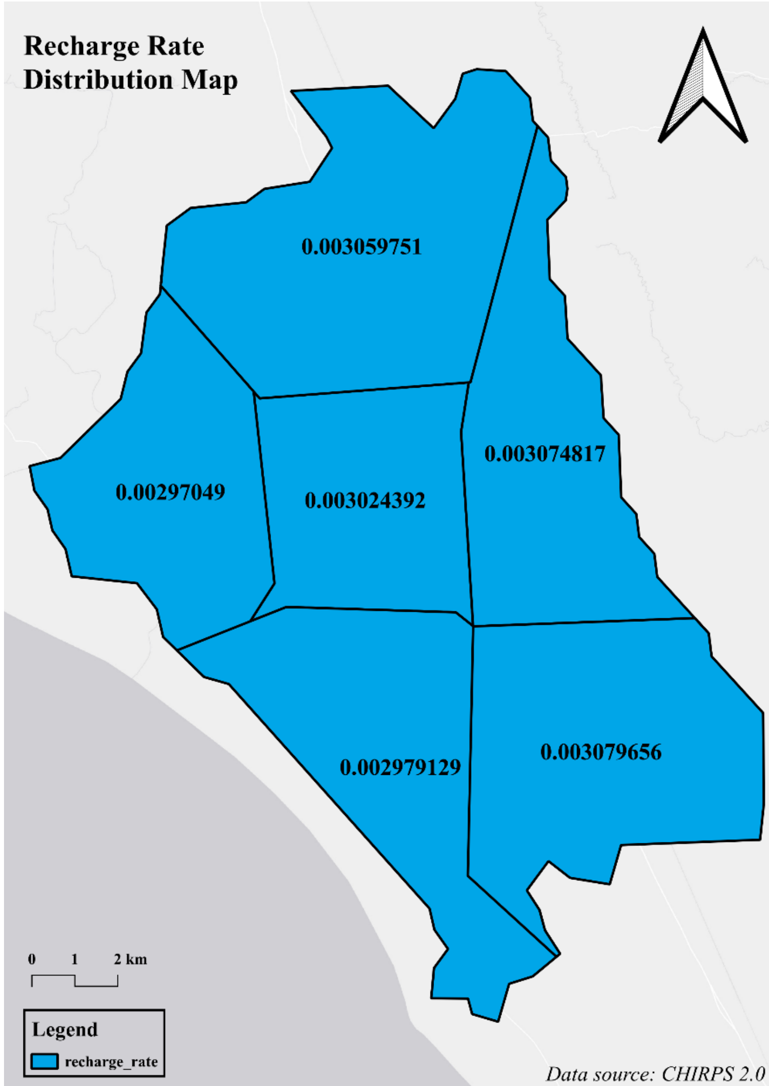

Figure 1.7: Recharge Rate Distribution map of the study area

The average drain depth and the average drain width was 1m and 5 m respectively based on reconnaissance survey. Calculation of the conductance of the drain and GHB has been done using the formula given in the GMS manual (GMS 10.8 Tutorial, 2024b):

$$Conductance = \frac{K \times w}{t}$$

Here, K is hydraulic conductivity, w is the width of drains, and t is the thickness of the bed material. In this model, sandy clay was considered as the bed material. Lastly, constant sea water level for the model was 1 m.

1.3.4 Model Simulation

After importing all the data mentioned above and keeping the starting head for the model the same as the top elevation of the layer, MODFLOW was run. A color-coded grid is formed, with the groundwater head contour depicted at each grid. The color range is shown in the legend bar.

1.3.5 Model Calibration

There are generally two kinds of calibration processes, the first one is the trial-and-error process which should be manually changed repeatedly to calibrate parameters. This method can be considered a fundamental step for history matching because it gives much insight about the site modeled and how parameter changes affect different areas of the model and types of observations (Anderson et al., 2015). The second type is automated parameter estimation which in many cases can calibrate the model quickly. GMS contains an interface to do the mentioned calibration called PEST (Parameter ESTimation) (GMS 10.8 Tutorial, 2024a). PEST calibration can be performed in two ways including zonal and pilot point. The first approach (zonal) is the most common one and is applied in this study (XMS Wiki, 2022).

For calibration, the hydraulic head data of 3 observation wells or piezometers in the study area is imported into the model. Using trial-and-error approach, attempts are made to minimize the differences between the calculated and observed head values. The quality of the calibration is evaluated using some indices including coefficient of determination (R^2), mean error (ME), mean absolute error (MAE), and root mean square error (RMSE) according to the equations.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(h_o - h_c)^2}{\sum_{i=1}^{n}(h_o - \bar{h})^2}$$

$$ME = \frac{1}{n}\sum_{i=1}^{n}(h_0 - h_c)_i$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|(h_0 - h_c)_i|$$

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(h_0 - h_c)_i{}^2\right]^{0.5}$$

Here, n is the number of piezometers; h_0 and h_c are observed and calculated hydraulic head values (m) respectively and $\bar{h}$ is mean of observed heads. Calculation of the above-mentioned statistical indices is useful in evaluating the merit of the calibration (Thangarajan, 2007). It should be noted that the GMS software provides ME, MAE, and RMAE values for the model. Because both positive and negative residuals are used in the calculation. ME value should be close to zero for a good calibration. MAE is calculated using the absolute values of the error (only positive values) and is a measure of the average error in the model. The RMSE is the average of the squared differences in measured and simulated heads. RMSE is less robust compared to the effects of outlier residuals. Thus, the RMSE is typically larger than the MAE. As, GMS software doesn't provide R^2 values for the model. Hence, we have calculated the value manually.

1.4 Transient Model Development

"The transient phase is currently under development. The result of steady state model and methodology of transient model development will be uploaded in the next iteration. This version presents the completed steady-state methodology and calibration process."