A
Dissertation Report
On

Groundwater Modeling of Sanganer

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Submitted by
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CERTIFICATE

This is to certify that the dissertation report on **"Groundwater Modeling of Sanganer"** which is submitted by **Yogendra Sharma** (2014PCW5237), in partial fulfillment for the Master of Technology in **Water Resource Engineering** to the Malaviya National Institute of Technology, Jaipur. It is a record of student's own work carried out by him under our supervision and guidance during academic session (2014-2016). This work is approved for submission.

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ABSTRACT

Groundwater is one the sources of potable water in the country. Groundwater fluctuations and also the detection of flow direction is of great environmental importance particularly once there's a risk for transport of contaminations. This report presents the results of groundwater modeling and calibration in the alluvial aquifer of Sanganer region.

A steady state three-dimensional groundwater model is developed for Sanganer block, one of the over exploited groundwater site as per the report of Jaipur district published by CGWB, 16 kilometers south of Jaipur district to stimulate and predict the aquifer conditions. The aim of the study was to determine the groundwater elevations of the region using a mathematical model, to obtain the spatial distribution of the seasonal groundwater decline and to calibrate the heads in observation wells. The model was run as steady-state conditions by application in unconfined aquifer.

For this purpose, Visual MODFLOW is used. The model uses finite difference method (FDM) to solve the partial equation for the water movement with constant density through a porous medium. A numerical model with finite difference method is utilized by making two layers. GIS (Geographic Info System) is used to produce top and bottom elevation of the layers by interpolating the elevation data.

The water balance in the single layer model was happy in each grid sizes. The 3D groundwater model was with success applied to the Sanganer region. The selection of grid size was studied, and higher agreements between discovered and simulated groundwater heads were found within the fine grid model. Some simulation errors and shortcomings were also seen due to the lack of required data.

As a result, the groundwater heads, the flow directions, the water balance and calibrated observation well water levels were obtained.

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ABBREVIATION

S_y	Specific Yield
S_s	Storativity
K_X	Horizontal Conductivity along x-direction
K_X	Hydraulic Conductivity along x-direction
K_Z	Hydraulic Conductivity along x-direction
NRMS	Normalized Root Mean Squared
1-D	One-dimensional
2-D	Two-dimensional
3-D	Three-dimensional

CHAPTER 1

INTRODUCTION

1.1 General

According to the UN-Water 2011 statistics, 30% of the world freshwater resources are stored in the form of groundwater. It is of both environmental and economic importance, therefore, to grasp and study the properties and controlling factors groundwater flow, further to develop methods and techniques for its study and attainable modification (TÓTH 2009).

Water has been considered as the largest natural resources in the form of groundwater and surface water. Groundwater is about 20% of the world's fresh water supply; that is about 0.61% of the whole world's water, including oceans and permanent snow. Rajasthan state is taken into account as an arid and semi-arid region. Because of the scarceness of surface water, the majority of the individuals in Rajasthan, have to depend on groundwater resources. In several areas, groundwater is the only available source for drinking water. In this context, the rapid increase in human population, as well as increasing industrialization and urbanization, has led to a greater imbalance between water demand and water availability.

Groundwater is a major contributor to the water needs of the State. More than 80% of drinking water and the majority industrial water needs, and more than 60% of the State’s irrigation water needs are met from groundwater. The stage of groundwater development is conterminous with the increase of the population and its living standard, industrial growth and agricultural production.

Therefore, it is essential to review the groundwater systems so as to take care of this crucial source and provide necessary information for finding solutions for problematic areas.

Groundwater modeling in some form is now a major a part of most projects dealing with groundwater development, protection, and remediation. As computer hardware and soft- ware continue to be improved and become more affordable, the role of models in extremely quantitative earth sciences such as hydrogeology will continue to increase accordingly. It is essential, however, that for any groundwater model to be interpreted and used properly, its limitations should be clearly understood. in addition to strictly ‘‘technical’’ limitations, like the accuracy of computations (hardware and software),

It is based on various assumptions regarding the real natural system being modelled. Hydrogeologic and hydrologic parameters utilized by the model are just an approximation of their actual field distribution, which can never be determined with an accuracy of 100 percent. Theoretical differential equations describing groundwater flow are replaced with systems of algebraic equations that are more or less accurate.

It is, therefore, obvious that a model will have a varying degree of reliability, and that it could not be ‘‘misused’’ as long as all the limitations involved are clearly stated, the modeling process follows industry-established procedures and standards, and the modeling documentation and any generated reports are transparent, and also follow the industry standards.

1.2 Purpose and Objectives

The purpose of this study is to get a better understanding of groundwater resources in the Sanganer region. The objective of the principle study is the development of a comprehensive data set to provide a scientific basis for water management of the Sanganer aquifer. The study will include the construction of numerical groundwater to support the conjunctive management of both groundwaters in the area.

The primary objective of this study was to develop and execute a numerical groundwater flow model for one of the over-drafted groundwater regions of Sanganer block of Jaipur district. The developed model also can be used for prediction. A groundwater flow model of the realm may also prove helpful for the analysis of temperature change impact situations. It is, therefore, an important precursor for any kind of hydrological study.

The results of this study will provide tools for the evaluation and management of alternate water resources. However, the determination of management scenarios and application of the ground-water models will not be conducted as part of this study.

Specific study objectives include the following:

1. To simulate and predict the aquifer conditions and to represent the natural groundwater flow in the environment.

2. To simulate groundwater flow rates and hydraulic heads within and across the boundaries of the system.
3. Quantify the rates and temporal and spatial distribution of ground-water withdrawals.
4. Develop a comprehensive water budget for the study area aquifer and document temporal variations in budget components.
5. Identify discharge and sources of aquifer recharge, the direction of groundwater flow.
6. Develop an independent, hydrologic, land use, spatially-oriented database of geologic, and other data sets to include information on aquifer recharge and discharge, aquifer hydraulic properties, ground-water levels, streamflow, lake levels, and water chemistry.
7. Construct a numerical ground-water model representing the current understanding of aquifer flow characteristics.
8. Calibrate the model to steady-state by current and historical data using automated parameter estimation methods that enable quantification of parameter uncertainty. The model will be used to simulate changes in groundwater levels to projected increases in regional aquifer withdrawals. Use of parameter estimation methods will allow for the evaluation of uncertainty and sensitivity associated with model simulations.
9. To generate a hypothetical system that will be utilized to study principles of groundwater flow associated with various general or specific problems.

Groundwater models are mathematical models derived from Darcy’s law that is used to calculate the rate and movement of groundwater through the aquifer [16].

1.3 Scope of work

Groundwater is a distinguished part of the hydrologic cycle. Surface water storage and groundwater withdrawal are traditional engineering approaches which will continue to be followed in future. The uncertainty regarding the occurrence, distribution and quality aspect of the groundwater and also the energy requirement for its withdrawal impose a restriction on the exploitation of groundwater. In spite of its uncertainty, groundwater has some obvious benefits.

Groundwater modeling is a crucial tool to guide management of groundwater notably in the areas where the hydrological cycles are expected to be accelerated as a result of climate change (Mall et al., 2006). Groundwater modeling becomes even more important owing to rapidly falling groundwater levels due to overexploitation, particularly in the state of Rajasthan that is one of the four states/union territories where severe groundwater depletion is going on as a result of human consumption instead of natural variability (Rodell et al.).

Groundwater models which can also be used to evaluate impact assessment needed for water in a controlled aquifer system have been of importance to agriculturists, environmentalists, hydrologists, etc. It is necessary to review the groundwater resource potentials of a site. The simulation of groundwater flow needs an intensive data and understanding of hydrogeologic characteristics of the site. Groundwater models are being used as tools for decision making in the management of a water resource system. They may also be used to predict some future ground- water flow. Some of the established solution techniques available for solving the governing equations of the model are a Finite Element, and Finite difference approximation or a combination of both providing model parameters and initial and boundary conditions are properly specified [1,4].

A groundwater flow model was developed for the Sanganer block. The study comprised of two main tasks; the primary task was data collection necessary knowledge, both from existing databases and previous studies. The second task was the practical and theoretical development of the groundwater flow model. A geographic information system (GIS) was utilized for organizing and process of various data, and map production and illustration of modeling results. After the groundwater flow model was set up, it was calibrated and also verified using two different sets of observed water level data. Calibration statistics and different indicators of model performance were calculated for both the calibrated and verified models to assess the validity of the groundwater flow model. Contour maps of hydraulic head and Maps showing groundwater flow directions were generated and interpreted concerning local hydrogeology.

1.4 Limitations

Groundwater flow models are simplified mathematical representations of complex natural systems. Due to this, there are limits to the accuracy with that groundwater systems are often simulated. These limitations should be known when using models and interpreting model results. The groundwater model cannot accurately predict the behavior of groundwater flow in real world situations. There are several sources of error and uncertainty in models. Model error normally stems from practical limitations of parameter structure, grid spacing, time discretization, insufficient calibration data, and the processes not simulated by the model. These factors, along with an inescapable error in observations, result in uncertainty in model predictions. A major cause of the lack of accuracy is the severe discrepancy between the scale of measurement necessary to understand aquifer parameter for accurate modeling and the scale of measurement generally made under the constraints of limited time and limited budgets.

Specific sources of uncertainty in the Sanganer block sub-watershed model include lack of the different type of data required. Pumping well data for different stress periods was not available. The number of Observation wells were very less, and water levels of these wells were also missing. Hence the frequency of data was inconsistent. Model error and uncertainty can be reduced in the future by further model refinements and collection of new calibration data.

1.5 Thesis Outlines

The whole work is segmented into various sections while writing a thesis. The thesis is divided into the following chapters-

Chapter 2. Literature Review- In this chapter, previous works are done by various researcher are elaborated the theoretical consideration and to support the present study

Chapter 3. Methodology- In this chapter method adopted for groundwater modeling is described.

Chapter 4. Results and Discussion- In this chapter, uncalibrated and calibrated results of various parameters are discussed.

Chapter 5. Conclusion and Recommendations- In this last chapter, the whole work is concluded and various improvements recommended.

CHAPTER 2

LITERATURE REVIEW

Water is the need of all life on earth. The distribution of water is quite variable. Several locations have plenty of it whereas others have very little. Water exists on earth as a solid (ice), vapor, and in liquid form above and below the ground surface. Both subsurface and surface water originate from precipitation, which incorporates all forms of moisture from clouds, as well as rain and snow. A part of the precipitation water runs off over the land, infiltrates and flows through the subsurface, and eventually finds its manner back to the atmosphere through evaporation from rivers, lakes, and the oceans; transpiration from plants and trees; or evapotranspiration from vegetation.

Not all subsurface water is groundwater. Groundwater is all the water that has penetrated the layer and is found in one of two soil layers. The one nearest the surface where gaps between soil particles are full of both air and water is called the vadose zone. Below this layer where the gaps are full of water is called the saturated zone. The water table is the boundary between these two layers. As the quantity of groundwater water increases or decreases, the water table rises or falls consequently. Once the whole area below the ground is saturated, flooding happens as a result of all subsequent precipitation is forced to stay on the surface.

Groundwater provides wells and springs, and it replenishes rivers, streams, lakes and also provides fresh water for irrigation, industry, and communities. It's blessings and drawbacks when comparing with surface water. The benefits of using groundwater are often listed as follows:

1. considerably higher quality compared to surface water and little to no water treatment costs.
2. Passage through the soil and granular materials permit the filtering of microorganisms and minute particles, also the attachment of organic compounds and a few metals to clay minerals.
3. Temperature and chemical quality are relatively constant over time.

4. Dispersion of pollution is slower.
5. Sediment content is mostly negligible.
6. Supply is mostly unaffected by short-run fluctuations in climate.

The disadvantages of groundwater:

1. Dissolved mineral content and hardness are more than surface water.
2. Management is more difficult.
3. Exploration and characterization of groundwater resources need advanced skills and strategies.
4. Once groundwater is contaminated, subsurface cleanup is troublesome and expensive, and also the application of cost-ineffective pump-and-treat strategies may be the only viable choice.

2.1 Modeling of Groundwater Flow

Groundwater modeling is often defined as the quantification and simulation of the natural movement of groundwater through any porous media. This can be achieved by mathematical or physical means. Modeling plays a very important role in the management of water resources. Groundwater models that replicate the groundwater flow process at the site of interest may be accustomed complement monitoring studies in evaluating and prediction groundwater flow and transport. However, every reliable groundwater model is based on correct field data and good prior information of the site. The groundwater modeling process charts us presented in Figure 2.1.

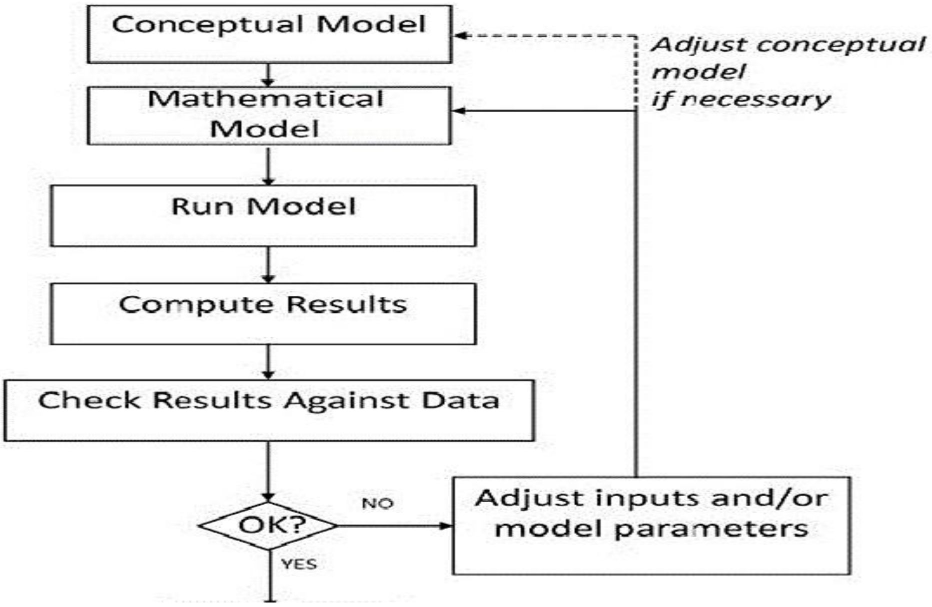


Figure 2.1 The groundwater modeling process

2.2 Types of Groundwater Models

There are many ways to classify groundwater flow models. Models are often either steady-state or transient, unconfined or confined, and take into account one, two or three spatial dimensions. In setting up the grid of a numerical model, the classification that is most relevant is one based on the spatial dimension (Anderson, 1990). In general, there are three types of models to be used for modeling as physical, mathematical, empirical methods. A mathematical model was employed in the study bestowed here.

A mathematical model is a precise or approximate solution to the governing equations of the process. Mathematical models of groundwater flow that are also referred to as white box model have been in use since the late 1800s. Basic theories, principles, and a few simplifying assumptions are used to derive equations. Simplifying assumptions must always be created so as to construct a model as a result of the field situations are too sophisticated to be simulated specifically. Usually the assumptions necessary to solve a mathematical model analytically are fairly restrictive. for instance, several analytical solutions need the subsurface medium to be homogenous and isotropic. To handle more realistic situations, it is usually necessary to resolve mathematical model approximately using numerical techniques.

The general governing equation for three-dimensional, transient groundwater flow in a heterogeneous and anisotropic aquifer is given as:

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right)=S_s\frac{\partial h}{\partial t}$$

Here, x,y,z, and t represent the spatial dimensions and time, respectively; h is the hydraulic head, Kx, Ky, Kz are the hydraulic conductivities in the x,y and z directions respectively, and Ss is the storativity of the aquifer. The derivation of this equation is based on the mass balance principle on a finite element representing the substitution of groundwater flux terms with Darcy's law and the saturated porous medium.
Mathematical models can be classified as analytical and numerical models:

2.2.1 Analytical models

Analytical models are exact solutions to the differential equations expressed as elementary or known functions. The governing equation can be written for onedimensional, transient groundwater flow in a homogeneous, confined aquifer as equation given below

$$S_s\frac{\partial h}{\partial t}=K\frac{\partial^2 h}{\partial x^2}$$

Here, initial and boundary conditions are defined and hydraulic head, which depends on time and space, is obtained. On the other side, the "Theis solution" is a well-known analytical model and is widely used. The Theis solution is formulated as equation given below:

$$s(u)=\frac{Q}{4\pi T}W(u)$$

In the above equation, W and S represent "well function" and drawdown respectively. T is the transmissivity of the formation. Analytical models give continuous solutions over the model domain. Analytical models are computationally more efficient than numerical models and provide correct solutions. Also, they are applicable for limited data and helpful for quick initial estimation of systems behavior. In situations where model geometry is difficult, analytical models are troublesome to use. The analytical resolution for the governing equation needs subtle mathematical techniques.

Analytical models typically have several limitations, resulting in simplistic solutions, and they are typically restricted to 1-D or 2-D.

2.2.2 Numerical Models

Numerical modeling of groundwater is a comparatively new field. It was not extensively pursued till the mid-1960s once digital computers with adequate capacity became available. Since then, significant progress has been created in the development and application of such techniques to groundwater flow. Numerical models are employed in groundwater modeling because it yields approximate solutions to the governing equations through the discretization of time and space. It helps in determining the impact of pollution on an aquifer [9].

Groundwater models usually require the solution of partial differential equations. The equations showing the groundwater flows are second order partial differential equations which may be classified on the premise of their mathematical properties. There are primarily three types of second order partial differential equations: parabolic, hyperbolic and elliptic equation [9].

The numerical models or mathematical the are usually based on the real physics that is followed by the groundwater flow. These mathematical equations are solved with the help of numerical codes like MODFLOW, ParFlow, HydroGeoSphere, OpenGeoSys, etc.

Nowadays, several computer programs are employed in groundwater modeling. One of them is software system Visual Modflow that uses a finite difference method to unravel the equation. They can be used to simulate the behavior of complex aquifers including the effects of irregular boundaries, heterogeneity, and different processes like groundwater flow, and solute transport. This study aims to reveal that the suitability of modflow software under numerous hydrogeologic conditions. The hydrogeologic system is also disturbed by some natural or manmade processes. To predict the system behavior, visual modflow is the straightforward to use modeling environment for 2-D and 3-D groundwater flow and contaminant transport simulations [8]. in this context; MODFLOW is employed for the modeling and calibration purposes.

Numerical models enable analysis of flow or transport solutions if the complexness of the mathematical model prevents an analytical solution. Numerical modeling techniques are utilized to solve a large set of equations, that delineate the physical flow processes in an aquifer. Two numerical techniques of numerical models that are referred to as finite differences and finite elements methods. These two approximate methods provide a principle for operating on the differential equations that structure a model and for convert them into a set of algebraic equations.

Numerical modeling provides a definite solution over the model domain utilized by algebraic equations. It uses direct methods or iterative methods for the approximate solution. For many problems, numerical solution is more realistic than the analytical solution. In this case, usually, numerical models are preferred to use in the mathematical model. Values are calculated at only some points by the numerical models.

The governing differential equations are numerically approximated by solving it numerically over a grid. The choice between a finite distinction and finite element model is} a matter of preference and depends typically on the problem to be solved.
The numerical solution methods used:

Finite Difference Method

The Finite Difference method (FDM) is one of the oldest methods for the solution of partial differential equations. The procedure domain is discretized by quadrilateral or rectangular cells (Figure). Often, the cell dimensions Δx and Δz are constant or even Δx=Δz. The unknown defined in nodes that are placed at the intersection points of cell boundaries or centers of the cells or (Hinkelmann, 2008). Depending on the finitedifference model, groundwater heads or concentrations are calculated as distinct values at the grid nodes, or at the center points of cells. (Spitz & Moreno, 1996)

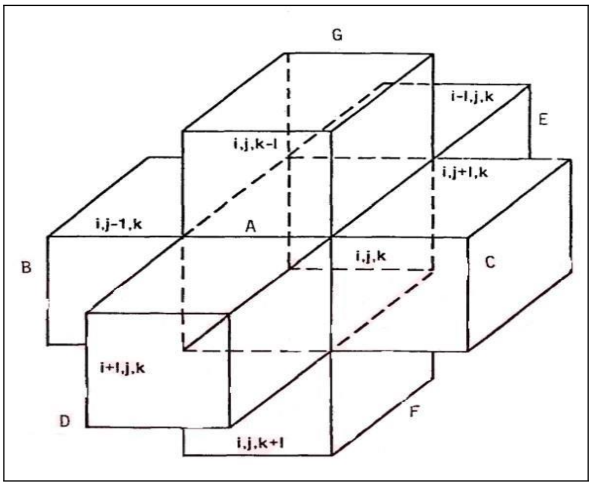


Figure Representation of a finite-difference computational model

Geometrically, it is obvious that complex boundaries or complex inner structures will solely be reproduced in an exceedingly very simplified approach by step functions. Derivatives of the unknown function “e” can be developed with the assistance of a Taylor-series expansion, shown here for the x direction. For simplicity’s sake, constant Δx=Δz.

$$e_{i+1j} = e_{ij} + \Delta x \frac{\partial e_{ij}}{\partial x} + \frac{(\Delta x)^2}{2} * \frac{\partial^2 e_{ij}}{\partial x^2} + \frac{(\Delta x)^3}{6} * \frac{\partial^3 e_{ij}}{\partial x^3} + \frac{(\Delta x)^4}{24} * \frac{\partial^4 e_{ij}}{\partial x^4} + 0(\Delta x^5)$$

In the following, the principle use of the finite difference method is explained using flow process in groundwater. Furthermore, one-dimensional problem is taken into account with a constant storage term S0 and a constant hydraulic conductivity Kf and without sink and source terms assumed.

$$S_0 \frac{\partial h}{\partial t} - div - \left(K_f gradh\right) = 0 \Leftrightarrow \frac{\partial h}{\partial t} - \frac{K_f}{S_0} \frac{\partial^2 h}{\partial^2 x^2} = 0$$

The method is established the continuity equation for each cell taking into consideration initial and / or boundary conditions. Depending on the governing equation, inflow and outflow are calculated for cell individually. After expressing the continuity equation for unknown heads, a set of the equation is solved for each cell. Various groundwater flow codes exist that can solve the general equations of groundwater flow using the FDM. One of them is MODFLOW-2000 (Harbaugh, 2000).

MODFLOW-2000 is the third major release developed by the U.S. Geological Survey 3-D finite difference groundwater flow model. MODFLOW was originally developed under the FORTRAN-77 language setting to solve the finite difference equations that represent 3-D saturated groundwater flow. It was initially developed by McDonald and Harbaugh (1984) of the U.S. Geological Survey in 1984 and was updated four times ensuing with the versions MODFLOW-88, MODFLOW-96, MODFLOW-2000, and MODFLOW-2005. At the same time, several new packages were added into the code, which can simulate the hydrologic problems far better than ever. These packages can be used one by one by the main program throughout scheming the model, and each package is split into different|completely different} modules and each module executes a different procedure to complete certain part of simulation like defining the model, allocating memory, reading data, formulating equations (Wang et.al. 2007).

MODFLOW incorporates a standard structure that enables it to be modified to adapt the code for special applications. It simulates transient and steady flow in an irregularly shaped flow system in which aquifer layers will be unconfined, confined or a combination of confined and unconfined. Flow from external stresses, such as evapotranspiration, flow to drains, flow to wells and flow through river beds and aerial recharge can be simulated. Specified head and specified flux boundaries can be simulated as a head dependent flux across the model's outer boundary that enables water to be provided to a boundary block in the modeled area at a rate proportional to the current head difference between boundary block and a source of water outside the modeled area. In simulating ground-water flow, it incorporates related capabilities such as solute transport and parameter estimation. The groundwater flow equation is solved using the finite-difference method. The flow region is divided into blocks in which the medium properties are assumed to be uniform. (USGS, 2008).

Finite Element Method

The applicability of the finite element (FE) method to groundwater problems may be a recent development in comparison to the finite difference method. The finite element method is applied to a variety of element types; however, the triangular element is the nice starting point for describing the method. (Anderson & Wang, 1990).

The FE model differs from the FD model by approximating the flow equation by integration instead of differentiation. As in the FD model, the area of the model is divided into sub-areas, referred to as elements. One commonly chooses triangular elements as sub-areas. Since there are primarily no restrictions on the shapes of the elements, the model user is more flexible in the model discretization than once using the finite distinction scheme. (Spitz & Moreno, 1996).

2.3 Data Requirements for Groundwater Modeling

Compiling the field data relevant to the assembly of the groundwater flow model is an important step in modeling. Data requirements for groundwater modeling can be divided be classified into 2 sections; the physical and hydrologic framework. The primary step of a model study comprises the collection and evaluating required relevant data on flow system under investigation. Input data for the model are used for (Spitz & Moreno, 1996):

1. Problem definition (material properties and geometry of hydraulic units).
2. Numerical requirements (boundary conditions, initial conditions, and transient conditions).
3. Modeling requirements (calibration, validation, and definition of alternate scenarios).

Data within the physical framework outline the geometry of the system further as thickness and real extent of every hydrostratigraphic unit. Data within the hydrologic framework embrace information on heads and fluxes that are needed to formulate the conceptual model and check model calibration. Hydrogeologic data also outline aquifer properties and hydrologic stresses. They embody pumping, recharge and evapotranspiration. Recharge is the one amongst the most difficult parameters to estimate. (Anderson & Woessner, 1990).

The physical framework consists of all geologic information regarding the natural system like cross-sections, residential, a geological map showing vertical profile industrial areas, fault lines and formations, a topographic map showing surface water bodies, surface elevation contours, etc., contour maps showing the elevation of the bottom of aquifers and confining beds, maps showing the thickness of streams and lake sediments. The physical framework primarily defines the geometry of the system likewise the thickness of the hydrostratigraphic units.

Data on fluxes, hydraulic heads, precipitation, evapotranspiration are enclosed within the hydrological framework. Hydrological data also define hydrologic stresses like pumping, recharge, and evapotranspiration. Hydrological data can be available in the form of the water table and potentiometric maps for the aquifers of interest maps showing hydraulic conductivity and transmissivity distribution, hydrographs of groundwater head and surface water levels and discharge rates, spatial and temporal distribution of rates of groundwater recharge, groundwater pumping, natural groundwater discharge and evapotranspiration.

2.4 Model Calibration and Verification

Model Calibration

Model calibration is defined as consistently dynamic values of model input parameters in an attempt to match field conditions within some acceptable criteria.

Calibration is accomplished by finding a set of parameters, boundary conditions, and stresses that produce simulated fluxes and heads that match field-measured values within a pre-established range of error. Finding a set of values amounts to solve of what is referred to as the inverse problem. In an inverse problem the target is to determine values of parameters and hydrologic stresses from information concerning heads, whereas in forward problem system parameters like recharge rate specified and the model calculates heads.

The objective of the calibration is to reduce this error, generally referred to as the calibration criterion. Calibration statistics are expressed in many ways, however, the most common are listed below:

Mean error (ME) is the mean of variations between measured and simulated heads (residuals) where is the number of calibration values. Caution ought to be exercised once interpreting this error as negative, and positive residual may eliminate and yield a low error.

$$ME = \frac{1}{n}\sum_{i=1}^{n}(h_m - h_s)$$

In this formulation, h_s indicates simulated heads and h_m is measured heads. The ME is easy to calculate but is sometimes not a wise alternative because both positive and negative differences are incorporated in the mean and may cancel out the error.

The mean absolute error is a mean of the absolute errors $e_i = h_s - h_m$, where hs is the calculated and the measured head.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|h_{s\_}h_m| = \frac{1}{n}\sum_{i=1}^{n}|ei|$$

Root mean square (RMS) error: the standard deviation of the differences in measured and simulated heads. The RMS is sometimes thought to be the most effective measure of error if the errors are normally distributed. The maximum acceptable value of the calibration criterion depends on the magnitude of the modification in heads over the problem domain. If the ratio of the RMS error to the total head range in the system is small, the errors are solely a little part of the general model response.

$$x_{rms} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} x^{2}\, i} = \sqrt{\frac{x_1^2 + x_2^2 + \cdots \ldots \ldots . + x_n^2}{n}}$$

The RMS is usually thought to be the most effective measure of error if errors are normally distributed.

The three measures of error mentioned above quantify the average error in the calibration but say nothing regarding the distribution of error. For example, comparison of head contours offers a strictly subjective and qualitative indication of spatial distribution error. A quantitative analysis of the distribution or error should be a part of calibration assessment. The error in the residuals should be arbitrarily distributed over the grid or contours (Anderson & Woessner, 1990).

There are primarily two ways that to estimate model parameters and solve the inverse problem: the manual trial-error adjustment of the parameter and automated parameter estimation. In trial and error calibration, parameter values at the start assigned to each node or element in the grid are adjusted in successive model runs to check simulated heads or flows to the standardization target. On the opposite hand, the automatic standardization method is performed using specially developed codes that use either a direct or indirect approach to unravel the inverse problem. In a direct answer, the unknown parameters are treated as dependent variables. This suggests that values for head should be input for all nodes. Heads are best-known only at points where there are observation wells, creating it necessary to estimate heads elsewhere in the grid, sometimes by interpolation ways like kriging. The solution minimizes the nodal mass balance error caused by mistreatment these heads and the model parameter values. The indirect approach is analogous to performing trial-error calibrations in that the forward problem is repeatedly solved in an automatic fashion.

An example for an automatic calibration code is PEST. It is a calibration tool, developed by John Doherty of Watermark Computing that works with all types of models that use one or more input files and produce one or more output files (Doherty, 2004). PEST works by employing a template file that is a copy of the MODFLOW file with parameters to be estimated. The parameters are substituted by a special code that tells PEST where to get the parameters. This suggests that the parameters to be estimated must be the ones written to the MODFLOW file (usually the boundary condition files or BCF Package file or).

Model Verification

Model verification is a check of whether or not the model will be used as a predictive tool, by showing that the calibrated model is an adequate illustration of the physical system. Owing to uncertainties within the model input data, the set of parameter values received after the calibration process may not represent actual field values accurately. Consequently, the calibrated parameters may not accurately represent the system under a distinct set of hydrologic stresses or boundary conditions or the calibrated solution may be non-unique.

Model verification helps to establish greater confidence in the calibrated model. In a typical verification exercise, hydrologic stresses and values of parameters and defined throughout calibration and need to simulate a transient response for which a freelance and a different set of field data exists. If the calibrated parameters were modified considerably during verification, it might not be possible to match the calibration targets using the new parameter values. In this case, it will be necessary to repeat the method till a set of parameter values is known that producers an honest match to each the calibration and what were supposed to be verification targets. If it is necessary to regulate parameters throughout verification, the verification becomes the second calibration, and another freelance data set is required to perform the verification. Verification is accomplished when the verification targets match without changing the tag parameter values. (Anderson & Woessner, 1991).

2.5 Synopsis of Literature about Previous Groundwater Modeling Studies

Palma & Bentley (2007) set up a regional scale groundwater flow model that was simulated using steady and transient state and numerical models for the Leon-Chinandega aquifer in Nicaragua utilized by Visual MDOFLOW. The study targeted on a quantitative assessment of the potential of the aquifer as a source of water for irrigation. The motive of this work was to check the groundwater flow system in a subbasin of the Leon-Chinandega aquifer using steady and transient-state numerical groundwater low models and to analyze the consequences of further groundwater development. This model was calibrated by transmissivity and model discharge. The transient simulations were run for ten years, taking the results from either 1970–1971 or 2004–2005 to eliminate the influence of the steady-state simulation initial condition. Two different flow systems are known in the Leon-Chinandega aquifer. The primary one was a deep system, recharged in the Cordillera and then discharged in the central and lower plain, either as to pumping wells or base flow. The second was a shallow local flow system, recharged in the central and lower plain which was discharged into the pumping wells or rivers. Simulations indicated that groundwater from deep wells is recharged at high elevations, corresponding to the deep flow system. Shallow wells principally capture groundwater that was recharged locally. However, there was also an indication that mixing of the local and regional system can occur.

Kumar and Kumar (2014) developed a steady state finite difference model, MODFLOW, to measure groundwater in Choutuppal Mandal, Nalgonda (Dt) AP., with the use of GW data from 19 observation wells. Well, inventory and base map are used to assess surface features, GWL, and direction. MODFLOW is conceptualized as two layers fractured and weathered aquifer system spread over 19215 m x 10366 m area. The result revealed that the computed groundwater level contours are in good agreement with observed ones.

Sakiyan & Yazicigil (2004) investigate the aquifer system of the Küçük Menderes Basin for sustainable development and management of an aquifer system. The spatial distributions of the recharge and hydrogeological parameters were calculated by hydrologic simulations and geostatistical methods and. A finite-difference groundwater flow model was utilized to represent the unconfined flow in the aquifer system. This model was calibrated in sequent stages as a steady-state followed by a transient condition. The study’s objective was to develop a groundwater management plan using the groundwater flow model. Different groundwater management scenarios were developed to find out the safe yield for the Küçük Menderes aquifer system.

Soyaslan (2004) generated a modeling map of Yalvaç Basin groundwater flow based on steady state condition, 3-D, and finite difference methods using MODFLOW. A numerical groundwater flow model of the Yalvaç basin, which is a closed basin, was created to know the amount of groundwater discharge to the Eğirdir Lake. The basin has been modeled as different four layer aquifer system. In the bottom, It was distinguished that there are semi-confined karstic aquifer and less storage capacity and permeability. In this study, a numerical groundwater flow model of the Yalvaç basin, which is a closed basin, was created to determine the aquifer parameters and to determine the amount of groundwater discharge to Eğirdir Lake as per the validated conceptual hydrogeological model of the study area. Consequently, this model has been calibrated by spring discharges and drain level of 2000 and average groundwater level observations. As a result discharge amount has been obtained as a yearly total of 114×106 m3 to Eğirdir Lake.

O. Lehn Franke et al. described the properties of the seven most common boundary conditions encountered in groundwater systems and examine major aspects of their application. He also discussed the significance and specification of initial conditions and evaluates some common errors in applying this concept to ground-water-system models. He considered only boundary conditions that apply to saturated ground-water systems.

The city Water Utilities Public Service Board (2002) in the U.S.A. prepared a report concerning groundwater modeling study results for the Cãnutillo Wellfield. The aim of this model was to delineate the groundwater system of the Mesilla Bolson and as such provide information to be employed in water resources planning. The grid of the model domain was created uniform at a spacing of roughly 200 meters. Additional canals, laterals, and drains were added. During development of a groundwater flow model, parameters like hydraulic conductivity were input to the model based on knowledge of the aquifer hydrogeology, available test data, and interpolation between known values. On the other hand, based on the groundwater flow model, a contaminant transport model was formulated to provide more reliable estimates of changes in water quality over time than can be made analytically. The transport model included the same area as the Cañutillo flow model and utilized the solved head from the flow model as an input. Calibration of the groundwater transport model required that concentration in individual wells matched over time through changing selected parameters, boundary conditions, and initial concentrations. A baseline simulation was completed based on the most effective accessible information on model parameters and starting conditions. This simulation was then compared to simulations to gage model improvement with parameter changes. Model parameters like porosity, mountain- and slope-front recharge concentration, and irrigation recharge concentration were altered until the most effective solution was achieved.

The Miami-Dade and Sewer Department of Environmental Resource Management (2001) prepared a report; that was about groundwater modeling and risk assessment of the Miami-Dade area in the U.S.A. The Miami-Dade well field consisting of fifteen water supply wells had a maximum daily permissible allocation of 587.45×103 m3/day. The two WTPs sustain a combined permitted capacity 852.75×103 m3/day and use conventional lime softening treatment, followed by disinfection and filtration. Whereas this treatment was enough for groundwater sources, it would not be sufficiently protective if the source were under the direct influence of a surface water body. Although WTP and the well field are presently restricted by permit to 852.75×103 and 587.45 m3/day, respectively, MDWASD (The Northwest Wellfield was Miami-Dade Water and Sewer Department) stated that the planned future capacity of the North Well Field is 890.65×103 m3/day. This value would be employed in all future analyses within this report. The numerical model had to be used for more precise evaluation of paths of groundwater and the travel times. The Purpose of groundwater model was to estimate modeling of Cryptosporidium offers a protective and conservative approach the 180 days, and 230-day particle travels time distances in the vicinity of the NWWF.

The pumpage from the NWWF was simulated at MDWASD’s planned future extraction of 890.65×103 m3/day. The model results were used to generate travel-time contour plots derived from particle tracking simulations using the MODFLOW post-processor MODPATH.

Encon (2005) prepared a comprehensive environmental impact assessment report for a planned gold mine situated in Efemçukuru, Izmir. Groundwater levels, Groundwater resources, groundwater quality and flow direction around the area was searched and reported. Groundwater resources were classified as three sources like drilling wells, wells, and creeks. Groundwater level was measured due to seasonal alteration.

Hydraulic gradient and groundwater flow and were determined by the drilling and alluvial wells which were measured water levels. Hydraulic conductivity was obtained with some tests. Whereas groundwater flow was being known, the seasonal drawdown of water levels was measured. According to the results, the groundwater flow increased to the eastern of the mine. Also, hydraulic gradient increased due to topography. The contamination would be transported towards the Torbalı Pain.

Weiss & Gvirtzman (2007) studied twenty to thirty years of precipitation and spring discharge records to reconstruct the transient character of yearly recharge employing a groundwater flow model. Four different sites within the Yargon-Taninim aquifer, which is the main resource of fresh water of Israel, were selected for building conceptual and numerical hydrogeological models. Transient, finite difference numerical groundwater flow models were developed for four separate alert karstic aquifers in the Judean-Samarian Mountains in Israel using MODFLOW-2000. The ensuing numerical groundwater flow model was calibrated to both the rainfall data (using precipitation-recharge relationships) and the spring discharge data. Precipitation-recharge functions were calculated by numerical modeling. Best fitting between observed and computed spring hydrograph data allowed generate a set of empirical functions relating measured precipitation to recharge to the aquifer.

Moustadraf, Razack, Sinan (2008) developed a numerical and transient model which associated with intensive pumping throughout the periods of drought; that was forced the abandonment of wells due to the seawater intrusion in the aquifer of the Chaouia Coast of Morocco. Precipitation and temperature concerning climatical fluctuations data were analyzed. Before modeling, the conceptual model area was created at the top of the layer was delineated by the topographical surface. It comprises the recharge area by precipitation to the system. The bottom layer corresponds to the Paleozoic bedrock which is delineated by a no-flow boundary. Recharge and Hydraulic conductivity were used for calibration. Hydraulic conductivity was estimated by interpolation. The steadystate simulation is based on the lower and higher groundwater level periods in 1971. The objective of this simulation is the calibration of the model by adjusting the spatial distribution of the recharge and hydraulic conductivity. The transient simulation, based on the standardization obtained in steady- state simulation. It aims at simulating the evolution vs. time of the groundwater flow of the aquifer. The numerical modeling showed that the severe degradation of the resource was primarily associated with intensive pumping that was 7 meters during times of drought. This pumping has instigated seawater intrusion into the aquifer and consequently the abandonment of wells contaminated by saltwater.

Craner (2006) developed a steady-state numerical groundwater flow model using MODFLOW with MODPATH to grasp the direction of groundwater flow, groundwater age, and transport of nitrate, pathways of the Southern River Valley, Oregon, USA.

Atilla (1998) developed a transient groundwater flow model for the confined aquifer under the Afyon Plain in Turkey. The temporal and spatial extent of hydraulic head over the plain was simulated using MODFLOW. According to the piezometric level decline and water quality degradation conditions, the prediction of the results of the overexploitation entails the identification of the current head distribution. The hydraulic head distribution declines from NW to SE over the plain. The model shows that there is a rise in the decline of the piezometric levels after the year 1976 when intensive groundwater exploitation is started and after 1990 when the exploitation is significantly raised. It is simulated that the hydraulic head is changed from 5 to 10 m in some parts of the plain front the year 1965 to 1998. Under these conditions, groundwater usage in the Plain should be the regulated to determine the termination of uncontrolled groundwater exploitation and the natural hydraulic balance.

Ayenew, Demlie & Wohnlich (2007) conducted a numerical modeling study for the groundwater system in the Akaki catchment of central Ethiopia. A 3-D, steady-state, finite-difference groundwater flow model, was developed to quantify the groundwater fluxes and analyze the subsurface hydrodynamics in the Akaki catchment by giving particular emphasis to the well field that provides water to the city of Addis Ababa. The model was calibrated mistreatment head observations from 131 wells. The simulation was created in a two-layer unconfined aquifer with spatially variable hydraulic conductivities and recharge under well-defined boundary condition. The result indicated that the groundwater flows regionally to the south converging to the major well field.

Juckem, Hunt & Anderson (2006) provided extensive data that scale effects of hydrostratigraphy and recharge zone on base flow. This study’s objective was to present a strategy for estimating a critical basin size, above which base flows appear to be comparatively less sensitive to the spatial distribution of hydraulic conductivity and recharge. Influence of recharge zonation and hydrostratigraphic.

Layering on base flow was determined using MODFLOW for the Coon Creek Watershed, that is located in the Wisconsin, USA. This model was created as three-dimensional and for steady-state conditions. The results showed that there is a scale effect that influences the relative importance of recharge and hydraulic conductivity such at some scale, the influence of spatial parameter variability on base flow diminishes and can be approximated employing a simplified illustration.

Mazzilli et al. presented the analytical properties of the sensitivity of the 2-D steady state groundwater flow equation to the boundary conditions and the flow parameters based on the perturbation approach. These analytical properties are used to deliver guidelines for model design, calibration, and monitoring network design. The sensitivity patterns are shown to depend on the nature of both the variable investigated and the perturbed parameter. The sensitivity of the hydraulic head to the hydraulic conductivity extends mainly in the flow direction, and the sensitivity to the recharge spreads radially. Besides, the sensitivity of the longitudinal flow velocity to the hydraulic conductivity propagates in both the transverse and longitudinal directions, whereas the sensitivity of the transverse flow velocity propagates in the diagonal directions of the flow. The analytical results are established by application examples on real-world and idealized simulations. These analytical findings allow some general rules to be developed for model design, model calibration, and monitoring network design. In particular, the optimal location of measurement points depends on the nature of the variable of interest. Measurement network design hence proves to be problemdependent. Moreover, the adequate monitoring well network design may allow discriminating between the possible sources of error [13].

Elçi, Gündüz & Şimşek (2007) developed a mathematical flow model for the water table aquifer of the Torbalı plain in Izmir. This two-dimensional model was created for steady state conditions, and was executed using MODFLOW-2000. Groundwater levels were measured in the study area at 28 observance points. Aquifer recharge and Hydraulic conductivity and rates were used for model calibration. Water budget and groundwater flow directions for the Torbalı Basin were defined by this modeling study.

According to the modeling results, the plain receives the Gurgur Mountain in the east of Torbali and groundwater influx from the limestone units in the south, in addition to surface recharge originating from precipitation.

He, Takase & Wang (2007) used a 3-D finite element model; this study characterizes groundwater flow in a costal plain of the Seto inland sea, Japan. The model calibration occurred taking field data depicting the aquifer system and translating this information into input variables that the model code utilizes to solve governing flow equations. Geological geometry and the number of aquifers have been examined based on a large amount of hydrogeological, geological and topographical data. Results of study provide a high correlation between the groundwater level and the ground surface elevation in the shallow coastal aquifer. For calibrating the numerical groundwater model, the groundwater flow was simulated in steady state. Furthermore, the water table and trend in the transient state has also been explained. The numerical result provides excellent visual representations of groundwater flow, resource managers and decision makers with a clear understanding of the nature of the types of groundwater flow pathways. Results build a base for further analysis under different future eventualities.

McAda & Barroll (2002) developed a three-dimensional, finite difference groundwater flow model for the middle Rio Grande basin in New Mexico, U.S.A. The purpose of the model was to integrate the components of the groundwater flow system, together with the hydrologic interaction between the surface water systems in the basin, to provide a tool to facilitate water managers plan for, to understand the hydrogeology of the basin better and administer the use of basin water resources. Groundwater flow in the Middle Rio Grande basin was simulated from 1900 to March 2000. Steady-state conditions were assumed to exist prior to 1900, which was used as initial conditions for the transient simulation period of 1900 to 2000. The model was calibrated employing a judgmental trial-and-error procedure of adjusting aquifer properties and boundary conditions in an attempt to attenuate the difference between measured and simulated water-level data and flow data by MODFLOW-2000. Also, recharge parameters were defined as different kind of types such as tributary recharge, mountain-front recharge, and subsurface recharge. Also, hydraulic conductivity definitions were classified horizontal and vertical on model columns and rows. The different parameter of a model like, specific storage that was estimated to be 2×10-6 per foot in the model and specific yield was estimated to be 0.2.

CHAPTER 3

STUDY AREA AND DATA ACQUISITION

3.1 General Description

Sanganer is a town situated 16 km south of Jaipur, the capital of Indian state of Rajasthan, within 26°49’ to 26°51’N latitude and 75°46’ to 75°51’E longitude. The boundary of the study area was defined and created using toposheet no. 45N/5, 45N/9, 45N/10, 45N/13 and 45N/14 obtained from Survey of India, Jaipur. It covers an area of 697.8 sq. km.

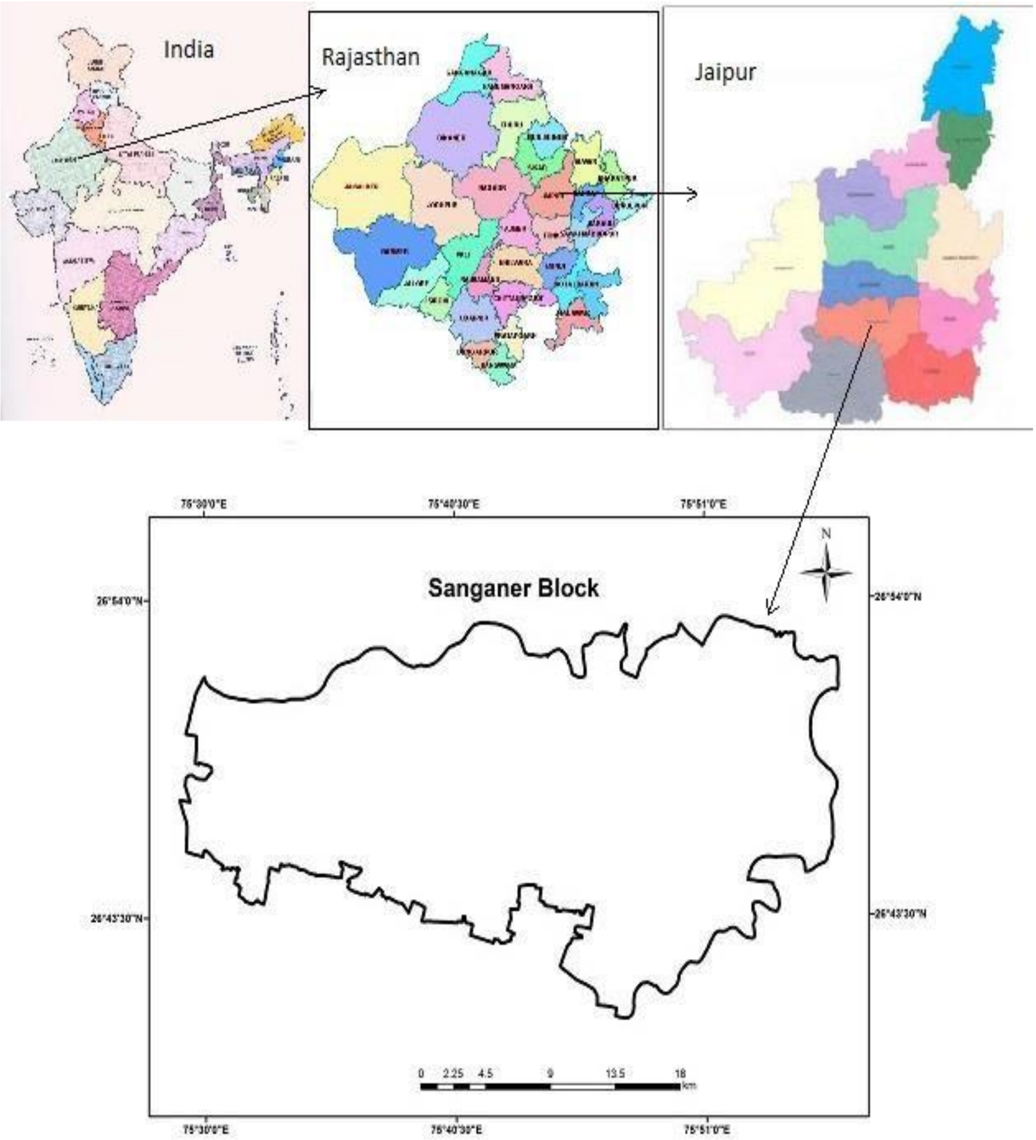


Figure 3.1 Illustration of Study Area

Annual average rainfall of the area during the period 2001 to 2010 has been 513.26 mm. Groundwater resources available in Sanganer has been over exploited. The decline in water levels is more than 0.40 m/year (As per water level trend pre-monsoon 19842009). The annual net groundwater availability and annual gross draft for all the blocks of Jaipur district are shown in the figure given below.

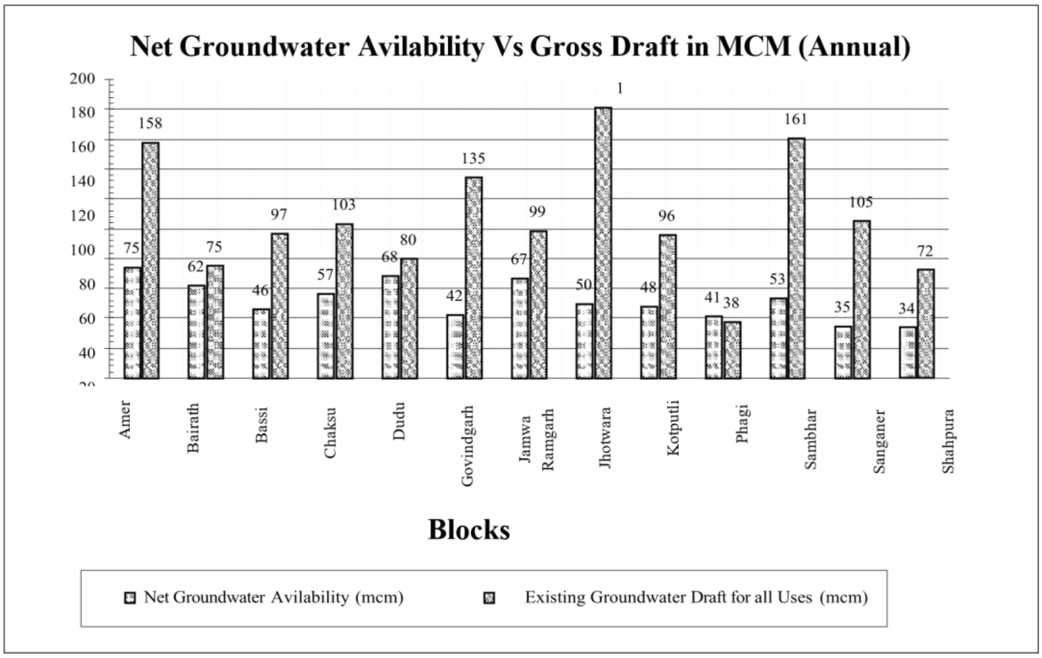


Figure 3.2 Groundwater Resources (March 2009)

In Sanganer alluvial deposits comprising of mainly, fine sand and silt serve as potential aquifers in addition to gravel zones as stated in groundwater report of Jaipur (CGWB, 2013).

Table 3.1 Average annual rainfall

Block	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Average
Sanganer	585.00	237.00	552.30	805.00	397.00	407.00	557.30	572.00	275.00	745.00	513.26

Table 3.1 Groundwater assessment report (As on 30 March 2011)

Block	Total Annual Groundwater Recharge (mcm)	Net Annual Groundwater Availability (mcm)	Gross Groundwater Draft For Irrigation (mcm)	Gross Ground water Draft For Dom.	Gross Groundwater Draft For	Stage of G.W. Development (%)	Category
Sanganer	38.3462	34.5092	82.7363	22.6631	105.3994	305.42	OE

3.2 Geology and Hydrogeology

The geological properties of the study area were obtained from the 1/3,200,000 scale geological map of Rajasthan courtesy of the Regional office of Water Resources Planning Department. Soil type of the region is blown sand, and soil originated from older alluvium formation.

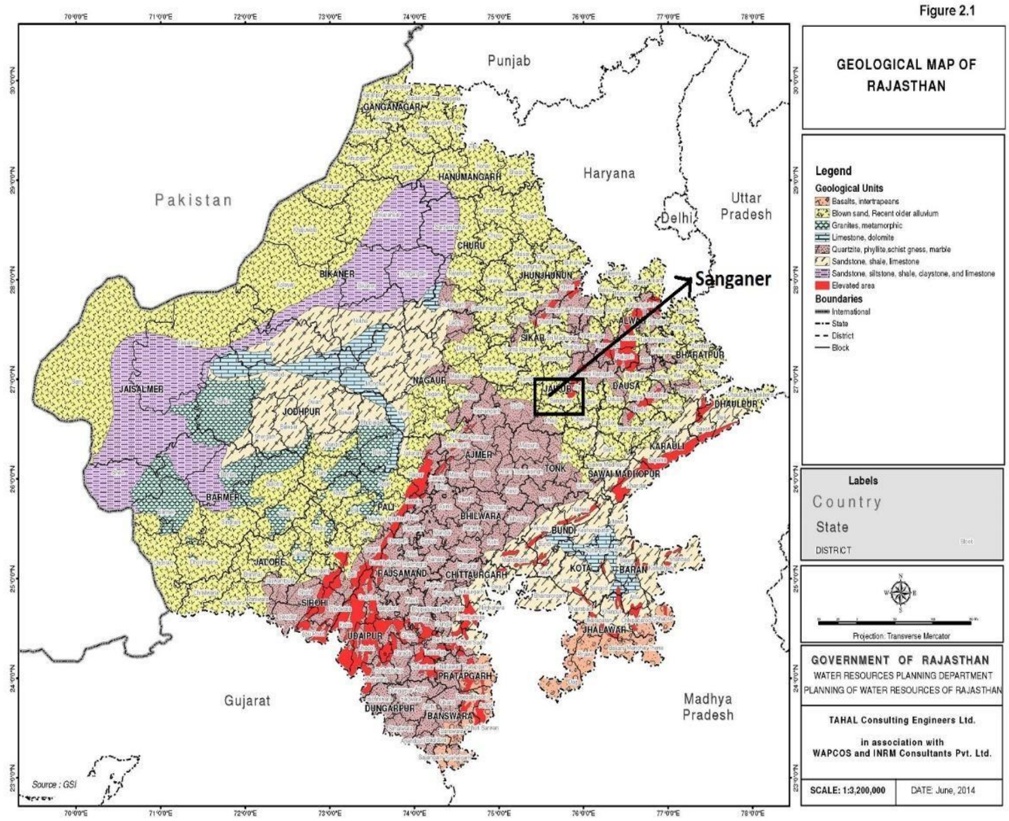


Figure 3.3 Geological map of the study area

In the greater part of the Jaipur district, alluvial deposits comprising of mainly fine sand and silt serve as potential aquifers in addition to gravel zones as encountered at Sanganer region. A map depicting hydrogeological features is presented in Figure 3.4.

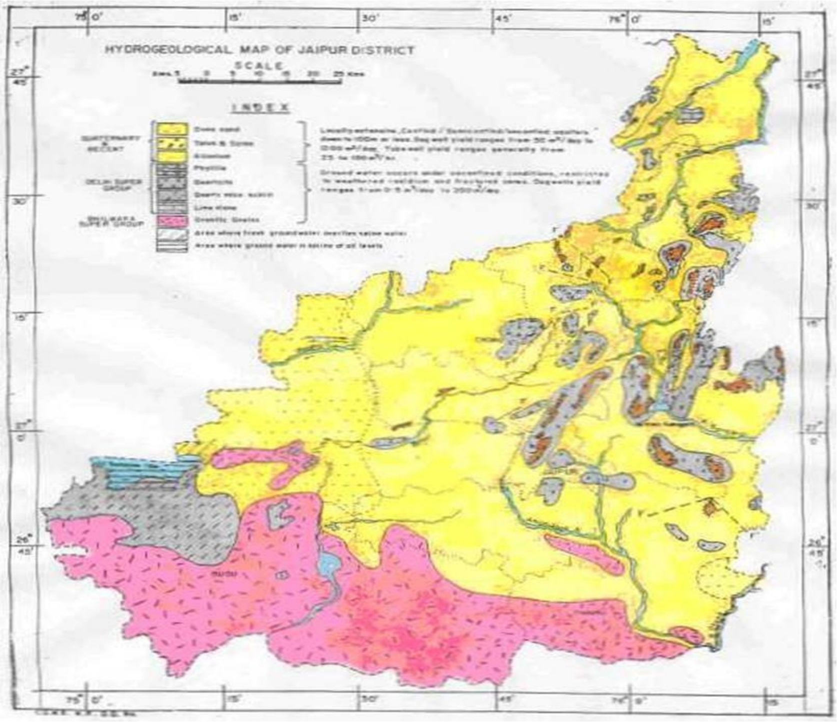


Figure 3.4 Hydrogeological Map of study area

3.3 Data Collection for Groundwater Flow Model

It is obvious that the field data can be obtained from various sources such as from maps, cross-sections, well-logs, borings, data on precipitation, etc. Developments in geographical information systems (GIS) and data processing are great potentials in the process of data gathering. Regrettably, in many of the cases sufficiently reliable data are still scarce because data collection is expensive and labor-intensive. The availability of enough reliable data is obviously, even more, pinching for three-dimensional models than for two-dimensional models. As such, the application of three-dimensional computer codes is restricted seriously.

The availability of data is important for the conceptual construction of the model as well as the calibration of the numerical model. Examples of data are rainfall data, subsoil parameters (e.g. the hydraulic conductivity, the exact position of aquitards, the effective porosity, the anisotropy, and the hydrodynamic dispersion), groundwater extraction rates, and salinity and piezometric head distributions as a function of space and time. Data are necessary to calibrate the applied model as accurately as possible. When the existing network of recording instruments should be augmented, the records will probably be too short to allow adequate calibration of the mathematical model.

Consequently, poor estimates will be given. Unfortunately, long time series are available only occasionally.

When data series are absent, the model data input should be filled by stochastic techniques to create data series with statistical characteristics identical to the original data series. Note that stochastic techniques do not account for changes in the hydrologic system, such as climate changes over long periods of time (for generating precipitation data).

Various type of surface and subsurface data are required as listed below-

Surface data

Surface data includes topography, surface water levels, the amount of recharge and pumping rates.

Subsurface data

Subsurface data required for groundwater modeling includes soil/aquifer properties and stratigraphy or lithology.

3.3.1 Boreholes data

The main source of boreholes data used for the purpose of this work was data from the Central Groundwater Board (CGWB). Boreholes data of Jaipur district was obtained from CGWB, Jaipur. The data includes exploratory tube wells and piezometer drilling data of CGWB, which contains information on coordinates, formations tapped, static water level, type of well, well yield, depth of well drilled, aquifer parameters such as storativity and transmissivity and the aquifers and chemical quality of groundwater. Data also includes information on depth of exploratory tube wells and piezometers drilled by State Groundwater Department, their water yielding capacity, drawdown, and chemical quality, etc. Well, data were rearranged into the main databases.

3.3.2 Pumping Wells

Pumping wells data was not available. Boreholes containing discharge was considered as pumping well. Only nine such boreholes were available and calibration over such data available might not provide reasonable results. Therefore, some more wells were also considered and thus a total of 125 wells considered as pumping well. The discharge data of such wells were derived from gross annual groundwater draft data. The data of discharge, available in mcm, was converted in m/day for three stress period of Ravi, Kharif, and Summer. Pumping is generally done for an average of 2000 hours in a year. Pumping schedule was considered 50% in Rabi season, 30% for Kharif and 20% for the summer season as recommended by NABARD.

3.3.3 Observation Wells

Groundwater level data as depth to water below the ground level for the period 1980 to 2015 were collected from CGWB. The data was not consistent with time. Rich data was available from 1996 but still missing some values in between.

A significant part of the data obtained were in the form of hard copy. Efforts, of many weeks, were put into typing the data and to bring them into workable spreadsheets. Other data sets obtained in soft copy were also in different formats and obtained at intervals during study. All the data collected were carefully reviewed and grouped into "Excel" format for the use in the preparation of input data to be used in groundwater modeling.

3.4 Data Validation

Special emphasis was given to data validation. During the screening of the raw data, mismatches, missing data and several inaccuracies in various raw files were found. The different data validation processes were applied so as to start the assignment. This include:

1. Errors in well code include missing well code.
2. Completion of missing data, such as formations and location errors.
3. Filling of missing reduced-level: This mainly included the determination of RL values, modified upto two digits after the decimal point.

No value was removed from the database even after corrections were made. To be able to recover initial or missing values, the original data sets were saved to the next new columns which were added to the spreadsheets that include the missing or corrected value. The same method was adopted for updating of CGWB databases, also.

CHAPTER 4 METHODOLOGY

Understanding of development of a model may be divided into steps. The flow chart given in the figure shows the major steps in modeling, including the uncertainties analysis that facilitates in defining the limitations of how a model can be applied.

Visual modflow MODFLOW is a computer program originally developed by the U.S. Geological Survey that simulates three-dimensional groundwater flow employing a finite difference technique for the solution of the governing flow equations [Harbaugh et al., 2000]. MODFLOW solves both confined and unconfined flow equations in an irregularly formed flow system to simulate the behavior of groundwater flow systems under many types of natural and artificial stresses. The flow region is divided into blocks within which the medium properties are assumed to be uniform.

In plan view, the blocks are made of a grid of mutually perpendicular lines that may be variably spaced. Model layers can have varying thickness. A flow equation is written for each cell. Many solvers are provided for determination the resulting matrix problem. The user can select the most effective problem solver for the particular problem. Cumulative-volume balances and Flow-rate from inflow and outflow are computed for each time step. Flow from external stresses, such as recharge, flow to wells, evapotranspiration, flow through riverbeds and flow to drains can be simulated.

Transmissivities and hydraulic conductivities for any layer may differ spatially and be anisotropic, and therefore the storage coefficient may be heterogeneous. Specified flux, specified head, and head-dependent flux boundaries can be simulated.

Groundwater models can be divided into two categories: groundwater flow models, that solve for the distribution of head in a domain. Solute transport models, that solve for the concentration of solute as affected by dispersion, advection, and chemical reactions. The groundwater flow and transport of contaminant in an aquifer can be simulated by numerical (Poeter and Hill 1997) models that involves:

1. Defining the study area and required data
2. Defining the boundary conditions
3. Development of initial model of the site of interest

4. Choosing the governing equations (or code) describing the physical problem
5. Calibration of the numerical model
6. Validation of the numerical model
7. Application of the numerical model

The whole process of groundwater flow modeling can be better represented as a flow chart given below-

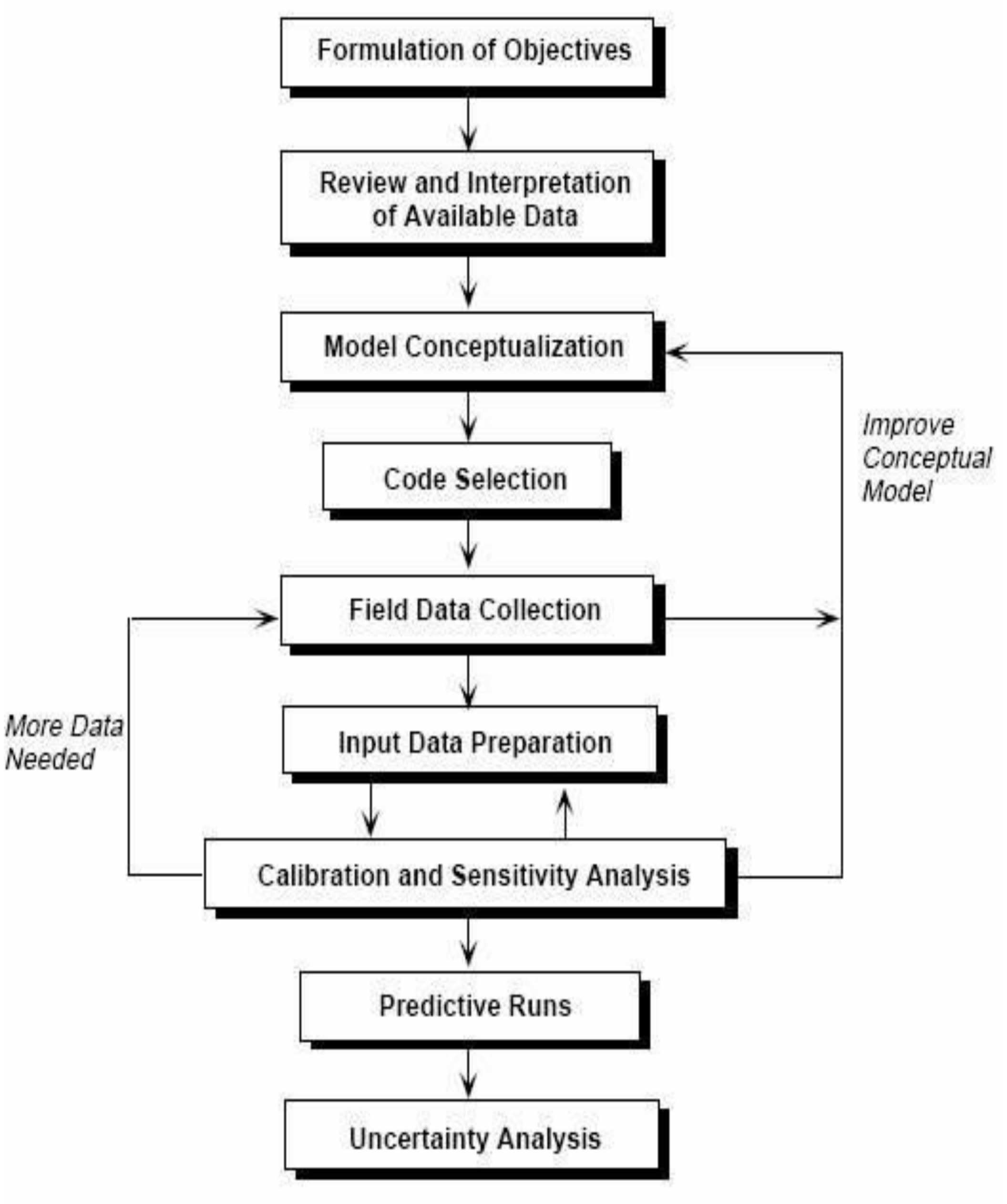


Figure 4.1 Hydrogeological Map of study area

4.1 Modeling Approach

4.1.1 Groundwater Flow Model Setup and Execution

The groundwater flow equations comprising the groundwater flow model of this study were solved using the model code MODFLOW-2000 that is based on the FDM. The groundwater flow model was set up as a one-layered, regional steady-state model. The purpose of the model was to simulate groundwater flow in the unconfined aquifer and thereby calculate the groundwater fluxes and distribution of water table elevations. The extent of the modeling domain and the extent of the study area boundaries were same as shown in Figure. The model boundaries cover the entire area of interest and coincides with hydrological boundaries, e.g. watershed boundaries, lake, and sea.

The modeling domain was discretized into equal-sized 80×80 m finite- difference grid cells. Besides, more than 100 borehole logs were processed to determine the depth to the impermeable layer, which was interpolated to obtain the surface representing the bottom surface of the model layer. The top surface of the model was obtained directly from interpolating elevation values of 283 points in the region obtained from google earth. Details about the spatial discretization and the boundary conditions of the model are discussed in the next chapter. Other secondary model input parameters were the extraction rates of major agricultural, domestic and industrial water supply wells in the study area.

4.1.2 Model Calibration and Verification

Vertical groundwater recharges from precipitation and hydraulic conductivity and were the key parameters of the model. During this study, recharge was taken as net recharge, i.e. the particular portion of water reaching the water table when being withdrawn by plants within the root zone, as a result of that eliminating the requirement for the evapotranspiration parameter. These model parameters were handled as calibration parameters, which were varied within a plausible range of values while performing the calibration process. Calibration of the model was carried out automatically using the parameter estimation code PEST (Doherty, 2004). The purpose of the calibration process was to rectify the calibration parameters in a systematic manner to get a satisfactory match between observed water table elevations and the calculated values by the model. The model was pre-calibrated manually on a trial-anderror basis before the automatic calibration procedure with PEST was taken place.

Hence, an optimum starting point was attained for the automatic calibration, which resulted in a more strong performance of the parameter estimation process with PEST.

4.2 Spatial Discretization

The model domain was divided into some discrete finite-difference grids. An 80×80 m, cell-centered finite-difference mesh grid cells was used. In the vertical dimension, the model was single-layered, and the top elevation surface of the model represented the ground surface of the study area. Using interpolated data of elevation points, obtained from google earth, top elevations for each grid cell was defined. The unconfined aquifer with the study area boundaries was modeled as two layers with the MODFLOW. The bottom elevations were ascertained by evaluating the stratigraphic information in well logs; the depth at each well log location to the impermeable layer below the unconfined aquifer was interpolated on a surface, which was set as the bottom elevation surface of the model layer. Total aquifer depth was taken as 125 m. The maximum and minimum elevation of the study area were 436m. And 180m. respectively. Model description of layers is shown below.

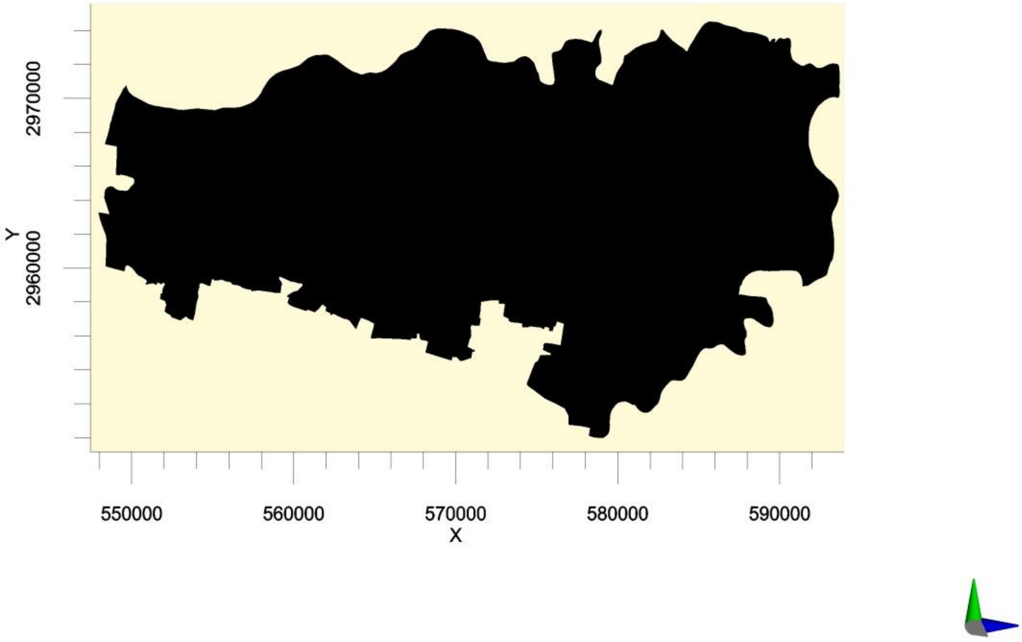


Figure 4.1 Presentation of study area in model domain

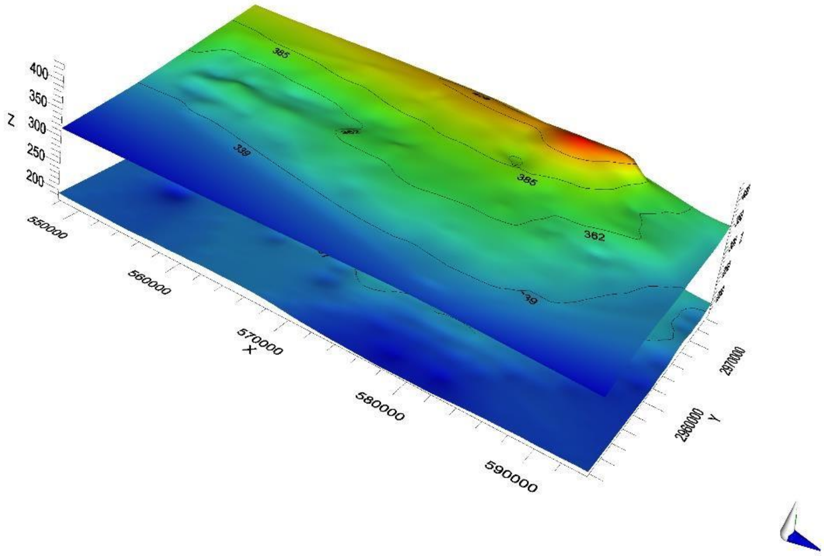


Figure 4.2 Layers view showing thickness of model layers

4.3 Model Parameters and Input Data

4.3.1 Hydraulic Conductivity

One of the key model parameters was the hydraulic conductivity. It is a measurable property of any aquifer system. Because of the lack of sufficient measurements for the study area, it was taken as an uncertain parameter and determine using the calibration process. Since the groundwater flow model was single-layered. The model domain was divided into two hydraulic conductivity zones. The aquifers were of formations with similar properties. Therefore, zone was considered uniform hydraulic conductivity values. Initial hydraulic conductivity values were taken from literature according to aquifer properties and available statistics. These values were varied within a pre-defined plausible range during the calibration process. Initial hydraulic conductivity values and the calibration ranges are given in Table.

Horizontal hydraulic conductivity of layer was assigned as 10 m/day. The value for K_y for both layers was remained same as K_x.The value for K_z was assumed 1/10 times of K_x for the single layered aquifer.

Table 4.2 Hydraulic conductivity initial values

Hydraulic conductivity zone	Initial Value (m/d)	Lower Bound (m/d)	Upper Bound (m/d)
Kx-1	10	1	100
Ky-1	10	0.01	10
Kz-1	0.1	0.001	1

4.3.2 Pumping Wells

Pumping wells data were not available. Hence boreholes containing exploratory wells and Piezometer well, obtained from CGWB, were assumed to be acted as pumping well. Only nine wells were available. T. The locations of pumping wells are shown in the following figure.

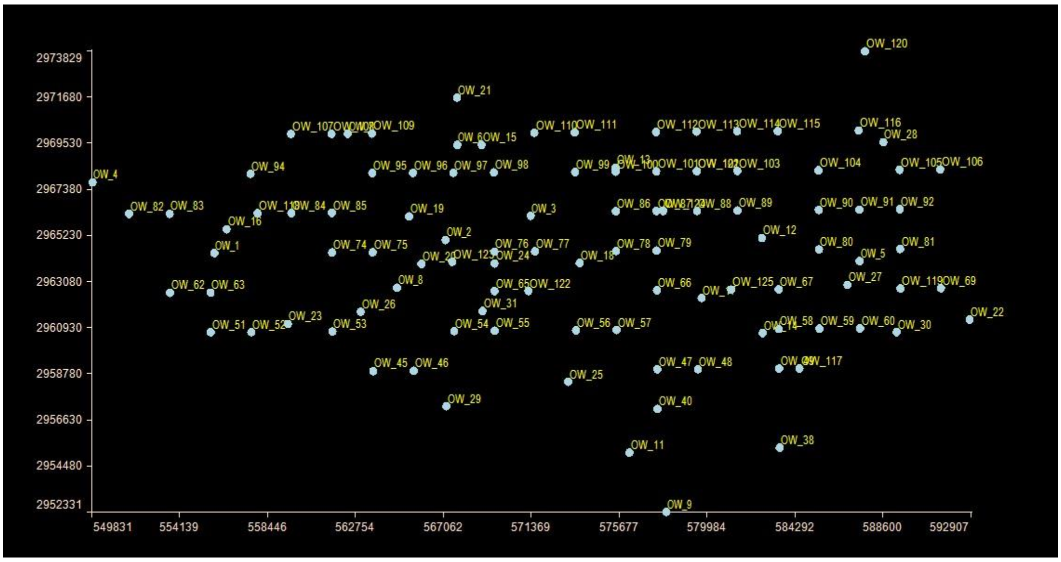


Figure 4.3 Pumping wells location in model domain

4.3.3 Observation wells

Total seven observation wells used for the calibration of the heads in observation wells in the study area. The locations of observation wells are shown in the following figure

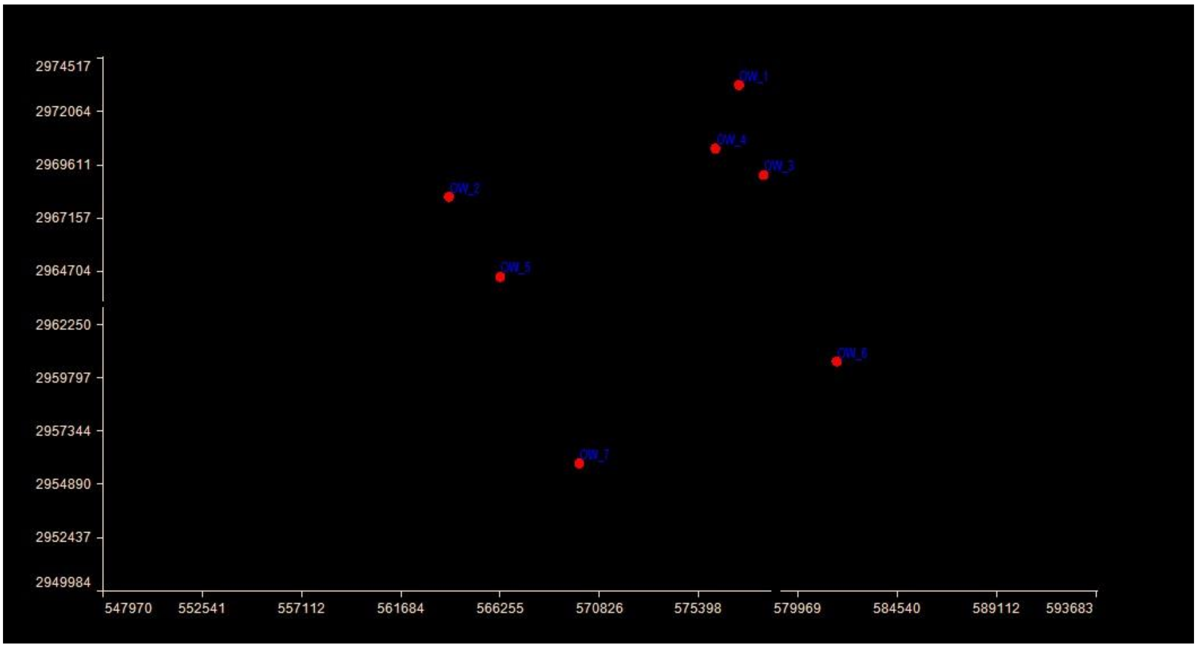


Figure 4.4 Observation wells location in model domain

4.4 Boundary Conditions

Boundaries of groundwater flow model can be defined as hydrological and geological features that affect the groundwater flow pattern such as surface water features, watershed boundaries, faults, outcrops and water table divides. Model boundaries and the types of boundary conditions are shown in Figure.

The boundaries of the model coincided mostly with the boundaries of the Sanganer sub-basin with the exception in the west and the east of the model domain towards where two ephemeral rivers were flowing. Only one type of boundary conditions, namely constant-head (Dirichlet), was applied in this study. Boundary condition used in the model is discussed in the following sections.

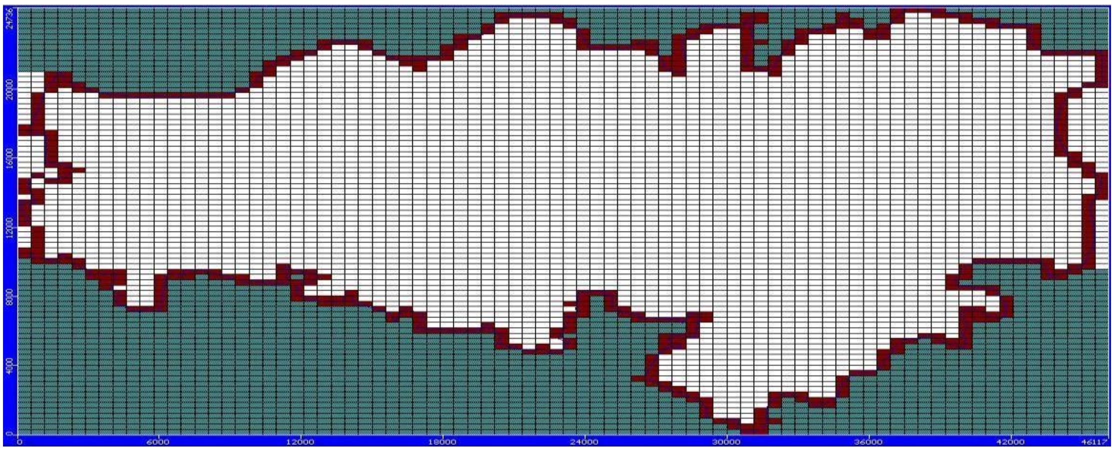


Figure 4.5 Boundary conditions used in the model

4.4.1 Constant-Head Boundaries

Constant head boundaries were selected to serve as a boundary condition for the model. The boundary of the study area was considered as constant head boundary. Therefore, model boundary was divided into five constant head boundaries. Data for each constant head boundary was derived from the interpolation of water levels of observation wells for four different measurement of water levels taken in a year. Two of them were at the east and west boundary of the area, one was at the North and one was at the South of the model area.

4.4.2 Recharge

Recharge was estimated as 10% of total annual rainfall as provided in the groundwater assessment report (as on 30 March, 2011). Consequently, recharge was derived as 10% of annual average rainfall for each year.

CHAPTER 5 RESULTS AND DISCUSSION

5.1 Groundwater Modeling Results Before Calibration

In this section, the initial groundwater flow modeling results using uncalibrated model parameters are presented. Calculated water table levels were compared with measurements. A direct comparison of calculated values obtained from the uncalibrated model with observed values is illustrated in Figure 5.3. The straight line in the graph indicates a perfect fit of modeled values to measurements. Statistics and the summary of model performance criteria are summarized in Table 5.1.

Table 5.1 Statistics of the initial simulation

Criteria	**Result**
Residual Mean (m)	7.764
Root mean squared (m)	22.126
Sum of residual squares (m^2)	3426.9
Abs. Res. Mean (m)	17.454
Min. Residual (m)	0.884
Max. Residual (m)	41.973
Normalized RMS (m)	30.14
Std. Error of the Estimate (m)	8.458

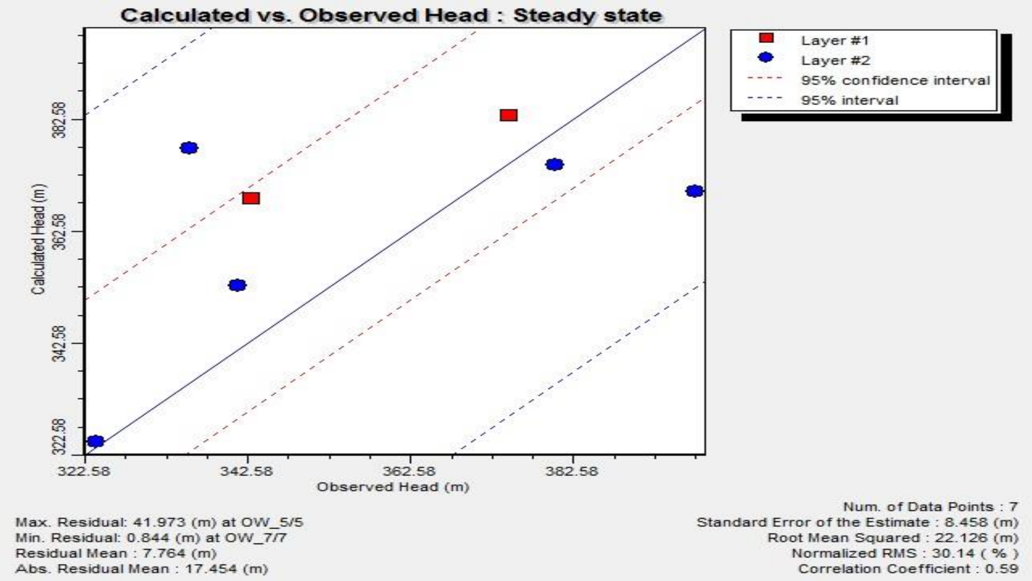


Figure 5.1 Comparison of modeled with measured head values for the uncalibrated model

5.2 Calibrated Groundwater Flow Modeling Results

Calibrated model parameters are presented in Tables. Calibrated hydraulic conductivity values remained within defined calibration boundaries, which represented the alluvium formation. The hydraulic conductivity value was decreased to the lowest possible value of 0.1 m/d. The recharge rate for the zone was decreased to the multiplier of 0.94 of the calibration range.

Model calibration statistics and performance criteria are given in Table. The calibrated groundwater flow model yielded satisfactory calibration statistics; residuals were distributed randomly around zero (Figure), and the residual mean, the absolute residual and the root mean squared residual (RMSD) were determined as 0.6, 11.0 and 16.4 m, respectively. The RMSD value was only 5% of the range of measured values. Overall, these values were acceptable within predefined model performance limits.

Table 5.2 Hydraulic Conductivity optimization results

Zone	Calibration Interval	Initial Value	Calibrated Value
	Hydraulic Conductivity (m/d)		
Kx-1	1 ~ 100	10	16.8
Ky-1	0.01~10	10	10
Kz-1	0.001 ~ 1	0.1	0.1
Recharge Multiplier	0 ~ 1.00E29	1	0.94
S_s	1.00E-15~ 1.00E29	3	1.00E-05
S_y	1.00E-15 ~ 1.00E-05	0.2	0.2

Model performance criteria are project-specific. There are no universal criteria. However, there are certain guidelines to get a successfully calibrate a groundwater flow model. For the evaluation, the model performance for this study, the guidelines published by ASTM (2008) was taken as a basis. Furthermore, it is evident from the figure that the model generated comparable head values for most of the observation points; however, it was less successful for some of the study areas. The linear correlation coefficient (Zheng & Bennett, 2002) was calculated as 0.9125, which indicates positively correlated observed and calculated head values. Better calibrated models tend to have linear regression coefficients close to 1.

Table 5.3 Statistics for the uncalibrated and the final calibrated model

Criteria	**Uncalibrated**	**Calibrated model**
Residual Mean (m)	7.764	-2.7
Root Mean Squared (m)	22.126	16.40
Sum of residual squares (m^2)	3426.9	1073.4
Abs. Res. Mean (m)	17.454	8.576
Min. Residual (m)	0.844	-0.312
Max. Residual (m)	41.973	-28.007
Normalized RMS (%)	30.14	16.868
Std. Error of the Estimate (m)	8.458	4.934

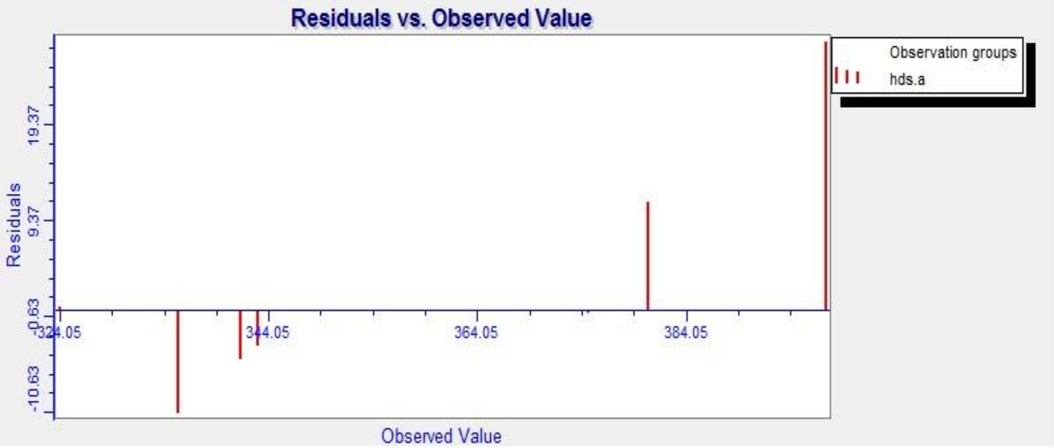
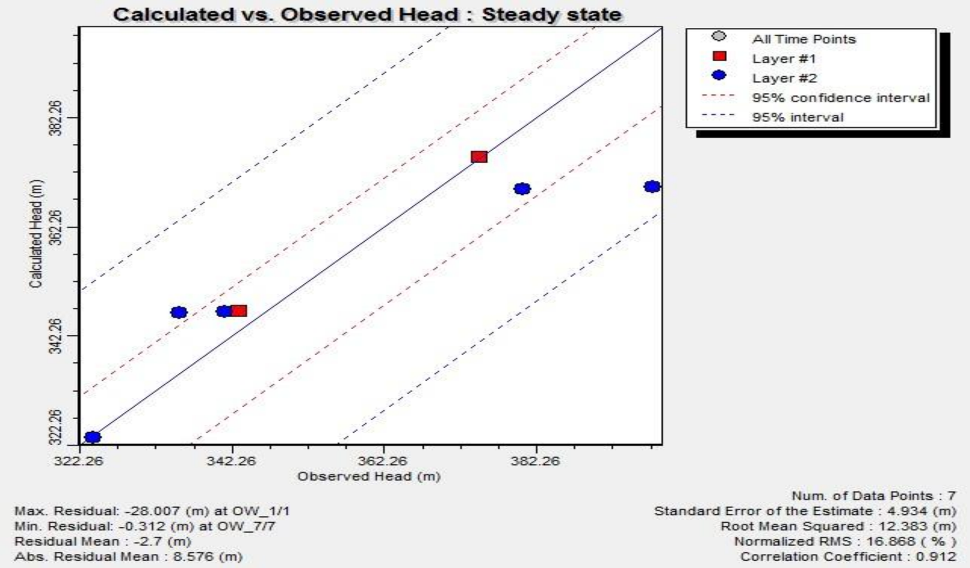


Figure 5.2 Comparison of residuals with observed values for the calibrated model



Num. of Data Points : 7
Standard Error of the Estimate : 4.934 (m)
Root Mean Squared : 12.383 (m)
Normalized RMS : 16.868 (%)
Correlation Coefficient : 0.912

Max. Residual: -28.007 (m) at OW_1/1
Min. Residual: -0.312 (m) at OW_7/7
Residual Mean : -2.7 (m)
Abs. Residual Mean : 8.576 (m)

Figure 5.3 Comparison of modeled with measured head values for the calibrated model

Calculated water table elevations and groundwater flow directions are shown in Figure. Water budget results of the model, shown in Table, revealed that groundwater recharge comprised about 41% of the total water input for the entire study area. Recharge was the second largest component in the budget after leakage from the river into the subsurface.

Table 5.4 Water budget of the calibrated model

Flow rate (m^3/d)		**Flow rate (m^3/d)**	
IN		**OUT**	
Constant Head	92546	Constant Head	314500
Recharge	130000	Recharge	0
Wells	91961	Wells	0
Total In	**314507**	**Total Out**	**314500**

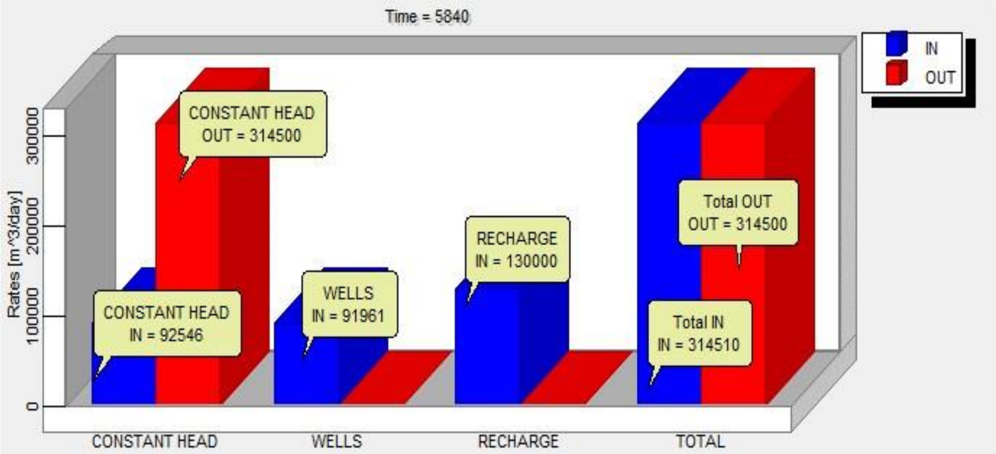


Figure 5.4 Water budget of the calibrated model

Examining the water table contour map (Figure 6.7) reveals other interesting results; a groundwater mound is formed near Jhalana, where flow diverges in several directions.

Furthermore, the hydraulic gradient in the urban part of the study area (north) is relatively steep, in particular in the northwest, where elevated groundwater flow velocities are expected to occur. This result can be confirmed with the rough topography and steep terrain in that region. Flow in the Sanganer alluvial basin is generally to the south as shown in figure 5.6.

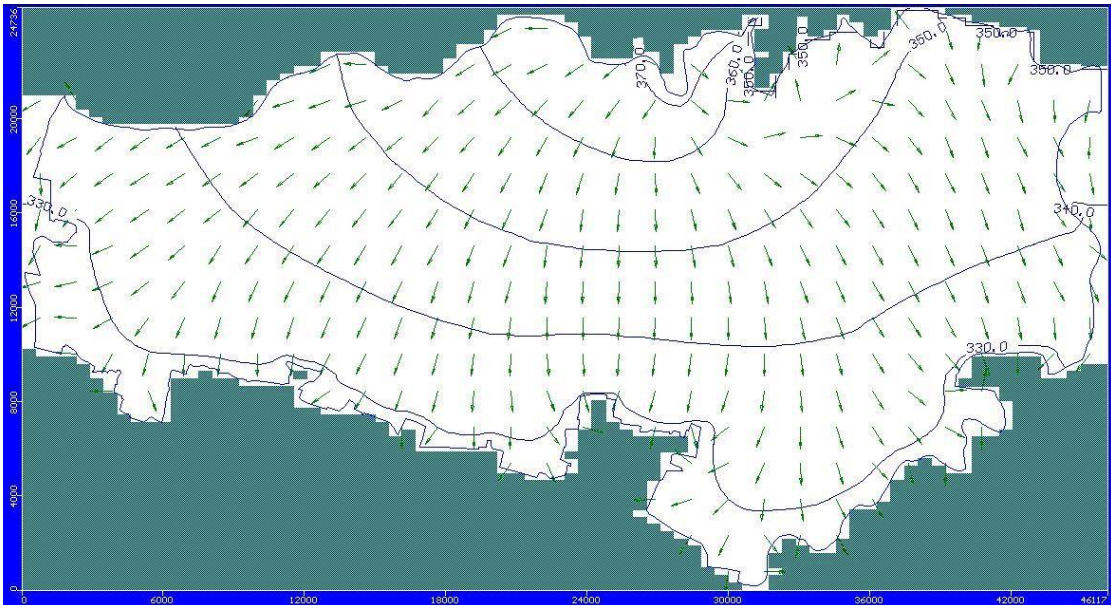


Figure 5.5 water table elevation contours and groundwater flow directions

5.2.1 Mass Balance

A mass balance was performed, and used along with Darcy's law, to arrive at the transient groundwater flow equation. It is simply a statement of accounting, which for a given control volume, aside from sources or sinks mass cannot be created or destroyed. The conservation of mass states that, for a given increment of time (Δt), the difference between the mass flowing in across the boundaries, the mass flowing out across the boundaries, and the sources within the volume, is the change in storage. Mass balance for the simulated model is presented in the following figure.

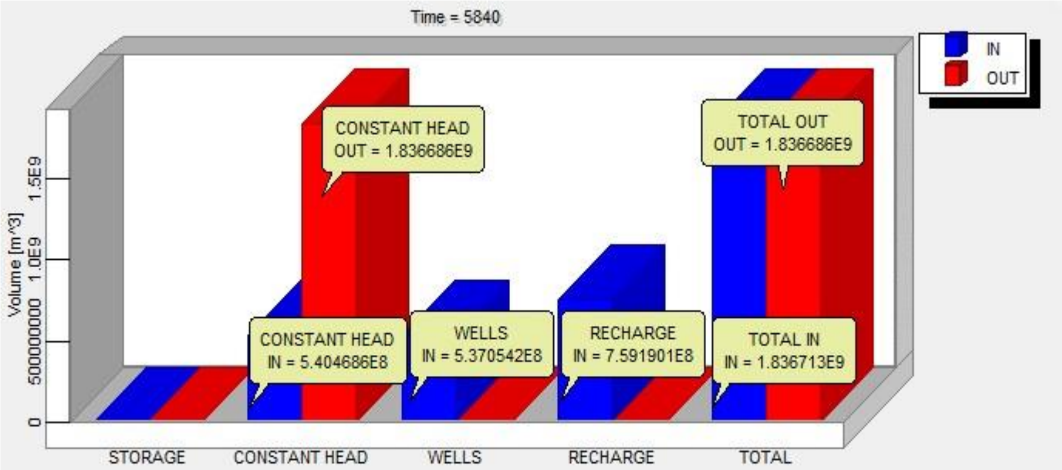


Figure 5.6 Mass balance before calibration

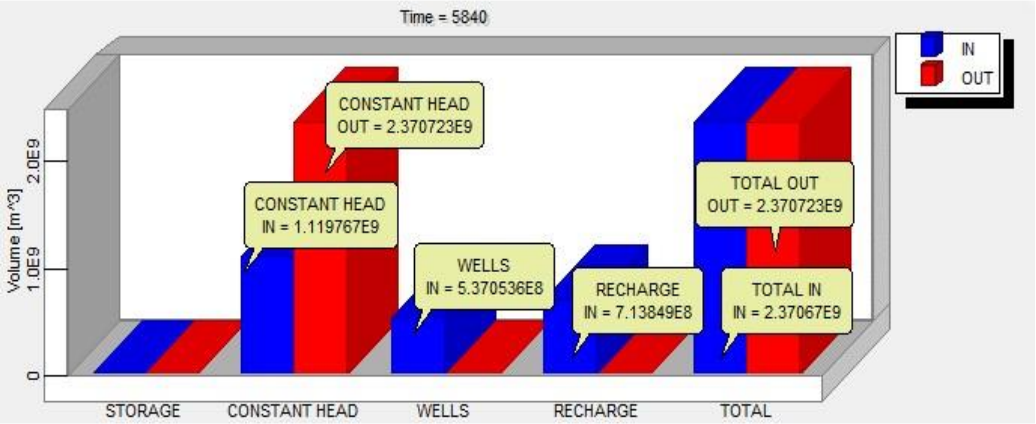


Figure 5.7 Mass balance After calibration

5.2.2 Sensitivity Analysis

Sensitivity analysis for the parameter selected for optimization on the iteration numbers is shown in the following figure. Total nine parameters were selected for optimization including hydraulic conductivities, storage coefficient, recharge and specific yield.

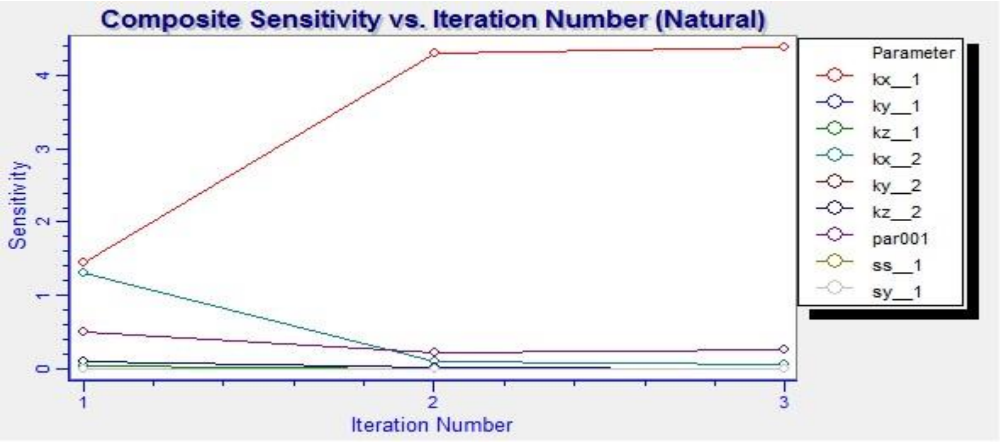


Figure 5.8 Composite sensitivity vs iteration number

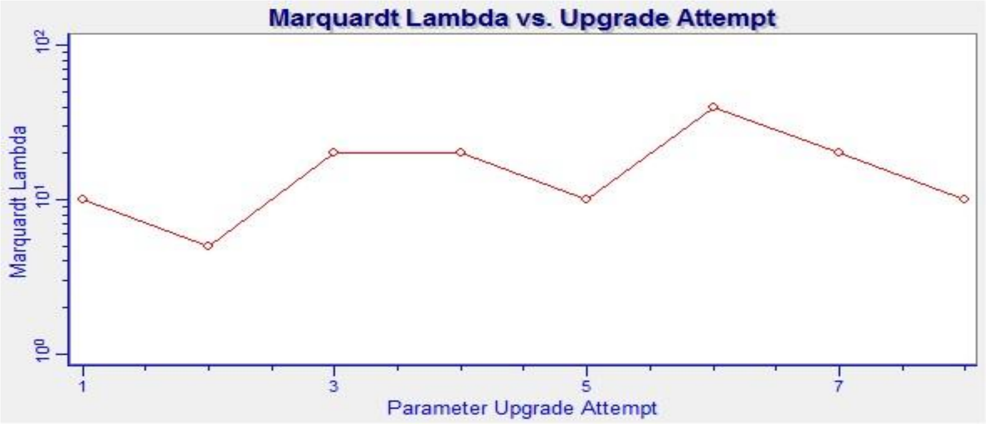


Figure 5.9 Lambda vs Parameter Upgrade Attempt

PEST provides a set of parameter values that result in a minimum objective function based on the parameters chosen, and the objective function defined. The objective function with the iteration number shown in the figure below.

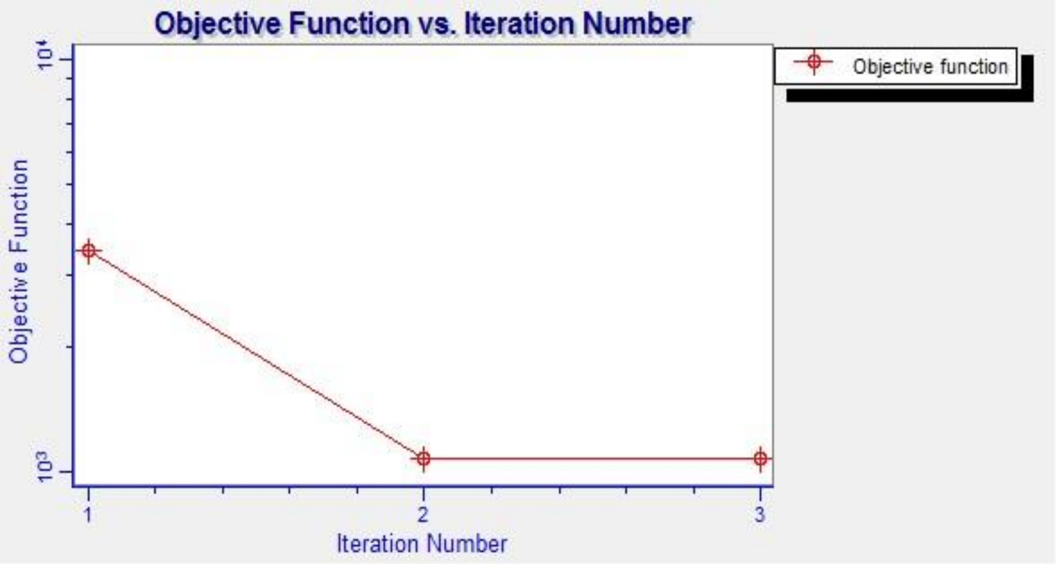


Figure 5.10 Objective function vs iteration number

5.3 Model Verification

The model was verified against the head measurements. Groundwater levels, at 7 wells after calibration, used as targets in the verification process. Recharge rates and boundary conditions were modified accordingly to match the conditions of the study area. The model was run once using the modified model parameters and the steadystate simulation for summer conditions was obtained. The model was verified for four years from 2011 to 2015.

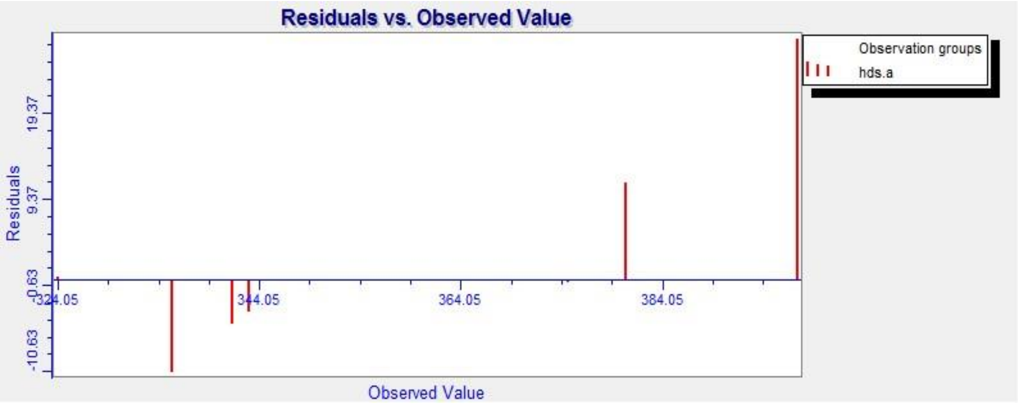


Figure 5.11 Comparison of residuals with observed values for the calibrated model

The model performed satisfactorily but statistics indicated poorer performance compared to the calibrated model. But most criteria were within acceptable limits.

Table 5.5 Model performance statistics of the verification run

Criteria	**Result**
Residual Mean (m)	-0.27
Res. Std. Dev. (RMSD) (m)	15.40
Sum of residual squares (m^2)	1005.07
Abs. Res. Mean (m)	17.15
Min. Residual (m)	-0.65
Max. Residual (m)	-29.02
Std. error in estimate (%)	4.29

The linear correlation coefficient was calculated as 0.942, slightly lower than the coefficient for the calibrated model. The water budget for the verified model is summarized in Table 5.6. In comparison to the calibrated model, total groundwater recharge decreased.

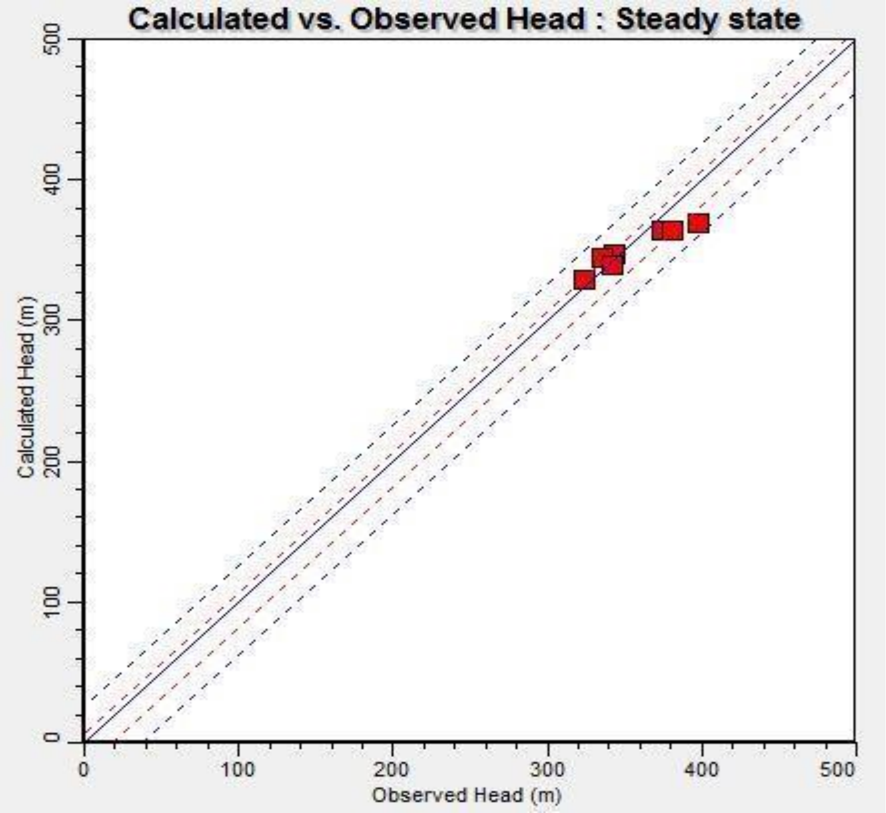


Figure 5.12 Comparison of modeled with measured head values for the verified mode

Table 5.6 Water budget of the calibrated model

Flow rate (m^3/d)		Flow rate (m^3/d)	
IN		**OUT**	
Constant Head	92750	Constant Head	313920
Recharge	129923	Recharge	0
Wells	91987	Wells	750.31
Total In	**314660**	**Total Out**	**314670.31**

5.3 General Discussion and Shortcomings

A modeling study of groundwater flow for the Sanganer sub-basin, the southern part of the Jaipur district, which was categorized in one of the "over-drafted" groundwater zones as found by CGWB, was presented. A comprehensive model was developed to estimate groundwater heads, water table elevations, groundwater flow directions, seasonal decline in groundwater levels, and water budgets were determined with the developed model over a single stress period of twenty years. Water budget results of the model revealed that groundwater recharge comprised about 32% of the total water input for the entire study area. Recharge was the second largest component in the budget after leakage from rivers into the subsurface. However, to better evaluate the vulnerability of water resources in the area to diffuse pollution, a contaminant transport modeling study that is based on the presented flow model may be warranted. Therefore, contaminant transport model could be run within the basin boundary.

Furthermore, it was demonstrated with this study that a robust modeling approach can be taken by combining results of a lumped, water budget based precipitation-runoff model with a distributed groundwater flow model. Groundwater recharge in groundwater flow models is often one of the most uncertain model parameters since it is almost impossible to measure it directly in the field for large watersheds. Nevertheless, it is important to quantify recharge, in particular somehow for diffused pollution vulnerability studies.

Some shortcomings and limitations of the developed groundwater flow model are discussed in the following section:

1. Water levels of observation well were missing for several years. In the others words, water levels data was not consistent.

2. It is conceivable that the well heads did not reflect the true depth to the water table because the monitoring wells were actually irrigation wells long well screens. It is likely that this fact affected the performance of the model.
3. The monitoring wells were screened over several aquifer units and sometimes over units with different properties. Therefore, the representativeness of the well measurements is somewhat questionable. Nevertheless, conceptually the groundwater flow model would not be different if perfect measurements would be available, only the accuracy of the model would be better.
4. Errors in SRTM data are likely to have affected the calibration of the model because they were used to determine water table elevations.
5. Observation wells are sparse in most of the parts of the study area. Accessible monitoring wells were unavailable in particular in mountainous parts of the study area or in areas where groundwater was either deep or not available.
6. The groundwater withdrawal amount in the study area could only be grossly estimated. The actual amount is unknown and hard to quantify since numerous irrigation wells exist in the fertile plains. Many wells are not licensed and are not accounted for by the water authorities. Therefore, the total groundwater withdrawal is expected to be much higher. It is possible to enhance the groundwater flow model through more additions of pumping wells in the study area.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATION

6.1 Conclusions

It was concluded that the performance of the model was satisfactory in producing groundwater head distribution based on the current data in the steady state. The choice of the grid size affects the modeling results. On the other hand, a finer grid will exaggerate the variation in the topography while interpolating the elevation values for creating the model layers.

This study clearly indicated the need for accurate and reliable data for both creating and calibrating a groundwater model. It also recognizes some shortcomings because of the data sparsity. Therefore, Improvements are highly recommended for modeling a significantly varied topography of Sanganer.

The study also reveals that geological, hydrogeological and geophysical surveys are necessary to get data for constructing 3D hydrogeological framework models. Continuous measurements of water budget components and groundwater levels will build up databases required for analysis of regional flow systems and construction of regional transient groundwater models. The model can be used to simulate impacts of human activities on groundwater flow systems, to formulate sustainable groundwater resources development scenarios, and to communicate the results to public and decision-makers.

6.2 Recommendation for Future Work

The presented groundwater flow model can be undoubtedly improved. Also, the purpose and thereby the application of the model can be re-defined. Recommendations for future studies can be listed as follows:

1. Recharge rate used in the model can be modified to accommodate climate change scenarios eventually to assess the effects of climate change on water resources in the study area
2. Investigate more observation wells to improve the calibration of the model
3. Obtain more sets of monitoring data to improve the overall reliability and usability of the model
4. Inclusion of more pumping wells to account for a more accurate groundwater withdrawal

5. Enhance the calibration of the groundwater flow model by including the calibration to spring flow measurements
6. Revisit the parameters and formulations of groundwater flow model for higher model accuracy
7. Conduct particle-tracking simulation to support the interpretation of modeling results
8. The model results can be used as input for contaminant transport modeling studies to evaluate the effects of different land-use practices or diffuse pollution scenarios.

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APPENDIX I

Recharge Data (mm/year) for 20 years from 1996 to 2015

Year	Avg. Annual Rainfall	Recharge
1996	706.5	70.65
1997	808	80.8
1998	619	61.9
1999	316.1	31.61
2000	455	45.5
2001	582	58.2
2002	237	23.7
2003	563	56.3
2004	805	80.5
2005	392	39.2
2006	407	40.7
2007	553.3	55.33
2008	572	57.2
2009	377	37.7
2010	750	75
2011	646	64.6
2012	907	90.7
2013	757	75.7
2014	606.7	60.67
2015	512	51.2

APPENDIX II

Boreholes features of the study area (Data collected from CGWB)

Serial no	District	Taluka	Village	Well.No	Type of well	Easting	Northing	RL of Surface Elevation m (AMSL)	Total depth (m)	Waterlevel (M) BGL	RL of Water level (m) AMSL
1	Jaipur	Sanganer	Dhami Kalan	4	Piezometer	5,57,794.62	29,66,271.75	353	59	12.4	340.6
2	Jaipur	Sanganer	Mohana	4	Piezometer	5,66,327.45	29,64,551.96	356	63.01	22.65	333.35
3	Jaipur	Sanganer	Nowata	4	Piezometer	5,66,724.33	29,63,956.64	368	48	9.39	358.61
4	Jaipur	Sanganer	Mohana	15	EW	5,71,222.25	29,62,633.72	367	65.6	12.65	354.35
5	Jaipur	Sanganer	Sanganer	14	EW	5,77,836.85	29,66,470.19	384	65.3	7.695	376.305
6	Jaipur	Sanganer	Jawahar Nagar	16	EW	5,79,490.50	29,68,388.42	391	42	36.5	354.5
7	Jaipur	Sanganer	Sukhpuria	17	EW	5,81,078.00	29,62,633.72	297	71.38	20.19	276.81
8	Jaipur	Sanganer	Belwa	16	EW	5,84,517.59	29,59,127.99	350	36.02	8.635	341.365
9	Jaipur	Sanganer	Jamroli	20	EW	5,87,758.74	29,73,878.54	375	37.62	7.492	367.508
10	Jaipur	Sanganer	Goner	17	EW	5,89,544.69	29,62,699.87	345	52.21	5.139	339.861