CHAPTER-V
5. GROUNDWATER FLOW MODELING

5.1 Introduction

Groundwater models are mathematical and digital tools of analyzing and predicting the behaviour of aquifer systems on local and regional scale, under varying geological environments (Balasubramanian 2001). Models can be used in an interpretative sense to gain insight into the controlling parameters in a site-specific setting or a framework for assembling and organizing field data and formulations of ideas about system dynamics. Models are used to help in establishing locations and characteristics of aquifer boundaries and assess the quantity of water within the system and the amount of recharge to the aquifer (Anderson and Woessner 2002).

Mathematical models provide a quantitative framework for analysing data from monitoring and assess quantitatively responses of the groundwater systems subjected to external stresses. Over the last four decades there has been a continuous improvement in the development of numerical groundwater models (Mohan 2001).

Numerical modeling employs approximate methods to solve the partial differential equation (PDE), which describe the flow in porous medium. The emphasis is not given on obtaining an exact solution rather a reasonable approximate solution is preferred. A computer programme or code solves a set of algebraic equations generated by approximating the partial differential equations that forms the mathematical model. The hydraulic head is obtained from the solution of three dimensioned groundwater flow equation through MODFLOW software (McDonald & Harbaugh 1988).

Mathematical modeling involves four basic steps namely (i) formulation, (ii) approximation and transformation (iii) computation and (iv) application (Balasubramanian 2001).

**Formulation:** Formulation refers to the process of deriving or selecting the basic equation(s) governing the flow and solute transport of groundwater, with the domain specification and initial boundary conditions.

**Approximation:** Approximation refers to the selection of a numerical method which can be used to solve the system of algebraic equations. Finite Difference, Finite element and Integrated Finite-difference (IFD), methods are the widely used solution strategies for modeling the groundwater systems.

**Computation:** Computation is the most important step in the process of modeling. This part refers to the process of obtaining a solution to a large number of differential equations. This is done using a digital computer and a method of coding the steps, in a computer programming language.
Application: The application part of groundwater modeling includes calibration or history matching of the observed and simulated heads, sensitivity analysis and prediction, sensitivity tests are to show how the model reacts to various extreme values of transmissivity, storage coefficient and recharge and discharge volumes.

The aquifer modeling of alluvial aquifers of Ganga basin in western Uttar Pradesh had been carried out in krishni-Hindon interstream region (Gupta et al, 1979) and Daha region (Gupta et al, 1985). They have assessed the stream aquifer interaction as well as conjunctive use of surface water and groundwater in Daha region. The initiation of groundwater flow modeling studies in parts of central Ganga plain is carried out with dual objectives to understand the complex hydrodynamics of the flow regime and work out groundwater budget estimation including small components like subsurface horizontal flows.

The groundwater flow modeling study is undertaken with the objective to establish and quantify groundwater inflow and outflow to the area and thus to establish an effective and realistic groundwater budget. The realistic groundwater budget is essential for implementation of any groundwater management plan. Groundwater budget studies in alluvial areas often present unrealistic figure as various inflows and river-aquifer interaction is not carefully dealt with.

5.2 Finite Difference Approximation

In finite difference method (FDM), a continuous medium is replaced by a discrete set of points called nodes and various hydrogeological parameters are assigned to each of these nodes. Accordingly, difference operators defining the spatial-temporal relationships between various parameters replace the partial derivatives. A set of finite difference equation, one for each node is, thus obtained. In order to solve a finite difference equation, one has to start with the initial distribution of heads and computation of heads at the later time instants. This is an iterative process and fast converging iterative algorithms have been developed to solve the set of algebraic equation obtained through discretization of groundwater flow equation under non-equilibrium condition. The continuous model can be replaced with a set of discrete point arranged in a grid pattern. This pattern more often known as finite difference grid. The general flow equation for unsteady flow of groundwater in confined condition in the horizontal direction

\[ T_r \frac{\partial^2 h}{\partial x^2} + T_r \frac{\partial^2 h}{\partial y^2} = S_r \frac{\partial h}{\partial t} + q \]  

When eqn (1) is applied to an unconfined aquifer, the Dupuit assumptions are used: (1) flow lines are horizontal and equipotential lines are vertical and (2) the horizontal hydraulic gradient is equal to the slope of the free surface and is invariant with
depth. It is understood that $T_x = K_x h$ and $T_y = K_y h$, where $h$ is the elevation of water table above the bottom of the aquifer.

$$K_x \frac{\partial^2 h}{\partial x^2} + K_y \frac{\partial^2 h}{\partial y^2} + K_z \frac{\partial^2 h}{\partial z^2} = S_x \frac{\partial h}{\partial t} - R$$  \hspace{1cm} (2)

Where $K_x$, $K_y$, and $K_z$ are components of the hydraulic conductivity tensor. $S_x$ is the specific storage, $R$ is a general sink/source term that is intrinsically positive and defines the volume of inflow to the system per unit volume of aquifer per unit of time.

The flow of water in an aquifer can be mathematically described by equation. This is the partial difference equation in which the head $h$, is described in terms of variables, $x, y$, and $t$. They are solved by means of mathematical model consisting of the applicable governing flow equation, equation describing the hydraulic head at each of the aquifer, and equation describing the initial conditions of head in the aquifer. Finite difference method for solving partial difference equation is much-agreed subject. With the development of high-speed computers, finite difference method for solving partial difference equation can be operated to solve problems in subsurface hydrology.

The basic idea of these methods is to replace derivatives at a point by ratios of the changes in appropriate variable over a small but finite interval. Thus

$$\frac{d\Phi}{dx} = \frac{Lt}{\Delta x} \left( \frac{\Delta \Phi}{\Delta x} \right) \approx \frac{\Delta \Phi}{\Delta x}$$

How small $\Delta x$ may be for above equation to be an acceptable approximation depends on the particular problem. This type of approximation is made at the finite number of points and reduces a continuous boundary problem to a set of algebraic equations.

5.3 Construction of Finite-Difference Approximations

Consider a function $f(x)$ sufficiently smooth so that the series developed below are sensible. Then function $f$ may be expanded in to a Taylor series about $x$ in the positive direction (Remson 1971).

$$f(x + \Delta x) = f(x) + \Delta x \frac{df}{dx} + \frac{\Delta x^2}{2!} \frac{d^2 f}{dx^2} + \hdots$$  \hspace{1cm} (2)
This equation can be solved for \( \frac{df}{dx} \) to give

\[
\frac{df}{dx} = \frac{f(x + \Delta x) - f(x)}{\Delta x} + 0(\Delta x)..........................(3)
\]

The term 0(\( \Delta x \)) represent the remaining terms of the series. The forward difference approximation to the derivative of \( f \) may be obtained from 3-4 by dropping the 0(\( \Delta x \)) Term and is given by

\[
\frac{df}{dx} \approx \frac{f(x + \Delta x) - f(x)}{\Delta x} ..................................................(4)
\]

In similar fashion \( f(x) \) may be expanded in to a Taylor series about \( x \) in the negative direction.

\[
f(x - \Delta x) = f(x) - \Delta x \frac{df}{dx} + \frac{(\Delta x)^2}{2!} \frac{d^2 f}{dx^2} - \frac{(\Delta x)^3}{3!} \frac{d^3 f}{dx^3} + ......................(5)
\]

Solving for \( \frac{df}{dx} \) and dropping 0(\( \Delta x \)), the backward difference approximate to the derivative of \( f \) is

\[
\frac{df}{dx} \approx \frac{f(x) - f(x - \Delta x)}{\Delta x} ......................(6)
\]

The error that derives from the truncation of the Taylor series is the “truncation error”. The truncation error in both cases is 0(\( \Delta x \)). If Eqn. (5) is subtracted from (2), the result is

\[
f(x + \Delta x) - f(x - \Delta x) = 2\Delta x \frac{df}{dx} + 2 \frac{(\Delta x)^2}{3!} \frac{d^3 f}{dx^3} + ......................(7)
\]

From (7) the central difference approximation can be written as

\[
\frac{df}{dx} \approx \frac{f(x + \Delta x) - f(x - \Delta x)}{2\Delta x} .........................(8)
\]

When all the terms containing expression of 0(\( \Delta x \)^2) and higher degree are dropped, this approximation has the advantage of having a truncation error 0(\( \Delta x \)^2). To clarify the above ideas involved in approximating a derivative, it is instructive to consider the geometric mean.
Figure 5.1 shows that slope at point B as given respectively by the forward difference (4), the backward difference (6), and the central difference (8) approximations. It may be appreciated that the difference between the approximations decreases with $\Delta x$.

To obtain an approximation to the second derivative of (2) and (5) can be added

$$f(x + \Delta x) + f(x - \Delta x) = 2f(x) + 2\frac{(\Delta x)^2}{2!} \frac{d^2 f}{dx^2} + 0(\Delta x^4) ...................(9)$$

The desired approximation is

$$\frac{d^2 f}{dx^2} \approx \frac{f(x + \Delta x) - 2f(x) + f(x - \Delta x)}{(\Delta x)^2} .......................(10)$$

With truncation error $0(\Delta x^4)$

Approximation to higher derivatives can be obtained in much the same way. Because the equations governing subsurface flow considered here in are of second order, only approximation, to first and second derivatives is required. Applying the first and second derivatives to the groundwater flow equations,
The above equation is solved for every grid with changed head values, with respect to time and space.

### 5.4 Model Formulation

The initiation of groundwater flow modeling is done with the proper understanding of groundwater flow regime. A detailed study of geology, borehole lithology and water level fluctuations in wells has helped to arrive at the conceptual model of the system. Development of a numerical model involves selecting or designing spatial grids and time.

The simplicity in developing groundwater model is much sought after and backed upon. The advantages of starting with simple models and building complexity slowly can be significant in the development of groundwater models. The principle of parsimony calls for keeping a model as simple as possible while (1) accounting for the system processes and characteristics that are evident in observations and important to predictions and (2) representing all system informations (Hill 2006).

#### 5.4.1 Data requirement

The data required for groundwater flow modeling is presented below (Moore 1979).

**A. Physical framework**
- Geologic map and cross sections showing the areal and vertical extent and boundaries of the system.
- Topographic map showing surface water bodies and divides.
- Contour maps showing the elevation of the base of the aquifers and confining beds.
- Isopach maps showing the thickness of aquifers and confining beds.
- Maps showing the extent and thickness of stream and lake sediments.

**B. Hydrogeological framework**
- Water table and potentiometric maps for all aquifers.
- Hydrographs of groundwater head and surface water levels and discharge rates.
- Maps and cross sections showing the hydraulic conductivity and transmissivity distribution.
- Maps and cross sections showing the storage properties of the aquifers and confining beds.
- Hydraulic conductivity values and their distribution for stream and lake sediments.
• Spatial and temporal distribution of rates of evapotranspiration, groundwater recharge; surface water-groundwater interaction, groundwater pumping, and natural groundwater discharge.

5.4.2 Data Acquisition

5.4.2.1 Groundwater level data

A network of 60 observation wells virtually evenly distributed stations was established. The water level monitoring programme was initiated in November 2005. The monitoring was carried out twice a year under Ministry of Water Resources (MoWR) project. The monitoring wells furnish valuable information not only on the real time groundwater variations but also on the rate of application for some specific time period. Water levels were recorded from Nov 2005 to Nov 2007 at all observation points. Due care was taken in water level monitoring however error may introduce because practically it was impossible to stop all pumping in an extensively cultivated area where concentration of groundwater abstraction structures are so high.

5.4.2.2 Hydrogeology

The study area is flanked by river Yamuna and Krishni from western and eastern side, respectively. The fence diagram reveals the vertical and lateral disposition of aquifers, aquiclude and aquitard in the study area to depth of 122 m bgl. Nature of alluvial sediments is generally complex and there is quick alteration of pervious and impervious layer. The top clay bed is underlain by granular zone, which extends downward to different depths varying up to 122 m bgl. The granular material is composed of medium to coarse sand while clay and silt make up the aquitard. The granular zone is subdivided at places into two to three sub-groups by occurrence of sub-regional clay beds, local clay lenses are also common through out the area. By and large the aquifer down to 122 m appears to merge with each other and behaves as single bodied aquifer. In the present model three layers have been considered. The top sandy layer contains the water table and is of variable thickness ranging from 15-84 m bgl.

Transmissivity (T) and storage coefficient (S) values are the two parameters which define the physical framework of an aquifer and control the movement and storage of groundwater. A number of pumping test were carried out by Central Groundwater Board (CGWB) and State Groundwater Department (UPSGWD). The hydraulic conductivity values are assigned to appropriate grids corresponds to distinct zone. The specific yield (Sv) is taken uniform for the entire area.
5.4.2.3 Recharge

Apart from rainfall recharge, the irrigation returns and seepage through unlined canals significantly affect the groundwater regime in terms of groundwater recharge. Recharge through groundwater irrigation and surface water irrigation is taken out separately. The recharge factors form the basis for subdivision of area in to command and non-command. Site specific recharge data are often used purely as fitting parameters during model calibration (Varni and Usunoff 1999) where site specific information is available, an assumed fraction of it commonly assigned as the recharge boundary condition (Kennett-Smith et al. 1996, Hsu et al 2007). Such assumptions may be adequate for the long term simulation of the regional groundwater flow system (Jyrkama et al. 2002) as is done in the present case.

The total recharge estimated is in accordance with water table fluctuation method (Healy and Cook 2002) and Groundwater Estimation Committee (GEC 1997) methodology for groundwater resource estimation. Recharge through irrigation returns and seepage through unlined canal is estimated using standard norms recommended by GEC-97.

5.4.2.4 Water Use

Groundwater contributes 92% of agricultural requirement needs. On an average, only 8% of the surface water is utilized and consequently, groundwater is heavily relied upon in the study area. The groundwater abstraction is about 477.33 million m$^3$/year, which exceeds the estimated recharge of about 413.08 million m$^3$/year.

5.4.2.5 Groundwater Draft through pumping

The database of the tubewells existing in the study area for the year 2006 was created during several field visits (Nov 05-Nov 07). The data of tubewell census from statistical department is also used for the same purpose. Three types of tubewells were categorized on the basis of their yield. The state tubewells, governed by state tubewell department have a discharge rate of 1500 l/m. The private (electric) and private (diesel) tubewells have discharge rate of the order of 250 l/m and 60 l/m, respectively. The duration of pumping mainly depends on electric power supply, tubewell maintenance and time (season) of the year. Simulated pumping rates of 500 m$^3$/d, 1000 m$^3$/d, 1500 m$^3$/d and 2000 m$^3$/d were used in the pumping well package.

5.5 Conceptualization of Flow regime and Model Design

Model design and its application is the primitive step to define the nature of problem and the purpose of modeling. The step is linked with formulation of the conceptual model, which again is a prerequisite before the development of a mathematical model. The conceptual model is put into a form suitable for modeling. This
step includes design of the grid, selecting time steps, setting boundary and initial
condition, preliminary selection of values for the aquifer parameters and hydrologic
stresses.

To the extent possible, the grid should be aligned with the average direction of
groundwater flow. The boundaries of the grid also should be aligned with the natural
hydrologic and geologic boundaries of the system. Where it is not possible to extend the
grid to natural boundary, an appropriate boundary condition should be imposed at the
edge of the grid to represent the effect of continuation of the system beyond the grid.
The boundaries should also be placed as far as possible away from the area of interest
and areas of stresses on the system, so as to minimize any impact of conceptual error
associated with the artificial boundary conditions. Also the aspect ratios of cells should
be close to one as possible. Long linear cells can lead to numerical errors, and should be
avoided particularly if the aspect ratio is > 5 (GurunadhaRao and Rao 2006). In an
unconfined aquifer river-aquifer interaction is a sensitive issue and thus be taken with
due care. Interaction between an alluvial aquifer system and river will be influenced by
the spatial arrangement of hydrofacies at the interface between the river and the
underlying aquifer (Woessner 2000). The modeling studies that include river aquifer
interactions have been focused on questions of regional scale water management and
conjunctive use (Onta et al. 1991; Reichard 1995; Wang et al. 1995).

The aquifer model in Yamuna-Krishni interstream region consists of 47 rows and
40 columns. The numerical model has three layers with a uniform grid of 1000m x
1000m (Fig.5.2). The aquifer is dipping gently from North to South and south western
part of the study area. It can also be seen that the groundwater level in aquifer follows
the general topography of the study area. The conductivity in 7 separate zones is
assigned on the basis of pumping test data (Fig.5.3a and 5.3b). The permeability or
conductivity being a function of grain size and their mode of packing is variable through
out the study area. However, the specific yield for the entire domain is kept uniform due
to non-availability of data as well as more or less uniform geology. The clay horizons are
often present as lenses but do not extend through out the study area. Each aquifer
group embodies a number of granular layers alternating with thick or thin clay lenses
having almost similar log characteristics indicating hydraulic continuity between them
(Sinha and Singhal 2006). Therefore, the granular zones down to a depth of 122 m bgl
are hydrodynamically interconnected and aquifer is taken as single interconnected
system, by and large unconfined in nature. The inability of the software to recognize
lenses compel to design a three layer model instead of single tier aquifer. The
simulation of aquifer geometry is done accordingly and clay lenses are presented as
semi permeable layers.
Fig. 5.2 Grid pattern and location of observation wells in Yamuna-Krishni sub-basin
Fig. 5.3a Zone wise permeability distribution in first and third layer.
Fig. 5.3b Zone wise permeability distribution in second layer.
All the layers are interconnected through vertical conductivity and water level is same for all the layers. The absence of clay horizon in a particular area is achieved by assigning a value of conductivity equivalent to overlying and underlying aquifer. Clay layer is given conductivity value equivalent to overlying and underlying aquifer at places where the clay layer was discontinuous in actual as shown in fence diagram. The simulated three layer system is shown in figures 5.4a and 5.4b.

The conceptual model is a pictorial representation of the groundwater flow system, frequently in the form of a block diagram or a cross section. The nature of the conceptual model will determine the dimensions of the numerical model and the design of the grid. There are three steps in building a conceptual model: (1) defining hydrogeologic unit; (2) preparing a water budget; (3) defining the flow system.

I. The Yamuna-Krishni sub-basin is interfluve region, bounded by river Yamuna and river Krishni from western and eastern side respectively. Initial grid size of 1000m x 1000m is chosen in the model.

II. Seven permeability zones were assigned to first and third layers of entire study area which ranges from 12.25 m/day to 26.6 m/day.

III. The simulated three layer model extends up to maximum thickness of 122m with an average thickness of 95 m below ground level (Fig.5.4a & 5.4b).

IV. The bottom layer is aquitard and is assigned permeability of 1 m/day uniformly. They allow downward leakage and at places attain minimum thickness of 1 m.

V. Natural recharge from monsoon rainfall and recharge through return flows forms the main input in to the groundwater system. Eastern Yamuna Canal is the main source of canal seepage however distributaries like Bunta, Bhainswal, Goharni and Badheo also contributes to the groundwater system.

VI. The recharges values to command, non-command and seepage value for individual canal has been worked out and assigned to respective grids (Fig.5.5) using recharge boundary package.

VII. The pumping rates vary from 25-400m³/day. The simulation of the pumping rate is done accordingly and representative pumping of simulated pumping rates like 1000, 1500, 2000 and 2500 m³/day is used (Fig.5.6).

VIII. The stream bed elevation of Yamuna River, Eastern Yamuna canal and Krishni River were taken out with the help of GPS and assigned to appropriate grids.

IX. The river boundary condition was applied to the rivers Yamuna and Krishni. Heads are prescribed to all the boundary conditions.
Fig. 5.4a Hydrogeological cross section along row 9 showing three layer system.

Fig. 5.4b Hydrogeological cross section along row 25 showing three layer system.
Fig. 5.5 Zone wise recharge distribution in Yamuna-Krishni model.
5.6 Numerical model of Yamuna-Krishni sub-basin

After hydrogeological characterization of the site has been completed and the conceptual model developed, computer model software is selected. The selected model software should be capable of simulating conditions encountered at site (Kinzelbach 1986, Mohan 2001).

5.6.1 MODFLOW 4.1P

MODFLOW is a versatile code to simulate groundwater flow in multilayered porous aquifer. The model simulates flow in three dimensions using a block centred finite difference approach. The groundwater flow in the aquifer may be simulated as confined or the combination of both. MODFLOW consists of a major program and a number of sub-routines called modules. These modules are grouped in various packages viz. basic, river, recharge, block centred flow, evapotranspiration, wells, general heads boundaries, drain, strongly implicit procedure (SIP), successive over relaxation (SSOR) and preconditioned conjugate gradient (PCG) etc.

A modular three dimensional finite difference groundwater flow model is developed by McDonald and Harbaugh (1988). United Stated Geological Society is continuing its activities to expand the capabilities of MODFLOW (Thangarajan 2004). The scope of MODFLOW has grown substantially since its first release in 1984. Its initial conceptualization as a groundwater flow model capable of simulating a wide range of groundwater features (wells, drains, rivers, and so forth) through the use of independent, modular programming packages has been expanded to the broader concept of simulation processes, wherein parts of the code solve a major equation or set of equations. Several processes are now available for MODFLOW, including solute transport, variable density flow, parameter estimation, and groundwater management, with the groundwater flow (GWF) process remaining the core process on which other capabilities are built (Barlow and Harbaugh 2006).

5.6.2 Steady State Calibration

The steady state condition is a condition that existed in the aquifer before any development had occurred. Matching the initial heads observed for the aquifer with the hydraulic heads simulated by MODFLOW is called steady state calibration. The groundwater flow solution is obtained through visual MODFLOW Pro version 4.1. The calibration was made by 60 observation wells.
Fig. 5.6 Simulated groundwater pumping centres in Yamuna-Krishni Model.
The aquifer condition of time period of November 2006 was assumed to be the initial condition for the steady state model calibration. Hydraulic conductivities estimated from pumping tests were used as initial values for the steady state simulation. By trial and error calibration, the conductivity values were increased during many sequential runs until the match between the observed and simulated water level contours were obtained.

The computed water level accuracy is judged by comparing mean error, mean absolute and root mean squared error calculated (Anderson and Woessner 1992). Mean error is the summation of the differences between calculated heads and observed heads for each observation well, divided by the total number of observations well. Mean error is -0.066 m.

The computed water level of Nov 2006 (steady state) indicate prevailing trend of groundwater flow in the interstream region (Fig.5.7).

Root mean square (rms) error is the square root of the sum of the square of the differences between calculated and observed heads, divided by the number of observation well and in the present simulation it was 1.8 m (Fig.5.8). The absolute residual mean is 1.26 m.

5.6.3 Transient State Calibration

The initial hydraulic conductivity values of steady state model are used as the initial values for transient state model. After having a number of trial runs by varying input/output stress, the computed water levels were brought about reasonably to match the observed values. The observed pre and post monsoon water levels for selected observation wells for the period 1999-2007 was used for transient state calibration.

It may be noted that estimation of recharge as a fraction of annual rainfall is only a first order approximation and actual recharge will depend not only upon the total rainfall but also upon the frequency and rate of precipitation. The actual amount of recharge was thus calculated for each year using GEC'97 methodology. Recharge through irrigation return flow and canal seepage was calculated using specific norms. The rms for the transient state model for the period June 1999 to June 2007 is 1.58 m (Fig.5.9). A stress is a time period in which all the stresses (boundary conditions, pumping and recharge rates etc.) are assumed constant. Visual MODFLOW uses boundary conditions imposed by the user to determine the length of each stress period. Transient simulation run during November 1999 to June 2007 has been divided in to 18 time steps. Each year has been divided in to two stress period of monsoon and non-monsoon months. The shorter time period represent the monsoon period and longer time period represents the non-monsoon months. However for recharge boundaries the stress period is increased and initial recharge value is given for 30 days period and gradually increased to 152 and 213
Fig. 5.7 Simulated water table contour map (Nov 2006).
Fig. 5.8 Calculated versus observed heads (Nov 2006).

Fig. 5.9 Calculated versus observed heads (June 1999-June 2007).
days. The comparison of observed and computed heads at different observation wells is shown in figures 5.10a, 5.10b, 5.10c and 5.10d.

5.6.4 Sensitivity Analysis

Sensitivity analysis brings out and helps to understand significant role played by individual parameters in computation of model simulation output. The purpose of sensitivity analysis is to quantify the uncertainty in the calibrated model caused by uncertainty in the estimates of aquifer parameters, stresses and boundary conditions (Santhilkumar and Elango 2004; Elango and Santhilkumar 2006). During the sensitivity analysis, calibrated values for the hydraulic conductivity, storage parameters, recharge and boundary condition are systematically changed within the permissible range. The magnitude of change in heads from the calibrated solution is a measure of the sensitivity of the solution to that particular parameter. The computed head values mimic observed head values in most of the well locations.

A sensitivity analysis may also test the effect of changes in particular values other than head. In the present modeling exercise the sensitivity of hydraulic conductivity and recharge was examined. The permeability varies from 9.8 to 26.6 m/day. Initially the permeability values were taken from the existing pump test and steady state water levels for November 2006. The comparison of computed heads and observed heads showed a mean error of -0.49 m, mean absolute error of 1.3 m and RMS error of 1.68 m. During first sensitivity analysis the permeability values were increased by 10% which come out with slightly high rms error of 1.703 m. Second and third run is made with 20% and 50% increase in the permeability values which again gives high rms error. Fourth run was made such that the minimum values of conductivity i.e. 9.8 and 10.1 m/day, encompassing area close to river Yamuna, were raised by 25%. The forth run provide better match of observed and simulated heads with rms error of 1.58 m. Thus the initial permeability of 9.8 and 10.1 m/day has become 12.25 and 12.6 m/day along the river Yamuna. The rest of the values represent the actual Pump test values.

The recharge parameter is changed during next sensitivity analysis run. It represents the recharges due to rainfall and irrigation return flow. Initially, the estimated recharge values were applied to command, non-command and canal tracks. The recharge sensitivity of model was tested for 1% increase and decrease which show the rms errors of 1.64 and 2.03 m, respectively. Thus, the model is very sensitive to recharges compared to conductivity.
Fig. 5.10a Observed and simulated heads at Kairana, Titoli and Thanabhawan.

Fig. 5.10b Observed and simulated heads at Shamli and Khurgyan
Fig. 5.10c Observed and simulated heads at Bhoora and Toda

Fig. 5.10d Observed and simulated heads at Jalalabad and Kandela
5.6.5 Groundwater Balance

Zone budget calculates sub-regional water budget using results from MODFLOW simulation. The estimated recharge values were initially given as recharge boundaries to command, non-command and canal tracks. The heads were assigned to river stage applying river boundary package.

The water balance of the model for June 2006-June 2007 is as follows: the total direct recharge to the Yamuna-Krishni sub-basin is 158.46 Mcum and the horizontal inflows are 20.58 Mcum. The total annual draft through pumpage is 277.42 Mcum and horizontal outflow is 3.75 Mcum. The various components of groundwater balance are tabulated in Table 5.1.

Table 5.1 Components of groundwater balance using MODFLOW.

<table>
<thead>
<tr>
<th>Components of groundwater balance</th>
<th>Monsoon (Mcum)</th>
<th>Non-monsoon (Mcum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct recharge</td>
<td>93.00</td>
<td>65.32</td>
</tr>
<tr>
<td>Subsurface inflows</td>
<td>7.50</td>
<td>13.03</td>
</tr>
<tr>
<td>Draft through pumpage</td>
<td>111.23</td>
<td>166.19</td>
</tr>
<tr>
<td>Subsurface outflows</td>
<td>1.90</td>
<td>1.80</td>
</tr>
</tbody>
</table>

5.6.6 Model verification and prediction

Model validation is in reality an extension of the calibrated process. Its purpose is to assure that the calibrated model properly assesses all the variables and conditions which can affect model results. While there are several approaches to validate a model, and the most effective procedure is to use only a portion of the available record of observed values for calibration. The period from June 2005-June 2007 was used for validation as maximum data were available during this time period.

Three different scenarios were considered to predict the behaviour of the groundwater regime in Yamuna-Krishni sub basin during the period 2006-2014. These scenarios are explained below:

5.6.6.1 Scenario 1: Increase in current withdrawal rate

During this prediction scenario, the ongoing abstraction rate was increased gradually by 20%. This increase is quite acceptable keeping in view the present rate of consumption. The initial recharge of November 2006 is kept constant through out the prediction time. It was observed during this prediction run that the area in the vicinity of river Krishni is drastically affected and four observation wells i.e. Bhabhisa, Bhanera, Kaidi and Sonta have gone dry in 2014 time period. The maximum drawdown of 10 m is observed around Makhmulpur villages. The minimum drawdowns were observed at locations close...
Fig. 11a Drawdown in prediction scenario 1
to river Yamuna e.g. Khurgyan, Chontra and Bhari observation wells where the drawdown is <2 m (Fig.5.11a).

5.6.6.2 Scenario 2: Decrease in recharge

In this prediction scenario, the combined increase in abstraction rate by 20% and reduction in rainfall by 20% were taken for future prediction. Both the situations are acceptable in reality. The combined impact of both the factors shows that the maximum drawdown of 10 m, is observed at the locations Makhmulpur, Malakpur and Salpa, close to river Krishni. The minimum drawdown of <2 is observed at Chontra and Bhari observation well. In this scenario five observation i.e. Gangeru, Bhabhisa, Bhanera, Kaidi and Sonta wells have gone dry by 2014. The extent of dry cells is large in comparison to scenario 1 (Fig.5.11b).

5.6.6.3 Scenario 3: Introducing Recharge through canals in non-command area

In order to mitigate the groundwater depletion and drying up of wells at some location of the study area, the additional recharge was applied to Kairana distributary and to its irrigation channels. The recharge of 300 mm/year was applied to dry Kairana distributary and its irrigation channels. This is again a practically possible scenario. The extent of dry cells has become reduced after the induced recharge (Fig.5.11c). Thus recharge through surface water structures and recharge through water harvesting is the need of hour in affected areas.

5.7 Summary and Conclusion

Processing MODFLOW 4.1 (PM 4.1) is used in this study to simulate the groundwater flow for steady and transient conditions, to forecast the future changes that occurred under different stresses and also to investigate scenario of additional groundwater recharge to evaluate their effect on the water table. The initiation of modeling exercise is done with conceptualization of flow regime. The data pertaining to hydrogeology, hydrometeorology was collected during several field visits.

The time period of November 2006 is taken as initial state for steady state model calibration. Model calibration for steady state condition shows good agreement between observed and simulated initial water level contours. Transient state model calibration is carried out for the period June 1999 to June 2007. Water level data of June 1999 was used as initial heads for the transient calibration. The transient state calibration also shows good agreement. The sensitivity of the model to input parameters was tested by varying only the parameters of interest over a range of values, and monitoring the
Fig. 11b Drawdown in prediction scenario 2

Dry cell
Fig. 5.11c Drawdown in prediction scenario 3
response of the model by determining the root mean square error of the simulated heads compared to the measured heads.

These analyses showed that the model is most sensitive to conductivity and recharge parameters.

Results of the calibrated flow model (steady state and transient state) indicate that the hydraulic conductivity ranges from 12.25 to 12.6 in the north part of the non-command area. The results of water balance of the model for June 2006-June 2007 is as follows: the total direct recharge to the Yamuna-Krishni sub-basin is 158.46 Mcum and the horizontal inflows are 20.58 Mcum. The total annual draft through pumpage is 277.42 Mcum and horizontal outflow is 3.75 Mcum. The groundwater balance for the period is -102.13 Mcum.

Three scenarios have been considered to predict aquifer responses under different stress conditions. All the three prediction scenarios are possible in the study area. According to prediction scenario 1 i.e. with 20% increased groundwater abstraction rate the maximum the drawdown will reach 10 m in the year 2014. The area in close vicinity to river Krishni shows high decline rate as four observation wells have gone dry in this scenario. The minimum drawdown is observed in the area close to river Yamuna.

By reducing rainfall by 20% and increase in current abstraction rate by 20% (scenario 2), the maximum drawdown in this scenario is very high (10 m). In this scenario, the area close to Krishni and southern part of the study area has observed decline in water levels as envisaged by dewatering of shallow aquifer at five locations.

The third prediction scenario pertains to the situation, where additional recharge is given to Kairana distributary and its irrigation channels. The extent of dry cells has become smaller after the induced recharge. Thus, to mitigate the water table decline, artificial recharge and conjunctive use of water is suggested.