ISSN: 2754-477X

Journal of Food Technology & Nutrition Sciences

Research Article Open Access

Groundwater Modeling: A Tool for Groundwater Management to Support Urban Water Supply and Food Security

Ghulam Zakir-Hassan[1,2]*, Faiz Raza Hassan[1], Saleem Akhtar[1], Sultán Ahmad Rizvi[3], Ghulam Shabir[1] and Muhammad Ali Hassan Khan[4]

[1]Irrigation Research Institute (IRI), Government of the Punjab, Irrigation Department, Library Road, Lahore, 54000, Pakistan

[2]Scholl of Environmental, Agricultural and Veterinary Sciences, Charles Sturt University, Albury, 2640, NSW, Australia

[3]Punjab Agriculture Research Board (PARB), Lahore, Pakistan.

[4]University of Agriculture, Faisalabad, Pakistan

ABSTRACT

Faisalabad is the 3rd largest city of Pakistan where underlying aquifer mostly contains saline water. Heavy population of the city needs huge quantity of fresh water. Water requirements for the existing Faisalabad city are being met by installation of well-fields along Jhang Branch canal, where groundwater is fresh. The increasing population pressure requires more water and identify more suitable sites for installation of well-field on sustainable basis. It was deemed imperative to elevate the existing well field. The MODFLOW, a numerical groundwater model developed by United States Geological Survey (USGS) for simulation and future prediction of aquifer behavior in response to pumping by various well fields was developed, calibrated and validated satisfactorily. A groundwater decomposition approach was also developed to tune various coefficients used in estimation of inflow and outflow components of groundwater system. The calibrated model was used to predict the future response of aquifer under different scenarios of pumping by existing and future/proposed well-fields. Calibrated flow model revealed that a sink has already been developed at the center of existing well-field of Water and Sanitation Agency (WASA) due to excessive pumpage. Future predictions of model indicate that there is no conspicuous change in regional groundwater flow pattern, even with all the existing tubewells remain in operation. However, the sink in the WASA well field area further deepens, and flow gradients become comparatively steep showing increase in groundwater flow velocity. Depth to watertable has already increased from 12 m in 2005 to 16 m in 2011 in the critical area of WASA well field. Model has predicted that this depth will further increase to 24 m in 2018. It has also been observed that groundwater quality along the river is fresh and becomes saline towards Faisalabad city. Due to pumpage in the freshwater zone model predicts that saline water will rush towards well fields deteriorating the quality of fresh water along Jhang Branch Canal. Therefore, it has been suggested that site for further pumping should be moved towards upstream of Jhang Branch Canal at least up to RD 180-187 and possibly on right side of the canal instead of left side.

***Corresponding author**
Ghulam Zakir-Hassan, Irrigation Research Institute (IRI), Government of the Punjab, Irrigation Department, Library Road, Lahore, 54000, Pakistan. E-mail: zakirjg@gmail.com

Received: April 25, 2022; **Accepted:** May 02, 2022; **Published:** May12, 2022

Keywords: Aquifer, Groundwater; Groundwater Modeling, Faisalabad, Modflow, Punjab, Pakistan

Introduction

Groundwater is essential component of the natural environment and plays a backbone role for livelihood and health of people. It is a renewable but finite resource and is widely used for domestic, agriculture and industrial purposes. Fresh groundwater is preferred for drinking water supply because of its good quality. Water has emerged as one of the primary environmental concerns for the 21st century. Groundwater resources of the world are under threat due to increasing exploitation and decreasing recharge. The rapid development in agriculture and industrial sector over the few decades has resulted in great social and economic benefits on one hand and depleting the groundwater resources on the other hand. Development in these sectors depends on the supply and quality of water. The depletion of groundwater storage and decline in its level has two-fold economic impacts, i.e. increasing exploration cost and reducing remaining groundwater volume [1, 2].

The study area covers a part of Faisalabad district in 1904 as a Lyallpur district geographically it falls in the Rechna Doab (land between Chenab River and Ravi River). Groundwater underlying the Faisalabad city is brackish and is not fit for drinking purpose. About 512 large industrial units (textile, engineering & chemicals) have been developed and textile sector is biggest with 328 units. Other industrial units are included printing, hosiery, carpet and pharmaceutical. Due to huge industrial development, it is called as Manchester of Asia [3].

Due to increasing demographic pressure, the demand of groundwater is increasing day by day. This situation requires investigations on how much groundwater can safely be pumped. Development of groundwater model for the area can best estimate sustainable utilization of groundwater resources provides guidelines for proper management of the groundwater resources. Sustainability means "some for all, forever", utilization and allotment of groundwater to get social and economic benefit with environmentally sustainable. The over exploitation of groundwater has already resulted in lower water table and deteriorated quality in the Indus Basin of Pakistan [4,5].

Faisalabad Development Authority (FDA) has launched a housing scheme namely "FDA City Housing Scheme" to meet the housing demand for ever increasing population of Faisalabad. The housing scheme is located on Faisalabad-Sargodha Road near motorway (M3) interchange spreading over an area of 1,256 acres. FDA city would require a quantity of 20,000 m3/day. For this purpose, FDA wants to install tubewells along the Jhang Branch Canal near RD 209-216 to meet the water requirements of this new housing scheme.

Detailed groundwater investigation was not carried out earlier in the area before developing the existing well field. Intrinsic velocities of groundwater flow are very small; therefore, the source once polluted takes years of time to come back to the original position. If full attention to this hot issue is not paid, it may result in socioeconomic instability, environmental hazards and political stress which indirectly cause many other issues. Keeping in view the socio-environmental impacts under such circumstances in the existing well-fields, a groundwater model has been developed and applied in the area to predict possible changes in the hydrodynamics of groundwater flow system in response to various pumping patterns before development of the new well-field.

Groundwater modeling provides reliable management and development of groundwater resources on scientific lines. The future behavior of watertable has been predicted for considerable period of time under various expected inputs and outputs in future.

Materials and Methods

Description of Study Area

The study area comprises a part of Rechna Doab around Faisalabad Pakistan. Faisalabad is the 3rd largest populated city of the Pakistan with population of 2.5 million and situated in the northeast of the Punjab on its flat plains. It was established in 1904 as a Lyallpur district. Geographically, study area falls in the Rechna Doab (land between River Chenab and Ravi River). The Rechna Doab, as a whole, is an inter-fluvial area and lies between longitude 71°48′ E to 75°20′ E and latitude 30°31′N to 32°51′ N. Rechna Doab covers a gross area of about 2.97 million hectares which is mainly under irrigated agriculture and falls in the rice-wheat and wheat-sugarcane agro-ecological zones of the Punjab Province. It covers a vast canal network up to distributaries and minors. The Rechna irrigation system consists of Lower Chenab Canal (LCC), Upper Chenab Canal (UCC), Bomban-wala Ravi Badian Depalpur (BRBD) Canal, Marala-Ravi (MR) Link and Trimu-Sidhnai (TS) Link canal. The area of interest for development of well field mostly lies along Jhang Branch Canal off takes from Lower Chenab Canal (LCC). Location of study area is shown in Figure 1.

Climate of Rechna Doab is characterized by large seasonal fluctuations of air temperature and rainfall with maximum air temperature ranging from 21°C to 49°C. The monsoon rain occurs from mid-July to mid-September caused by winds arising from the Bay of Bengal whereas the winter rains normally originate from the Arabian Sea. Annual precipitation in the area estimated to be 370 mm of which about 75% of annual rainfall occurs during monsoon month from mid-July to mid-September.

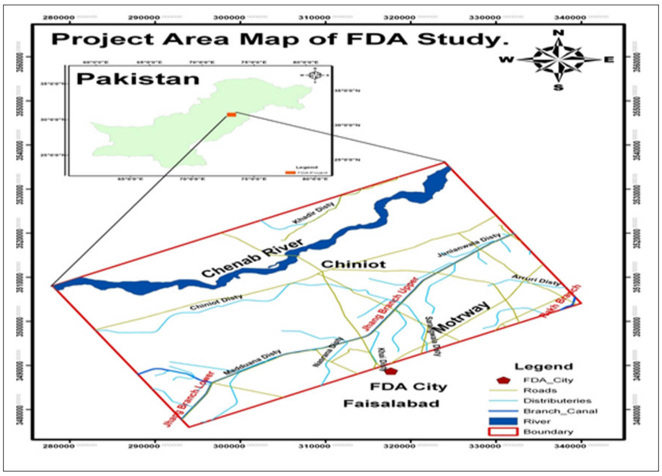


Figure 1: Area Selected for Groundwater Model

Groundwater Situation

As groundwater underlying the Faisalabad city is brackish and is not fit for drinking purpose. However, groundwater in the area between Jhang Branch Canal and Chenab River is fresh which is recharged by the irrigation network as well as Chenab River. In 1992, a well field containing 29 tube wells with discharge capacity of 1, 55,351 m^3/day was developed by Water and Sanitation Agency (WASA), Faisalabad. This well field lies at Dolat-Pur village, in the South-East of Chiniot City and on the Western side of Faisalabad city near Jhang Branch Canal (JBC). Water from this well field is transported by means of underground piping network for drinking purposes. Due to heavy pumping from the well field a sink has been developed. Recently another new well field with an anticipated pumping capacity of 1, 80,000 m^3/day has been developed along left bank of JBC. In addition to these pumping, a number of private tubewells are also pumping groundwater to meet the water requirements of crop in area.

Groundwater Modeling

Groundwater systems are complicated beyond our capability to evaluate them comprehensively in detail. Comprehensive analysis means that need to take into account all the characteristics of the system and predict the effect of hydrological and land use stresses. There are usually insufficient data to completely characterize the groundwater system under investigation; therefore, assumptions and simplifications are required to obtain a quantitative solution for the problem. Groundwater modeling is a tool used for assessment of groundwater potential and management. Groundwater modeling is used to understand the current situation of aquifer and future prediction after development of new tubewells. It helps in planning for well fields development and operation [9]. The model is also being applied for investigation of groundwater dynamic system, flow pattern and evaluation of recharge, discharge and storage of an aquifer [6].

A groundwater model is a computer based representation of the essential features of a natural hydro-geological system through numeric that uses the laws of science and mathematics. The model should be used principally as a tool to simulate aquifer response under various pumping rates and patterns. Subsequently, it may be developed into, or used conjunctively with decision models to aid in planning and water management more directly. There are two major types of groundwater model; Conceptual Model; and (ii) A Mathematical Model. The conceptual model is an idealized representation (i.e. a picture) of hydrogeological understanding of key flow processes of system. A mathematical model is a set of equations, which subject to certain assumptions; quantifies the physical processes active in the aquifer system(s) being modeled. Groundwater model is based on two well-known equations: Darcy's Law and the Law of Conservation of Mass (continuity equation). The combinations of these two equations result in a partial differential equation which governs the flow through porous media. General form of mathematical model for groundwater flow is as under:-

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)=S_s \frac{\partial h}{\partial t} \quad (1)$$

where, h is hydraulic head (L), K_x, K_y, K_z are hydraulic conductivities of aquifer in x, y and z directions respectively (L/T), t is time (T) and S_s is storage coefficient.

This is the governing equation for 3-D, anisotropic, heterogeneous, transient and saturated groundwater flow through porous media. This general equation then can be simplified further according to our site specific conditions. Solution of this partial differential equation becomes complicated due to complex boundary conditions and only a few simple problems can be solved directly. Generally, we need to apply numerical methods to solve the differential equations. The two best known numerical methods are the finite difference method and the finite element method. Both require that space be divided into small but finite intervals, the sub-areas thus formed are called nodal areas, as each area has a node that connects it mathematically to its neighbors. The nodal areas, also referred to as cells, make it possible to replace the partial differential equation with a set of algebraic equations.

Groundwater modeling under the subject study pertains to such area where aquifer is under stress and most part of which holds saline water and modeling is required to forecast aquifer behavior to the changing pumping patterns. It may be capable of providing guidelines for preparing design of well fields facilitating efficient management of limited groundwater resources.

On the basis of the above considerations a groundwater model has been developed by using the groundwater model of United States Geological Survey (USGS) that is "MODULAR THREE DIMENSIONAL FINITE-DIFFERENCE GROUND-WATER FLOW MODEL" commonly known as "MODFLOW". The flow model was, later on, linked with solute transport model by using the latest version of MT3D. Aquifer is recharged by different sources (rainfall, river, canals and irrigation return). Groundwater model (MODFLOW) is applied to find groundwater behavior and flow patter. It also helps to identify the locations of significant recharge/discharge. . It also helps to find the groundwater recharge source and its contribution to recharge [7]. MODFLOW River package was used to find river recharge. Riverbed, hydraulic conductivity, head, width and length in each grid are given to model [8].

Description of the Groundwater Model (MODFLOW)

The model simulates groundwater flow within the aquifer in three dimensions using a block-centered finite difference approach. Layers can be simulated as confined, unconfined or a combination of both. Its structure consists of a Main Program and a series of highly independent subroutines called "Modules". The modules are grouped into "packages", each package deals with a specific feature of the hydrologic system which is to be simulated such as "seepage" from rivers or canals, "recharge" from field applications and precipitation, "discharge" from the tubewells and through drains etc. and thus can be used for various situations, subject to different kinds of recharge and discharge sources, in a particular case study. Following packages i.e. Basic (BAS), Block Centered Flow (BCF), River (RIV), Recharge (RCH), Well (WEL), General Head Boundary (GHB), Strongly Implicit (SIP) and Solute Transport (MT3D) have been used in developing groundwater model of this area.

Methodology

The Methodology Adopted for the above Task is Best Illustrated and Described under the Flow Chart Given Below

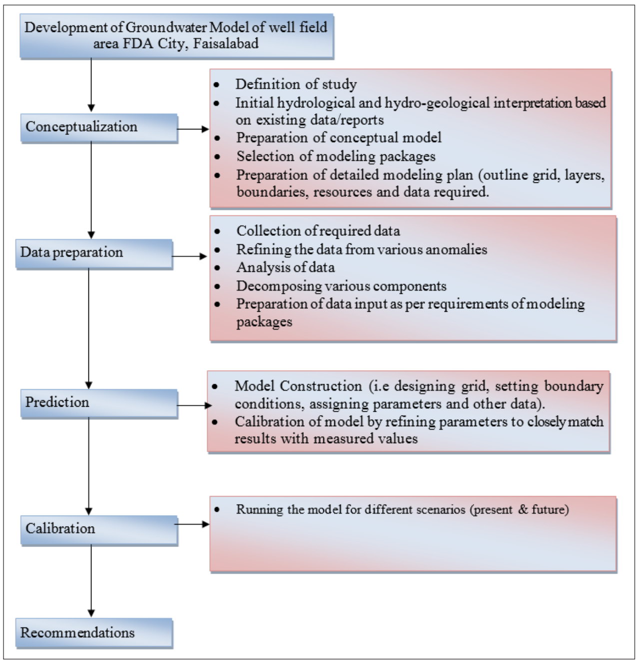


Figure 2: Flow Chart of the Model

Data Requirement

The Data Required for Groundwater Model can Be Divided Into two Broad Categories;

- Time Constant; and
- Time Variable

Time constant data are those which do not change with time; therefore, remain constant during calibration processes and future predictions. These include topography (top and bottom elevations of various aquifers), hydrogeology (hydraulic properties such as storage coefficient/specific yield, hydraulic conductance etc.).

Time variant data are those which change with time and relate to hydrological inputs and outputs (i.e. recharge and discharge components) that depend upon the climatic conditions such as recharge from irrigation applications, seepage from canals, rivers, groundwater abstractions and water table fluctuations. Time variant data are required for transient simulation. For steady state condition simulation data of one stress period is required. Time variant data are required for the period being used for calibration of the model. Setting up of groundwater model requires that the project area be divided into sub areas called nodes or cells. Both time constant and time variant data are required for each cell.

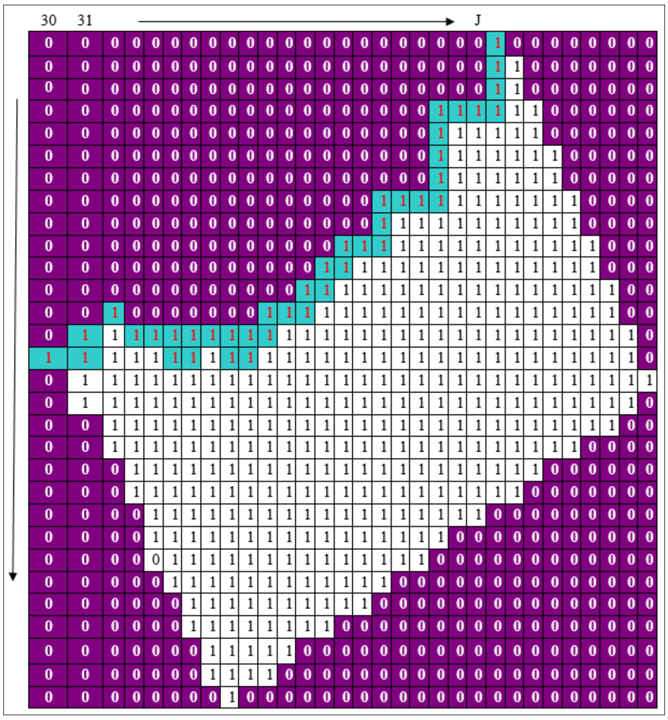
Conceptualization of Groundwater Flow System

Selection of Model Area, Grids and Boundaries

Generally, it is preferred to select the area for some model bounded by some natural hydrologic boundaries such as rivers, streams, big canals or barrier etc. Chenab River and Jhang Branch may be acting as natural boundaries in present case. However, proposed well field for FDA-City and new well field installed under JICA are along the left bank of JBC. Accordingly, boundary of the groundwater model area was extended in south-east about 10 km from the proposed FDA well field. This boundary was approximately aligned with the groundwater flow path.

Boundaries on north-east and south-west were selected where effect of pumping from proposed FDA well field and existing WASA well field is envisaged to be zero. These three boundaries were simulated using General Head Boundary Package (GHB) while the boundary on the north-west side is represented by the Chenab River thus this study area of 60 km by 62 km (3,720 km^2) has been selected for modeling purpose. A uniform mesh spacing of 2 km has been used in each direction thus making the cells of square shape and size of 2 km by 2 km. This result into division of 930 cells comprising 30 rows (denoted by "i") and 31 columns (denoted by "j"). Out of these, 420 cells (covering 1,936 km^2) are active and 510 cells (covering 1,784 km^2) are inactive. Inactive cells lie on right side of the Chenab River and outside of the remaining three boundaries. At this mesh spacing, the model results will provide an overall assessment of present flow patterns and of changes in water level and flow pattern in response to future stresses, such as changing pumping patterns as a result of pumping from recently installed JICA tubewells and proposed Tubewells. Map showing model grids and boundaries and cell designations is shown in Figure 3.

Node (1, 1)



0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
0	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0
0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Node (30, 31)

Figure 3: Model Grids and Boundaries

Aquifer Thickness and Layering

In the model area a number of shallow and deep have been installed for irrigation purpose by farmer and supply Tubewells by WASA Faisalabad respectively. Average depth of irrigation tubewells is around 42 m whereas WASA tubewells are 130 m deep and the latest tubewells installed by JICA for WASA are 145 m deep. Maximum thickness of aquifer is about is 300 m that decreases towards Chiniot town where its thickness is about 100 m. To simulate groundwater abstractions by various tubewells the aquifer has been divided into 7 layers as described in Table 1.

Table 1: Different Layers of Aquifer for Model with Thickness

Layer No.	Layer extent/ thickness (m)	Description
1	0-42 = 42	Thickness of the first layer has been kept 42 m to simulate groundwater abstractions from the farmer tubewells, which are on the average 42 m deep. Groundwater in this layer exists under watertable conditions.
2	42-100 = 58	Thickness of the second layer is 58 m as the shallowest consolidated rocks were encountered at 100 m depth (42 m + 58 m = 100 m).
3	100-130 = 30	Third layer is 30 m thick that represents bottom (100 m + 30 m = 130 m) of WASA tubewells located in the old well field.
4	130-145 = 15	Fourth layer is 15 m thick with bottom (130 m + 15 m = 145m) equal to depth of tubewells installed by JICA.
5	145-150 = 5	Fifth and sixth layers are of 5 m thickness each to make the model flexible to simulate up-coning of saline water if exists below bottom of JICA tubewells.
6	150-155 = 5	Fifth and sixth layers are of 5 m thickness each to make the model flexible to simulate up-coning of saline water if exists below bottom of JICA tubewells.
7	155-300 = 145	The last seventh layer is 145 m thick to represent bottom (145 m + 5 m + 5 m + 145 m = 300 m) of the aquifer

Calibration Period and Time Steps

Aquifers always tend to achieve equilibrium state provided there is no change in recharge and discharge components for a considerable period of time. All the flows into or out of the cell are equal to net change in storage per unit of time. Watertable trends correspond to the net changes in aquifer storage. If net change in aquifer storage is positive watertable will rise and if the net change in aquifer storage is negative the watertable will decline. In case net change in storage is zero the watertable will neither fall nor rise. In case of recharges to the aquifer and discharges from the aquifer are not equal, the volume of groundwater and thereby potential groundwater heads will keep on changing. For a realistic prediction of the future behavior of the aquifer, each model is calibrated against known flows or behavior of the watertable.

Therefore, calibration period is selected on the basis of available data. For the Project Area, data on depth to watertable is available with SMO (WAPDA), Directorate of Land Reclamation (DLR) and Irrigation Research Institute (IRI) for the period from 2005 to 2011. Depth to watertable is measured twice a year representing wet and dry season (Kharif and Rabi seasons). Under this study the data have been validated by performing field checks on SMO and DLR observation points. Data on recharge components are also available and have also been validated by performing field checks and processed into the format required by the model set up. Accordingly, the model has been calibrated for the period (2005-2011). In the model, a stress period is defined as a period over which all the inflow and outflow components remain more or less constant. In the present case, major components of the aquifer recharge and discharge vary in accordance with the cropping season i.e. Kharif (April to September 183 days) and Rabi (October to March next year 182 days). Data on groundwater levels are available for April/June and October, representing dry and wet cycles of the year. Hence, Kharif and Rabi seasons were selected as stress periods in the model. The calibrated model consists of 13 stress periods from 2005 to 2011. The model has the facility for further sub-dividing each stress period into several time steps. This provides a marginal increase in computational accuracy but at the expense of increased computer run time. For a regional groundwater model with a calibration period of 6.5 years the use of three time steps per stress period were considered to be adequate.

Derivation of Input Data for Model

Data Units

MODFLOW has the facility to work with any consistent set of units throughout the modeling process. For example, if you are using length units of meters and time units of days, then hydraulic conductivity will be expressed in units of m/day, pumping rates will be in units of m3/day. The values of simulation results are also expressed in the same units. Thus Metric system has been selected to use in the model under the current study.

Topographic Data

Topographic data are very important in determination of watertable elevation, recharge and discharge components. The NSL values reported with watertable data were checked in field and formed a large variations from point to point. Therefore, firstly NSL maps were prepared by using various sources on site. These include GPS, SRTM and Google Earth, but even a physical survey using the existing bench marks, was carried out in the field to countercheck the RLs of observation wells to convert the depth to watertable data into groundwater elevations. Further, NSL values at the location of different observation wells were interpolated using GIS software and snapped on the model grid to obtain the cell wise value of NSL for all active cells, in the mesh which are shown in Figure 4.

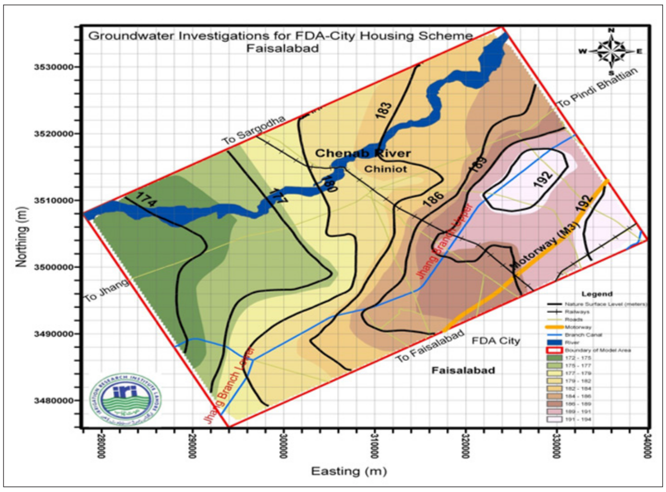


Figure 4: Contour map of Natural Surface Levels (Meters) for the model Area

Groundwater Levels

Groundwater levels were obtained from depth to watertable data by using NSL values at 65 observation wells for all stress periods. These point values of groundwater levels were interpolated using Surfer Contouring Software to map the point values to the model grid and cell wise values of groundwater levels for all stress periods. The groundwater levels of October 2005 were adopted the initial conditions (heads) the Basic Package (BAS) of "MODFLOW". Contour map of groundwater levels for 2005 (initial conditions) and 2011 (calibration period) are shown in Figures 5 and 6 respectively.

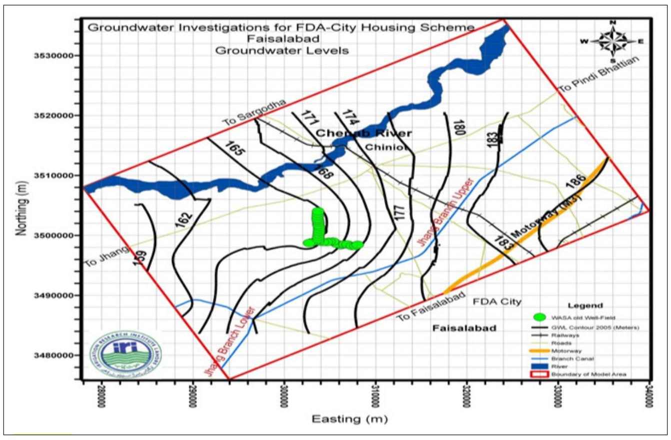


Figure 5: Counter of Initial heads (m) in June 2005

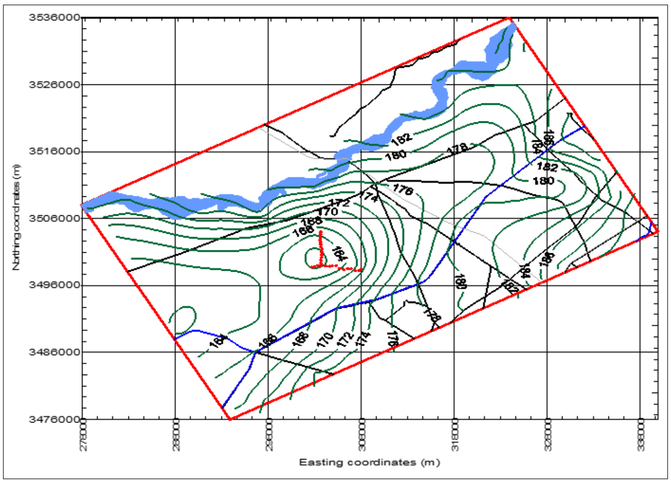


Figure 6: Contour of Groundwater Level (meters) in 2011

Aquifer Parameters

Aquifer parameters required for groundwater modeling include thickness of various layers in the aquifer, depth to bed rock, hydraulic conductivity, and transmissivity of the system and permeability of the aquifer material. The hydraulic conductivity and transmissivity of the aquifer system has derived from a series of pumping tests that have been done in different production wells [9]. Values of aquifer parameters as obtained from the previous studies conducted Water and Power Development Authority. Aquifer analysis in Rechna Doab was conducted through 47 aquifer tests.

The average lateral permeability from 49 tests in Rechna Doab was found to be 0.0038 cfs per sq ft. The range of lateral permeability (P) in study area was estimated .0009 to 0.007 Cusec/ft^2 [10]. Aquifer thickness varies in the study area from shallow to deep. Aquifer thickness is shallow near Chiniot city where rocks are exposure. The belt of shallow bed rock is spread from Chinot, Sangla Hill and Shah Kot. The aquifer thickness increases move away from Chiniot city. The range of aquifer thickness is less than 100 to more than 300 m. (from river Chenab to Faisalabad [11]. These values were interpolated using GIS software Arc GIS 9.3 and cell wise values of aquifer parameters were obtained to be utilized in the groundwater model. The data on depth to bed rock were interpolated by using GIS software and are shown in Figure 7.

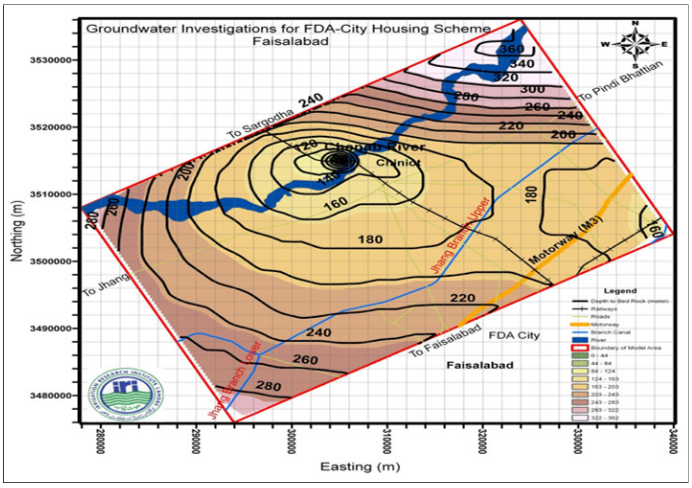


Figure 7: Depths to Bed Rock (Meters)

Net Groundwater Recharge

Using the decomposition technique, the cell wise net recharge values for each stress period were worked out taking into account all inflows and outflows are shown in Table 2. These values were used in the model for its calibration.

Table 2: Seasonal Groundwater Balance Sheet (2005-2011)

Sr. No	Seasons	Ground Water Recharge (MCM) by Different Sources					Total Recharge (MCM)	Discharge by Tubewells (MCM)	Net Balance (MCM)
		Rainfall	Main Canal	Distributary/ Minors	Water Courses/ Irrigation Field	Irrigation Tubewell			
1	Kh-2005	182.96	89.61	0.0031	120.53	36	429.1	432.49	-3.39
2	Rabi(2005-06)	28.18	71.44	0.0029	102.25	36	237.87	429.21	-191.34
3	Kh-2006	163.9	89.34	0.0032	131.15	37	421.39	441.46	-20.07
4	Rabi(2006-07)	70.82	72.01	0.003	107.32	36	286.15	438.13	-151.98
5	kh2007	143.91	91.56	0.0032	132.59	38	406.06	447.25	-41.19
6	Rabi(2007-08)	39.59	70.13	0.0029	101.52	37	248.24	450.63	-202.39
7	kh-08	282.99	88.66	0.0032	130.32	38	539.97	460	79.97
8	Rabi(2008-09)	33.13	59.72	0.0028	87.24	38	218.09	456.57	-238.48
9	kh-2009	176.49	86.48	0.0031	124.77	39	426.74	469.38	-42.64
10	Rabi(2009-10)	14.39	65.7	0.0028	92.24	39	211.33	465.9	-254.57
11	Kh-2010	286.19	80.24	0.003	116.43	40	522.86	478.96	43.9
12	Rabi(2010-11)	26.07	71.9	0.0029	101.46	40	239.43	475.43	-236
13	kh-2011	277.07	86.79	0.003	115.05	41	519.91	488.75	31.16

Model Calibration and Predictions

General Approach

There are no specific and universal guidelines of calibration criteria for regional groundwater models. Each model has to be treated separately and the standards of calibration should reflect the quality of the model input data and the field observations used for comparison The calibration of a model largely depends upon the reliability of the available data particularly, quantification of the various recharge and discharge components and their distribution over the area to be modeled. The groundwater model was calibrated by considering various aquifer parameters and the time rate response of groundwater reservoir since 2005 in accordance with periodic changes in recharge and discharge components. The methodology adopted for calibrating the groundwater model includes a series of sensitivity checks over the typical ranges of the above parameters through a number of model runs. Under the prevailing facilities, the most reliable data that could be collected in the field is on depth to watertable. Accordingly, the model has been calibrated on the basis of the behavior of watertable and seasonal fluctuations observed at the groundwater monitoring points selected for the calibration. After each run, model computed groundwater potential heads were compared with the measured groundwater potential heads in the monitoring boreholes selected for calibration. The aquifer parameters giving the results, closest to the observed groundwater conditions in various periods were used for calibration. Checks were made on the aquifer water balance to ensure that flow into and out of the modeled aquifer are of the same order as estimated by decomposition approach and in line with the field conditions. Calibration was progressed by adjusting various parameters, until a reasonable match between computed and observed aquifer behavior was achieved.

Controlling Parameters for Calibration

The historic data on groundwater levels is available for considerable number of water points. These points comprise piezometers installed by SMO (WAPDA), DLR and IRI. These piezometers are sufficiently deep and installed in the main aquifer materials. Accordingly, calibration points were selected from these piezometers on the following considerations:

- Data was available for the maximum period;
- Data showing normal trends for considerable period; and
- The selected points should be fairly distributed over the entire Project Area so that the
- Calibrated model may be successfully used to predict future groundwater conditions in the model area.

Aquifer parameters, particularly, hydraulic conductivities were adjusted by carrying out sensitivity runs. The hydraulic conductivity values, given in the paper on "Aquifer Tests in the Punjab Region of West Pakistan by Geological Survey Water-Supply Paper 1608-G", were validated considering partial penetration effect of the testing wells. The validated hydraulic conductivity values vary between 27 and 65 m/day. On the basis of this range of hydraulic conductivity values sensitivity runs were carried out. The sensitivity runs were performed using constant values of hydraulic conductivity i.e. 25 m/day, 50 m/day and 75 m/day. Selection of hydraulic conductivities for various zones within the range of reported values gave matching results with the observed field condition. During calibration procedure, comparison between the model computed and the observed groundwater heads indicated that distribution of recharge from the irrigation system and estimated pumpage more or less represent the observed field conditions.

Selection of Solute Transport Model

The MT3D numerical model has been selected because it can easily be linked with the calibrated regional flow model developed using MODFLOW. MODFLOW and MT3D data bases can easily be updated and different possible scenarios can be run to assess the impact of changes in pumping patterns and canal irrigation etc. MODPATH (3-D Particle Tracking Program for MODFLOW) is a widely used particle-tracking program [12].

The solute transport model has been linked with the calibrated flow model, therefore, changes in groundwater quality at any location in the Model Area due to changes in flow dynamics caused by changed recharge and discharge rates can be readily assessed.MT3D is capable of simulating advection, dispersion and chemical reaction processes of solute transport. In the Project Area the major changes in groundwater flow system is creation of sink as a result of pumping from WASA tubewells. Groundwater flow model has revealed that watertable in this sink, and around it, will be further lowered as a result of pumping from JICA and FDA tubewells. Therefore, intrinsic velocities of groundwater will increase according to the induced watertable gradients. Therefore, major impact on solute transport would be that of advection. In the normal conditions about 98% solute transport is due to advection. For the solute transport model concentrations of groundwater at the boundary cells, quality of river in terms of ppm were given for the 12 stress periods as are for the future prediction by groundwater flow model. Concentrations of recharge were also calculated for future study period of 6 years and fed in the model. The solute transport model was run for 6 years.

Result and Discussion

The objective of the study was to evaluate the available groundwater potential to meet the demand of water supply for FDA-City housing scheme in Faisalabad, it was deemed to evaluate the impact of new groundwater interventions in the model area. Main stresses to aquifer in the model area are pumpage by WASA tubewells existing well-field, new JICA well-field and pumpage by private tubewells which are increasing every year. Estimated groundwater abstractions by private tubewells and old WASA are given in Table 3.

Table 3: Estimated Groundwater Abstractions

SP No.	Cropping Season	Groundwater Pumpage [m^3/day]		
		Agriculture Tubewells	WASA Tubewells	Total
SP-1	Kharif-2005	3,546,991	155,351	3,702,342
SP-2	Rabi-2005-06	3,718,565	154,764	3,873,329
SP-3	Kharif-06	3,183,543	155,351	3,338,894
SP-4	Rabi-2006-07	3,231,911	154,764	3,386,675
SP-5	Kharif-07	3,411,051	155,351	3,566,402
SP-6	Rabi-2007-08	3,514,152	154,764	3,668,916
SP-7	Kharif-08	3,440,431	155,351	3,595,782
SP-8	Rabi-2008-09	3,350,464	154,764	3,505,228
SP-9	Kharif-09	3,482,425	155,351	3,637,776
SP-10	Rabi-2009-10	3,452,761	154,764	3,607,525
SP-11	Kharif-10	3,803,700	155,351	3,959,051
SP-12	Rabi-2010-11	2,893,103	154,764	3,047,867
SP-13	Kharif-11	3,453,891	155,351	3,609,242

Among these pumpages, it is pointed out that farmer's tubewells are scattered more or less in the whole model area and their impact is uniformly distributed over the whole study area. Existing WASA well field is putting a concentrated stress on the groundwater reservoir which has caused serious depletion of groundwater levels in the shape of a depression which has led to closure of local hand pumps, ejector pumps and even tubewells. This situation will be further aggravated as a result of installation of new tubewells.

The hydrographs of selected calibration points showing observed groundwater levels and those calculated by the calibrated model were prepared to check quality of calibration and are shown in Figures 7a-j.

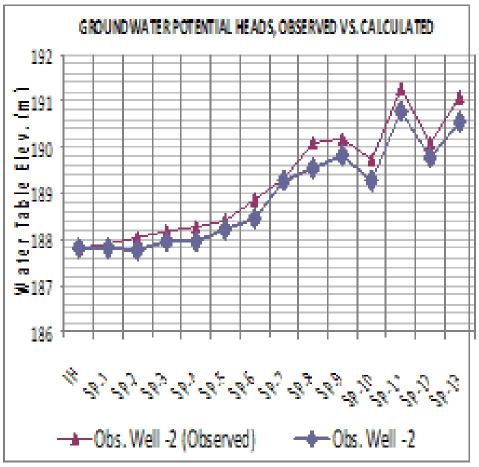


Figure 7a

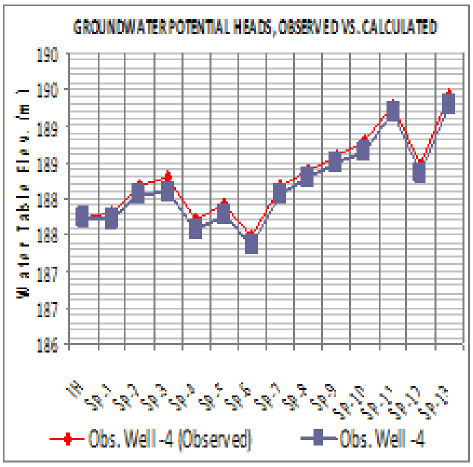


Figure 7b

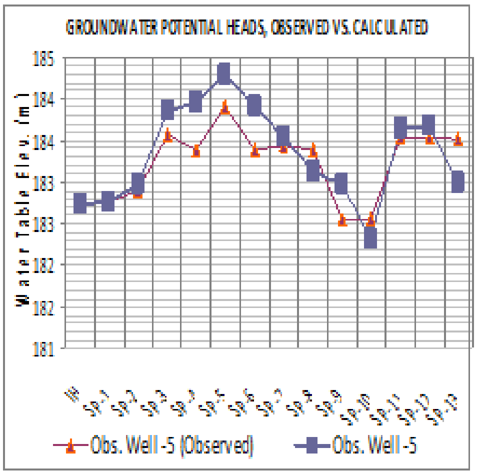


Figure 7c

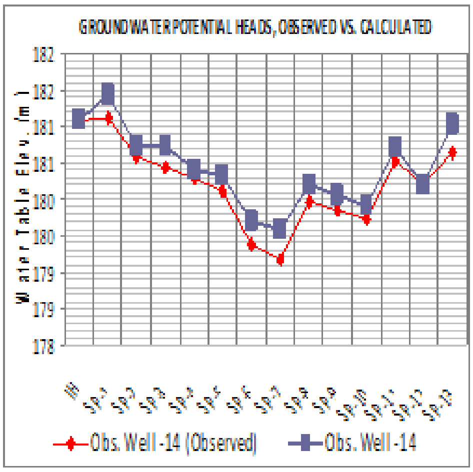


Figure 7d

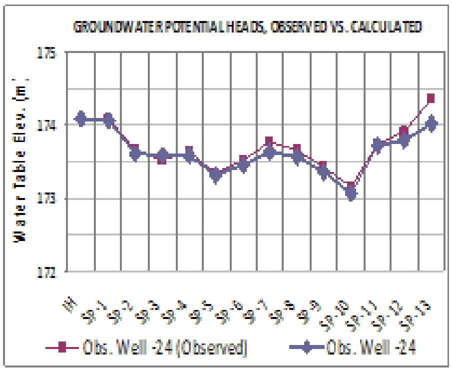


Figure 7e

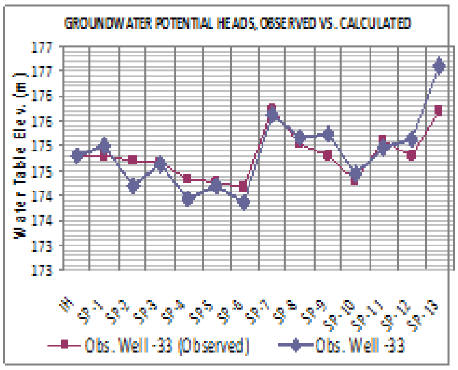


Figure 7f

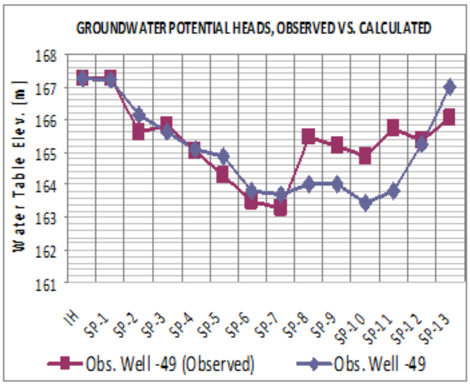


Figure 7g

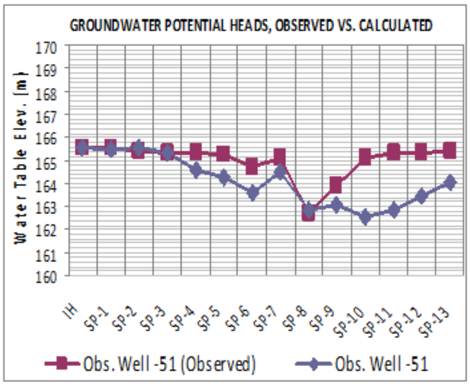


Figure 7h

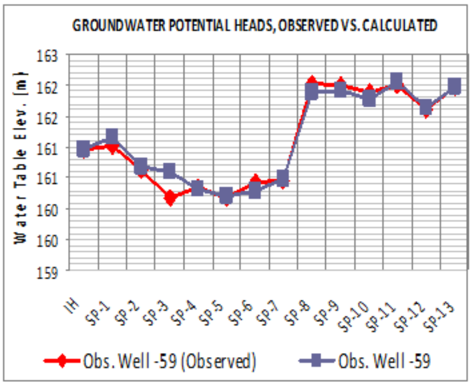


Figure 7i

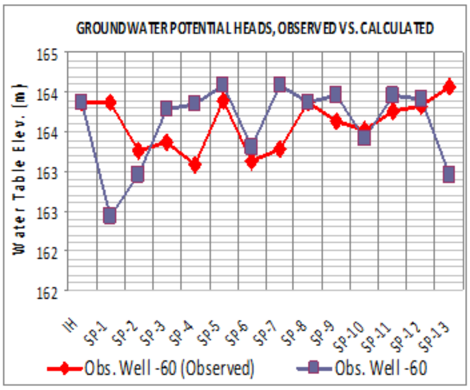


Figure 7j

Figure 7 a-j: Groundwater Hydrographs of watertable Elevation Observed and Calculated by Calibrated model

Groundwater level data monitored at the calibration points are given and placed above the hydrographs. The hydrographs at these points show similar trends. The small differences are due to the location of the observation points being not exactly at the nodal point of various cells where as the model computed heads are at the centre of the node. Since the computed and observed water levels closely match the calibrated model can be reliably used for predicting future groundwater conditions in the Project Area.

Groundwater Budget

At the end of each stress period the "MODFLOW" presents groundwater budget for various inputs and outputs. Budget computed by the model for the last stress period i.e. for cropping season Kharif 2011 is reproduced below in Table 4.

Table 4: Water Budgets of the Whole Model Domain at Time step 3 of stress period 13

FLOW TERM	IN	OUT	IN-OUT
STORAGE	6.54E+04	6.86E+05	-6.20E+05
CONSTANT HEAD	0.00E+00	0.00E+00	0.00E+00
WELLS	0.00E+00	3.67E+06	-3.67E+06
DRAINS	0.00E+00	0.00E+00	0.00E+00
RECHARGE	2.56E+06	0.00E+00	2.56E+06
ET	0.00E+00	0.00E+00	0.00E+00
RIVER LEAKAGE	9.11E+05	0.00E+00	9.11E+05
HEAD DEP BOUNDS	9.94E+05	1.71E+05	8.22E+05
STREAM LEAKAGE	0.00E+00	0.00E+00	0.00E+00
INTERBED STORAGE	0.00E+00	0.00E+00	0.00E+00
RESERV. LEAKAGE	0.00E+00	0.00E+00	0.00E+00
SUM	4.53E+06	4.53E+06	5.24E+01

Discrepancy [%] 0.00

Flows are considered "in" if they are entering a sub region and vice versa. The unit of the flows is [L3/T] meter and day units were selected, therefore, all budgets from different sources are in m3/day. Every aquifer contains water whose quantity depends upon storativity that may decrease or increase depending upon the inputs and outputs. Storage increases in case input is greater than output. It was the case when irrigation system was implemented and pumpage from open wells was small. The model can simulate all the flow terms given in the budget, however, model computes budget only for those flow terms which are activated by incorporating the input or output data. For example there is no stream or lake in the model area, therefore, it was not activated in the model, and accordingly, its budget is also zero. The rates of various inputs and outputs computed by the model for various stress periods are given in Table 4. These are the net groundwater abstractions and do not include return flow to groundwater in case of farmer tubewells.

Q = (NA – seepage from watercourse and fields)
Where Q is pumpage by farmer tubewells in m^3/day;
NA is the net abstraction given in the model budget "WELL OUT" in m^3/day.

Future runs have been carried out to study the response of aquifer when JICA and FDA proposed tubewells will also be set in operation. During the calibration period it has been found that groundwater abstractions for agriculture purpose do not increase. Lowering of watertable, particularly in the WASA well field area, may be one of the reasons. Accordingly, average pumping rates of the farmers tubewells experienced during the calibration period have been used in the study of future groundwater conditions.

Predicted Groundwater Flow System

In order to study change in groundwater flow patterns during the calibration period watertable contours were prepared for the groundwater potential heads measured in October 2005 and computed by the calibrated model for the same month of Year 2011. The watertable contours for October 2005 and October 2011 are depicted in Figure 5 and Figure 6 respectively. WASA had installed water supply tubewells for water supply to Faisalabad in 1992. These tubewells are supplying water to Faisalabad since then. After a period of about 13 years a conspicuous sink should have been developed in the WASA well field area. IRI measured static depth to water level in WASA wells, which represents groundwater conditions as computed by the model. Interviews of farmers also indicate that groundwater levels declined in the WASA well field area and they have to lower their centrifugal pumps and ultimately new wells with turbine pumps had to be installed. In order to see whether the calibrated groundwater numerical model has computed groundwater potential heads correctly or not, a sensitivity analysis was also carried out. The deepest groundwater potential head computed by the model is located in cell with row number 18 and column number 13. The groundwater potential head in this cell computed by model is 161.37 m. In the initial head file groundwater level in this cell was 166.6 m. It was changed to 161 m and run the model.

The model again computed the same water level in this cell i.e. 161.37. The result of sensitivity run indicate that the model has been stabilized with the various inputs and outputs and computed the resulting heads correctly during the calibration period of 6.5 years. Therefore, the model can safely be used for predicting groundwater conditions both for hydrodynamic and water quality changes. The resulting groundwater flow system shows that on the average groundwater flows from north-east to south-west direction with changing hydraulic gradients. Watertable gradients are less steep between Chenab River and Jhang Branch in the vicinity of proposed FDA well field and area located up-gradient. Watertable gradient is comparatively steep along Jhang Branch and Chenab River and its flow system indicate recharge from these two sources. The steeper gradients of watertable around the sink are due to:

- Pumping from the WASA well field; and
- Decreasing thickness of aquifer towards Chiniot.

Study of measured and model computed groundwater potential heads during October 2011 and predictions made for June 2018 do not show any conspicuous change in groundwater flow pattern except deepening of watertable. Model computed groundwater potential head for the June 2018 are shown in Figure 8.

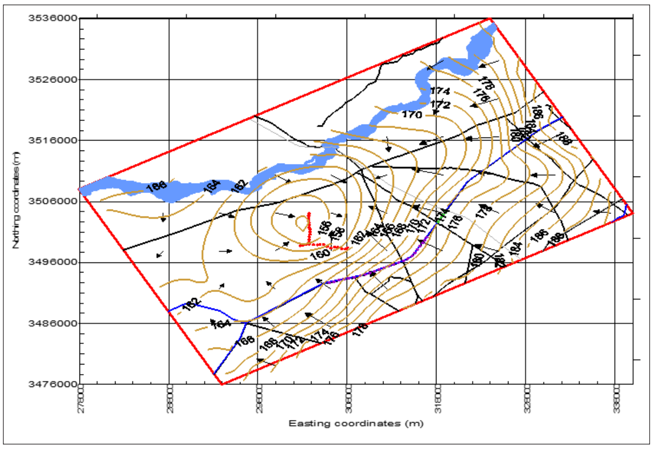


Figure 8: Model Computed Groundwater Potential Heads for June 2018 (meters)

Predicted Depth to Watertable Conditions

The model presents information on the computed groundwater levels at nodes of various cells. Depth to groundwater level can be calculated by subtracting groundwater potential heads from the natural surface levels. Lowering of watertable, at the critical points, has been calculated for the period of 6.5 years i.e. October 2011 to June 2018. The results are given in the Table 5. The predicted groundwater levels are shown in Figure 9.

Table 5: Water Table Elevation and Decline during October 2011 to June 2018

Sr. No.	Location of Cell	Groundwater Levels (m)		Total Decline in GW Level (m)
		October 2011	June 2018	
	WASA Well Field (row 18 col.13)	161.4	154	7.4
	FDA-City proposed Well Field (row 17 col. 21)	181.0	174.9	6.1
	At center of JICA Well Field (row 21 col. 17)	175.6	170.7	4.9

The table shows that groundwater levels will further decline to the tune of more than 5 m in various well field areas. In the WASA well field area the decline of watertable is expected to be more than 7 m when the JICA and FDA proposed tubewells were also set into operation.

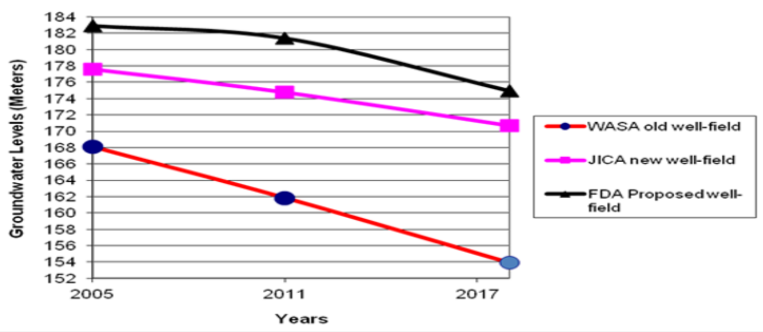


Figure 9: Predicted Groundwater Levels Near Different Well-Fields

Solute Transport Model

General

In order to assess the impact of additional groundwater abstractions for water supply to Faisalabad old and new cities on groundwater quality, solute transport analysis in aquifer system is imperative. The modelling study for groundwater flow has revealed that watertable has fallen considerably in WASA well field area and groundwater is flowing towards this cone of depression from surroundings. In addition to these, JICA has installed new 25 tubewells, along JBC. FDA also wants to install 5 more tubewells to get a water supply of 20,000m3 /day for new housing scheme FDA-City. At the same time pumpage by private tubewells will also increase as the number of private tubewells in increasing every year. All these stresses will change the hydrodynamics and geo-chemistry within the underlying aquifer and may result in decrease in quantity and deterioration of quality of groundwater resource. Therefore, to predict the groundwater quality under future scenarios, solute transport modelling study is imperative.

Water Quality Data used for Solute Transport Model

Generally, as in the case of the Project Area, the necessary data on chemical quality of groundwater with their time rate changes in aerial and vertical extent are not available to meet the requirements of the model. The available data on groundwater quality distribution in lateral and vertical extent was gathered from the reports and by performing electrical resistivity survey in the proposed FDA-City well field area. The groundwater quality data used in the model as initial conditions is depicted in Figure 10.

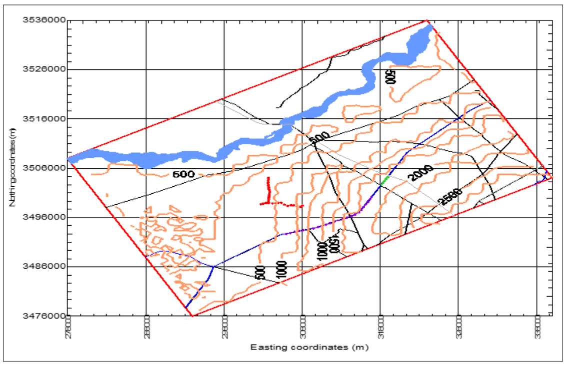


Figure 10: Initial Concentrations of TDS (ppm) June 2012

The figure shows that water quality in the south-eastern part is saline which is about 3,000 ppm along the boundary and gradually becomes fresh towards northwest. The groundwater quality improves towards Jhang Branch Canal and in the remaining project area. The fresh and saline interface is not regular and is restricted in the south-eastern part of the project area as shown in Figure 11.

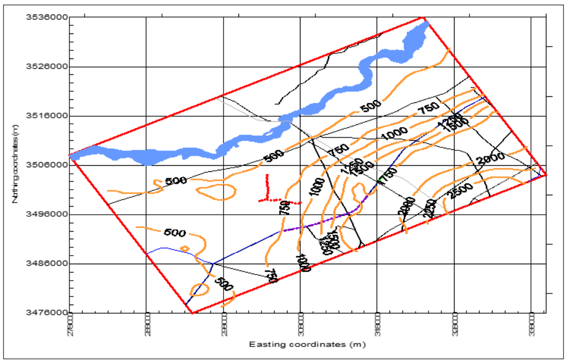


Figure 11: Model Computed Groundwater Quality TDS (ppm) October 2018

Parameters Required For Advective Transport of Solute

The solute movement due to advection for a given time step is simulated by the MT3D using the corresponding velocity field computed by the calibrated MODFLOW flow model and the effective porosity of the aquifer. Since the MODFLOW flow model has been calibrated for the historical data, i.e. the computed and observed water levels at the selected locations closely match with each other; therefore, the flow field used for advective transport has been accurately calculated.

Quality of Sources and Sinks

For the tubewells and seepage flow to the river Chenab (if any) MT3D internally calculates the quality from the salinity concentration of the layers from which the pumpage is taking place. The groundwater recharge, canal seepage and river seepage are the sources of solute influx in the groundwater. The concentrations of recharge from various sources increase depending upon the volume of recharge. For example:

- Canal deliveries in the project area are V;
- Recharge from the canal deliveries are R; and
- Concentration of canal water is 120 ppm.

The quality of recharge will be:
$C = 120 * V / R$

The concentrations of canal water were calculated for each cell and given in the recharge package of solute transport. In the river cells concentrations of 120 ppm were given and the solute transport calculates concentrations being fed through seepage/ recharge from the river.

In the general head boundary cells, concentrations of groundwater were given in the data for that cell and it ranges from 500 to 3000 ppm. General Head Boundary may add or remove concentrations in accordance with the groundwater flow pattern.

Tubewells pump concentrations along with groundwater. However, these salts are returned back into the aquifer through recharge. Concentrations of recharge from tube well irrigation also increase in accordance with the volume of water pumped divided by recharge from it. These concentrations were also calculated and used in the solute transport model in well source. The resulting water quality concentration in ppm is shown in Figure 6.8. This figure indicates that groundwater quality deteriorates towards JBC with passage of time.

Apart from the irrigation tubewells of farmers, WASA well field was also developed almost in the central part of the area between Chenab River and Jhang Branch Canal. Feasibility and design report of this well field was not made available for study and to understand the impact of this well field on environment. Detailed data on hydrodynamics when WASA well field was established is also not available. Therefore, impact of WASA tubewells in the real sense could not be established.

Recently JICA has installed tubewells along left bank of Jhang Branch Canal for WASA Faisalabad. These tubewells are meant to pump a total requirement of 91,000 m3/day. Feasibility study to estimate available safe yield of aquifer was mainly based on the recharge from the Jhang Branch Canal. Considering studies conducted by Irrigation Research Institute average seepage rate was considered as 12,840 m3/day [13,14]. It was assumed that this seepage is being utilized by the irrigation tubewells installed within a distance of 3 km from the canal. However, no watertable contour map was prepared to justify this assumption i.e. groundwater flow system should have shown a water divide at a distance of 3 km from the canal. It shows that the assumption was not adopted on the basis of required scientific studies/investigations.

A lot of advancements have been made in the field of groundwater resources evaluation, development and management by developing groundwater numerical models. Properly calibrated models are used to predict future behavior of watertable in response to various development options. Accordingly, groundwater numerical models (both flow and solute transport) have been developed to study the impact of proposed well-field. To have minimum possible error due to boundaries, the area for the model was selected up to Chenab River in the north-west and covering maximum saline area in the south-east. Maximum possible area has been covered in the model developed and calibrated for the groundwater development and management. This model is capable to predict groundwater behavior and water quality changes in response to future pumpages not only from the FDA-City tubewells but also impact of tubewells installed by JICA and WASA in the past.

Calibrated flow model reveals that as a result of pumping from WASA tubewells, a sink has already been developed at the center of WASA well field area. This shows that the assumption on which groundwater potential available for JICA tubewells was made, is most probably not correct and long term pumping from JICA tubewells in addition to pumping from WASA tubewells may create serious issues for the local farmers in utilizing groundwater for their crops.

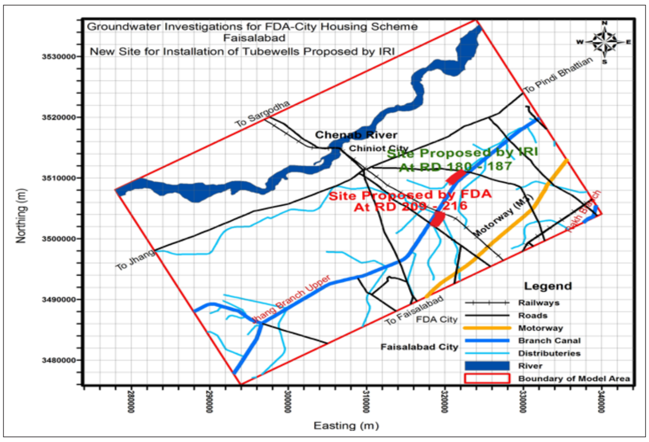


Figure 12: Location of New Site for Installation of Tubewells Proposed by IRI

The flow model has been successfully calibrated to simulate the hydrodynamics and flow conditions of the aquifer from 2012 to 2018. Solute transport model has been linked with the flow model to study the migration of salts due to additional pumping from the new interventions. It is a well-known fact that groundwater quality along the rivers is fresh and becomes saline towards center of various doabs. The same condition prevails in Rechna Doab. Groundwater quality is fresh along Chenab River and saline in the central parts of the doab. Water quality underlain by Faisalabad city is highly saline and that is why water supply tubewells were located on the right side of Jhang Branch Canal where groundwater quality is fresh. Groundwater is being used for irrigation and drinking purposes where its quality is fresh.

Comparatively there is less or negligible pumping of groundwater in the saline area. This situation will create imbalance between hydrodynamics in the fresh water and saline water areas. Therefore, ultimately saline water will start moving from saline zone to fresh water zones. In this case saline water can deteriorate water quality in the fresh water areas as a result of lateral intrusion due to decrease in groundwater potential heads in response to heavy concentrated pumping especially for water supply purpose. Accordingly, very efficient, precise planning and management of water resources (surface and groundwater) is required to protect groundwater resource so that it may be used beneficially on the long term basis, without any environmental hazard. Combining groundwater quality contours and depth to bed rock contours, the appropriate location for the proposed well field has been proposed near RD 180-187 of JBC. The overlay of these contours is shown in Figure13.

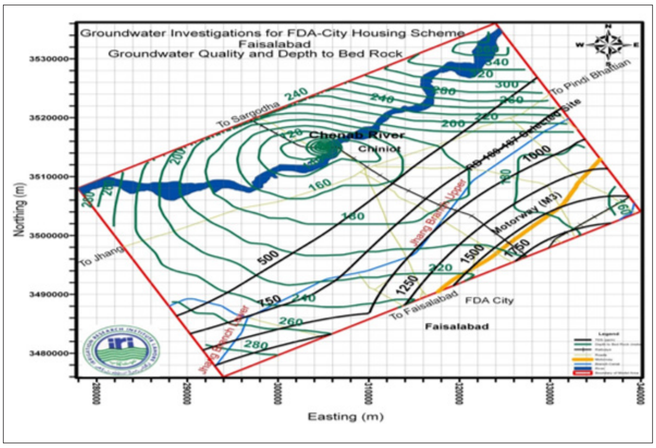


Figure 13: Depth to bed rock and groundwater quality in model area

Conclusions

1. Prevailing groundwater flow in the upper part of the model area is towards WASA well field area. The watertable contours indicate that Chenab River and Jhang branch canal are most of the time contributing water to underlying aquifer(s).
2. Future predictions of model indicate that there is no conspicuous change in regional groundwater flow pattern, even with all the existing tubewells remain in operation. However, the sink in the WASA well field area further deepens and flow gradients become comparatively steep showing increase in groundwater flow velocity.
3. Depth to watertable in WASA well field area has already increased from 12 m in 2005 to 16 m in 2011 which is the most critical area within the model boundaries. Model has predicted that this depth will further increase to 24 m in 2018, considering that all the JICA and FDA proposed tubewells are in operation provided other existing conditions remain same. This indicates over all depletion of groundwater reservoir.
4. The model has predicted that saline groundwater existing in south-eastern side of model area will move in north-west direction in 2018 causing deterioration of water quality subject to the existing situations.
5. However, water quality upstream of RD 187of JBC will more or less remain fit for drinking till 2018 provided all other conditions remain same.

Recommendations

WASA established its well field, in 1992. These tubewells have already completed their useful life. Now their replacement should not be clustered within this area. If required, locations of the tubewells should be selected on the basis of results of model studies by distributing the pumpage over larger area.

1. The well field proposed by FDA-City (RD 209-216 of JBC)

is located where transmissivity of aquifer decreases towards north-east. It starts increasing upstream in the vicinity of RD 187 of JBC. Water quality also improves upstream. It is therefore, recommended that the well field may be shifted to RD 180 to RD 187 preferably on right side of the JB canal. At this location major recharge will be from north-east, therefore, pumping from this area will have comparatively less impact on the hydrodynamics existing in the vicinity of Chiniot and old well fields of WASA and JICA which are already being affected badly.

2. Depth and capacity of tubewells should be carefully selected to cope with the saline water interface and on the basis of thickness of fresh groundwater aquifer.
3. Groundwater balance should be maintained by conducting a separate investigation regarding rainfall harvesting and artificial recharging of underlying aquifer after selection of potential sites in the recharge zone. Special site specific system for recharging the aquifer shall be designed and executed.
4. Systematic monitoring of depth to water table and quality should be carried out for timely understanding of aquifer behavior. In case of saline water intrusion, a battery of tube wells in saline groundwater area should be installed to avoid this intrusion. Saline water can be used for the purposes other than drinking (industry, irrigation, livestock and washing etc.) after low level treatment.
5. Pumping from the old well field should be minimized. If required new well field should be carefully designed by selecting the appropriate well spacing to avoid point impact, saline water intrusion and over exploitation of groundwater reservoir. Installation of well field shall be supervised by the technical experts for site specific decisions at the spot.
6. New proposed well field shall be located at reasonable distance from JBC so that groundwater flow lines are predominantly horizontal. Also it should follow the existing policy for maintenance of ROW.
7. WASA-FDA shall ensure the regular monitoring of groundwater levels and quality by strengthening further the monitoring network especially in the well field area.
8. Data on the surface drains in the model area needs to be collected and their impact on groundwater quality and quantity should be assessed.
9. Lining of irrigation channels within the area of well field and recharging zone around it should be avoided to maintain the groundwater recharge.
10. Post model evaluation is necessary to verify the findings of the model.

References

1. Ahmed M Din (2002) Estimation of Net Groundwater Use in Irrigated River Basins Using Geo-Information Techniques, A Case Study in Rechna Doab, Pakistan, Ph.D. Thesis, Wageningen University, Netherlands. ITC Dissertation Number 94.
2. Jac G, Lipponen A, (2010) Reconciling Groundwater Storage Depletion Due to Pumping with Sustainability. Journal of Sustainability 2: 3418-3435.
3. Information on http://www.faisalabad.gov.pk/statistics
4. Qureshi AS, Akhtar M (2003) Impact of Utilization Factor on the Estimation of Groundwater Pumpage. Pakistan Journal of Water Resources 7: 17-27.
5. Qureshi AS, Mc Cirnick PG, Sharam RB (2009) Challenges and Prospects of Sustainable Groundwater Management in the Indus Basin, Pakistan. Water Resource Manage, Springer Science 24: 1551-1569.
6. Zhou Y, Li W (2011) a Review of Regional Groundwater Flow Modeling. Geo Science Frontiers 2: 205-214.
7. Beckers J, Frind EO (2000) Simulating groundwater flow and runoff for the Oro moraine aquifer system. Part-1, Model formulation and conceptual analyses. Journal of Hydrology (Amsterdam) 229: 445e460.
8. Richard J Mandle (2002) Groundwater Modeling Guidance. Michigan department of environmental quality. Groundwater Modeling Program, 14, 1e30.
9. Camp M Van, Radfar M, Walraeven K (2010) Assessment of Groundwater Storage Depletion by Overexploitation Using Simple Indicators in an Irrigated Closed Aquifer Basin in Iran. Journal of Agricultural Water Management 97: 1876-1886.
10. Water and Soil Investigation Division (WASID) Publication No.30, 1964 and WAPDA, WASID -12, 1960.
11. Washington (1967) WAPDA (Water and Power Development Authority), Analysis of Aquifer Tests in the Punjab Region of West Pakistan. Geological Survey Water Supply- paper 1608-G, US.
12. Kumar CP (2002) Groundwater Flow Models. E1-National Institute of Hydrology, Roorkee, India.
13. Irrigation Research Institute (IRI) (2003) Seepage Measurement of Jhang Branch Canal at RD 215-280, Report No IRR-Phy/551, Lahore, Pakistan.
14. Irrigation Research Institute (IRI) (2009) Seepage Measurement of Jhang Branch Canal at RD 209+642 to 216+852, IRR-PHY/554, Lahore Pakistan.