Groundwater Flow Modelling and Aquifer vulnerability assessment studies in Yamuna–Krishni Sub-basin, Muzaffarnagar District

(Project No.23/36/2004-R&D)

Completion Report

Submitted to

Indian National Committee on Ground Water
Central Ground Water Board (CGWB)
Ministry of Water Resources
(Govt. of India)

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3. **Title of the scheme:**

"Groundwater Flow Modelling and Aquifer vulnerability Assessment Studies in Yamuna-Krishni Sub-basin, Muzaffarnagar District"

4. **Financial details:**

Sanctioned cost	**Amount released**	**Expenditure**	**Unspent balance**	**Return of unspent balance**
13,82,000	**11,18,900**	**10,43,928**	**74,972 CR**	**------**

5. Original objectives and methodology as in the sanctioned proposal:

Study Background

In most of the hydrogeological studies in alluvial aquifers, water balance studies are carried out using the norms provided by NABARD for evaluation of groundwater resources and there by deciding its status of utilization. However, these norms are mostly adhoc and based on large number of assumptions. Many facts are ignored just to simplify the procedure. For example, boundary flows are not often taken into account which practically implies that the system is always in steady state. Another important factor of exchange between river and aquifer are not considered while this is quite common feature in Ganga basin. Moreover, the status of utilization can be calculated only for present case and it is not always possible to project it to the future. In addition, various parameters for data budgeting are taken uniform ignoring high spatial variability often present in sub-surface. Therefore, to overcome all these disadvantage and minimizing the error of estimation, the system should be evaluated through aquifer modeling where water balance is established using partial differential equation of groundwater flow and is solved with boundary and initial boundary conditions.

Another important aspect is protection of aquifer from various contaminations, natural as well as anthropogenic. It would be practical to demarcate and systematically study the vulnerable zones. This zonation will facilitate any mitigation scheme proposed or considered necessary. Keeping this in view, a research proposal entitled “Groundwater flow modeling and aquifer vulnerability assessment studies in Yamuna-Krishni sub-basin Muzaffarnagar district, Uttar Pradesh” was submitted to the Ministry of Water Resources.

The study area is being famous as an intensive agriculture tract of western Uttar Pradesh. Heavy withdrawal of groundwater has set a declining trend of water table over the decade. Few blocks of the basin is reported to be over exploited and some are in semi-critical to critical position. With rise in population and agricultural development, the withdrawal will go at higher scale, which needs especial study in order to ascertain the future behaviour of water table in time and space.

(i) Original objective:

- Development and improvement of water balance of an aquifer incorporating natural condition of flow system.

- Demarcations of aquifer zone vulnerable to contaminations and feasibility study of its mitigation.

(ii) Methodology

The methodology applied to assess the water balance, using numerical modeling and vulnerability assessment of the aquifer is as follows.

(a) Groundwater Flow modelling

In order to generate quantitative database on hydrogeological parameters and water quality systematic field work will be carried out.

- Setting up of grid wise observation wells to collect water level data.
- Repeat measurements to monitor changes in water level will be made during the study period.
- Aquifer parameters will be collected from agencies like CGWB, GWIO, and Pumping test will conducted where data gap exist.
- Recharge estimations will be carried out using tracer technique.
- Borehole formation samples will be analyses to find vertical variation in hydraulic conductivity.
- Lithological logs of deep wells in the area will be collected to prepare hydrogeological cross-section.
- Rainfall and various hydrological data pertaining to the area will be collected and analysed.

(b) Model Preparation

The study area will be sub-divided into small areas called meshes of varying sizes depending upon data availability, spatial variability vital parameters viz. transmissivity (T) and water level.

Partial differential equation is then discriticized over the meshes of the model and difference equation are written using finite difference approximation and solved using appropriate method. All the parameters of the groundwater flow equation are estimated over the meshes of the model from the available data from the field. A geostatical krigging technique which is based on the minimum error variance could be employed.

The system once solved in steady state will provide solution in the form of water level in space and by solving system in transient state will provide water levels in space as well as time.

Once the model is satisfactorily calibrated both in steady and transient states the model could be used to predict the response in future with the assumed or extended values of input mainly the demand and rainfall recharge.

(c) Aquifer vulnerability

A detailed soil and hydrogeological investigation will be carried out by interpreting a range of soil properties such as texture, structure, thickness organic carbon content, clay mineral content, permeability, geologic and hydrogeologic criteria to zone land according to its intrinsic characteristics. Considering the above facts aquifer vulnerability map will be prepared.

6. Any changes in the objectives during the operation of the scheme. - No

7. All data collected and used in the analysis with sources of data

All the data generated and collected are listed in appendices (please see- Page No. i to xxxiii).

8. Methodology actually followed. (observations, analysis, results and inferences).

(i) Methodology

In order to generate quantitative data base to infer hydrogeology, groundwater resource evaluation and chemical characteristics of Yamuna-Krishni sub-basin, systematic groundwater surveys were carried out supported by laboratory investigations.

- The literature pertaining to study area was collected and background information on state-of-the-art was generated.
- Toposheets of the study area were used to generate base map for the field survey.
- Rainfall and various other hydrological and hydrogeological data pertaining to the area were collected. The rainfall data were statistically analysed and the mean, standard deviation, coefficient of variation were calculated.
- A Landuse and Landcover map for the area was generated, using the remote sensing data from IRS-1B LISS-II and IRS-1D, LISS-III. A change detection analysis in Landuse and Landcover using two time period data is also attempted.
- Initially 71 wells were selected for water level monitoring in November 2005. Later it was reduced to 60 wells and monitoring were carried out in these wells in 2006, 2007 respectively.

- Coordinates of the borewells were taken using GPS.
- Repeat measurements to monitor the changes in water level, for pre and post monsoon were carried out in year 2006 and 2007 in all the monitoring wells.
- Bimonthly monitoring were also carried out from February 2007 to November 2008.
- The water level data of monitoring wells were processed and various maps like depth to water maps, water table contour maps and water level fluctuation maps were prepared.
- Historical water level data of 14 hydrograph stations monitored by Central Ground Water Board and State Groundwater Department was utilized to prepare hydrographs to infer long term water level trends.
- Lithologs of deep tube wells were collected to prepare cross-sections and fence diagram.
- Sand samples were collected from varying depths of granular zones and were utilized for permeability estimation in the Laboratory using Permeameter.
- The sand samples were also mechanically analysed for grain size analysis and parameters like effective grain size and uniformity coefficient were determined.
- Groundwater Budget were prepared for June 2006 to May 2007 and June 2007 to May 2008 using guidelines provided by Groundwater Estimation Committee (GEC) 1997.
- Groundwater flow model was prepared using software Visual MODFLOW Version 4.1 Pro.
- Steady state model was prepared for November 2006 and transient state model was prepared from June 1999 to November 2007.
- Sustainability of groundwater regime was attempted for next 8 years under variable stresses.
- Classification of aquifer vulnerability to contamination is also carried out using modified DRASTIC model.
- In all, 144 groundwater samples were collected for physico-chemical analysis in four successive season's viz. post-monsoon and pre-monsoon period corresponding November 2005, June 2006, November 2006 and June 2007 respectively.

- Twenty six groundwater samples in June 2006 were analysed for trace elements using ICPMS.
- Fourteen surface water samples were collected from river Yamuna and Krishni for major ion analysis. In addition 4 drains and two sugar factory effluent samples were also collected for similar analyses.
- Six surface water samples were also analysed for trace element.
- Groundwater of the study area was classified into different chemical groups on the basis of major ions concentrations.
- Various mechanisms were identified and presented, which seem responsible for alteration in groundwater chemistry.
- Concurrence and synthesis of hydrogeological, hydrometeorological and hydro-chemical data was attempted to generate the model for groundwater regime of Yamuna – Krishni sub-basin presented in the present research work.

(ii) The work carried out and data generated are described and discussed under following chapters.

(1) The Study Area
(2) Hydrogeology
(3) Estimation of Dynamic Groundwater Resource
(4) Groundwater Flow Modelling
(5) Groundwater Vulnerability Assessment
(6) Hydrogeochemistry
(7) Project findings

1 - THE STUDY AREA

1.1 Location and Accessibility

Muzaffarnagar is an important district in western Uttar Pradesh and the town Muzaffarnagar is the district Headquarter. It lies in the interfluves of Ganga and Yamuna rivers in the western most part of the Uttar Pradesh.

The study area falls between Longitudes $77^0 05^/$ and $77^0 27^/$ E and latitude $29^0 15^/$ and $29^0 41^/$ N (Fig.1.1) and covers an area about 1100 km^2. The Rivers Yamuna and Krishni forms the western and eastern boundaries, respectively. It is well connected with adjoining town such as Saharanpur and Meerut by rail and roads. Almost all the villages of the area are approachable by motarable roads.

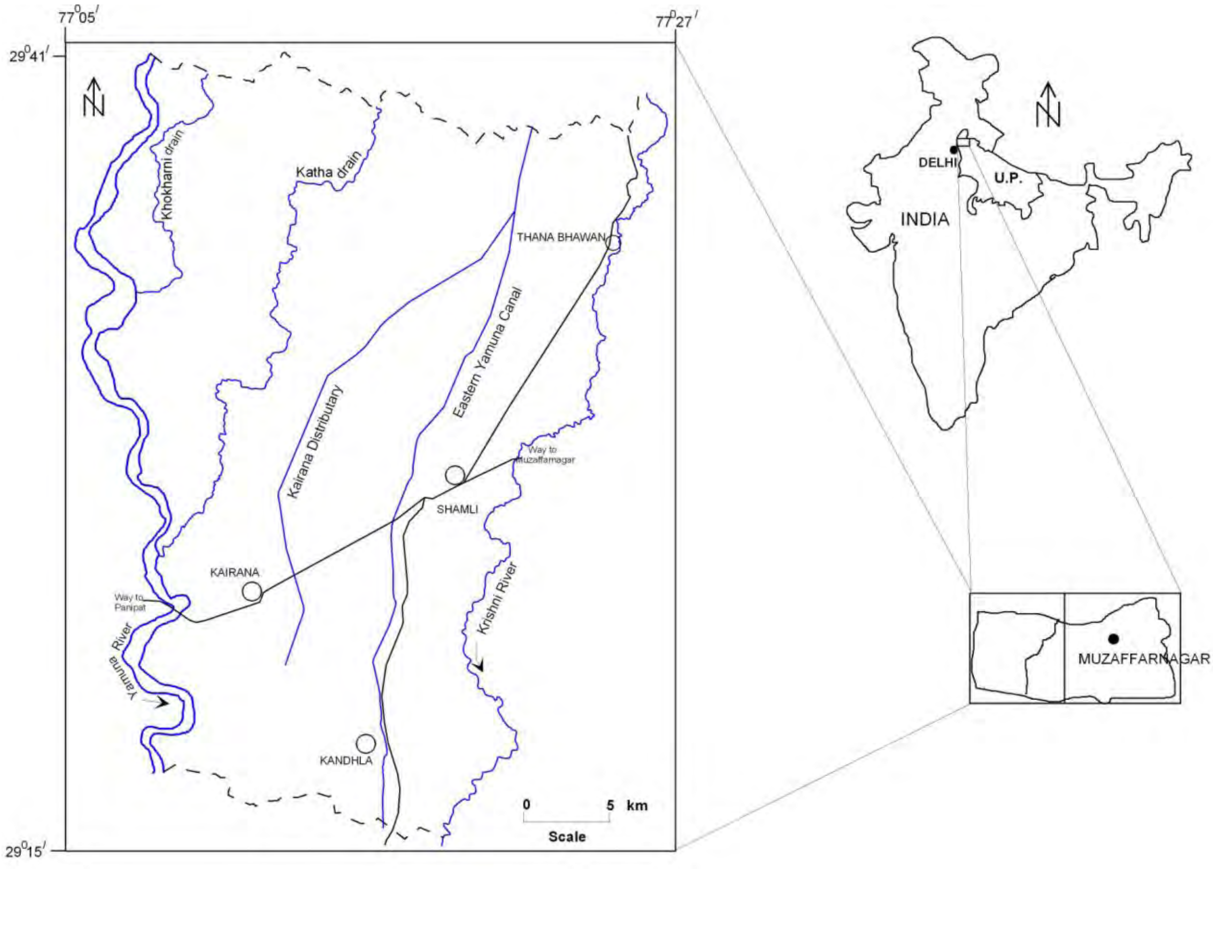


Fig.1.1 Location map of the study area

1.2 Climate

The climate of the area is characterized by general dryness except during the brief span of monsoon season. It has a hot summer and a cold winter. The year is divided into the four seasons. The period from the middle of November to about the ends of February is the cold season. The hot season which follows, continues up to the end of June. The rainy season spans over the period of mid June to September. The post-monsoon or the pre-winter extending from mid September to mid November follows this. The highest temperature, reaching to 45^0C is generally recorded during the month of June. The lowest temperature of about 4^0C is recorded during the month of January. The average mean daily temperature of the area ranges from 20^oC to 32^oC.

Winds are generally light and only a little strong in the summer and monsoon seasons. During October and April, they are mostly westerly or northwesterly. From May, they become easterly and during the southwest monsoon season, they are predominantly easterly or southeasterly.

1.3 Physiography and Drainage

District Muzaffarnagar is rectangular in shape and it is situated between the district of Saharanpur on the north, Meerut and Baghpat on the south, and is bounded by the Ganga on the east and the Yamuna on the west. The main rivers, the Ganga, the Kali, the Hindon and the Yamuna have played an important role in carving the topography of the district and divide it into four distinct tracts (Nevill, 1903, Varun, 1980) *i.e.* (i) the Ganga Khadir (ii) upland upto Kali Nadi (iii) the Kali Hindon doab and (iv) the Hindon Yamuna doab. The study area Krishni-Yamuna sub basin is a part of Hindon-Yamuna doab.

The river Yamuna, which forms the western boundary of the district, flows in an irregular course from north to south with uncertain and not well-defined channels (Plate-1a, b & c). The rivers command a large tract of low-lying area of newer alluvium, which is locally known as *Khadir*. The river krishni forms the eastern boundary of the area. Near the river Krishni there is as usual, much poor soil and low land areas are well adapted for rice cultivation. Krishni flows in a well-defined channel (Plate-2), and the *Khadir* is small as compared to Yamuna.

The central upland is somewhat like an elevated plateau. Near Yamuna river and the Katha drain the land are generally affected by saline soil. The villages lying along the Katha on both sides have suffered largely from the increased volume of the floods in this river, which now receives the contents of several drainage.

The eastern yamuna canal flows through water divide from north to south. The low grounds along the canal have saline soil, which has thrown considerable area out of cultivation (Plate-3). The soil is much less sandy than in and around the Yamuna canal tract.

The drainage of the study area is mainly controlled by the two rivers i.e. Krishni and Yamuna, which are flowing from north to south. Both the rivers are perennial and meandering in nature. Katha and Khokharni drains are small, left over channels of river Yamuna, which flow along the NW side of the area and join the Yamuna river near village Mawi and Kertu, respectively.

1.4 Digital Elevation Model

A digital elevation model (DEM) is a digital representation of ground surface topography of terrain. The topography of the sub-basin is based on Digital Elevation Model obtained with the help of SRTM data which is available at number of USGS websites (Fig.1.2). The coordinates of the study area were overlaid over the SRTM data and the Digital Elevation Model was prepared for the boundary assigned to the software. The perusal of DEM shows that altitude varies from 262-224 metres above mean sea level (m amsl). The extreme north east part of the area has maximum elevation ranging from 262-254. In general, the central track has got higher elevations which gently slope towards the rivers courses due west and east i.e. towards the river Yamuna and Krishni, respectively. River courses have lowest elevation comparing to the adjacent area. The Krishni river has elevation of 256 m amsl at the point where it enters in to the study area and 223 where it leaves the area at the bottom. The Yamuna river elevation from top to bottom ranges from 246 to 222 m amsl, respectively. The low elevation area in the vicinity of river Yamuna is characterized by flood plains.

In the middle of upper half of the study area, tracks of Katha drain, a left channel of river Yamuna is clearly visible because of less elevation than the adjacent area. The Katha drain finally joins the Yamuna river at the middle reaches near village Mawi.

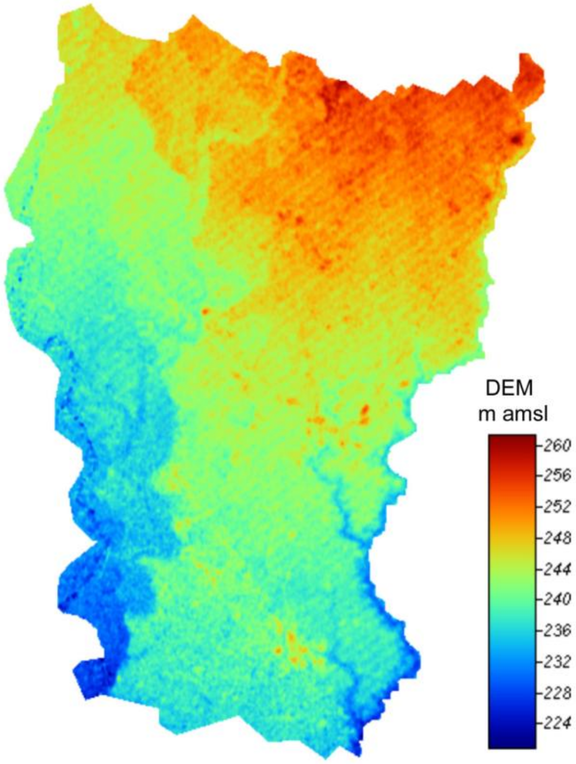


Fig.1.2 Digital Elevation Model of Yamuna-Krishni sub basin.

1.5 Land Use/Land Cover

A Landuse/Landcover (LU/LC) map for 1971 has been derived from Survey of India toposheets No. 53G/2, 53G/3, 53G/6 & 53G/7 on 1:50,000 scale (Fig.1.3a). The area has been categorized into five landuse classes. It includes settlement, water body, Agricultural land, waste land and plantation. The area covered by these classes is tabulated in Table 1.1.

Another LU/LC map (Fig.1.3b) was prepared using remote sensing IRS-1D Liss-III data (Path-Row 95-50) of 15 march 2002 of band combination 2 (green), 3 (red), and 4 (near infra-red), procured from National Remote Sensing Agency, Hyderabad, India. Standard visual image interpretation technique was used. Similar LULC classes were used in both time periods. Field verification of map generated was also carried out. The data obtained is listed in Table 1.1.

Table 1.1 Showing change in Landuse/Landcover pattern in the study area

S.No.	LULC Class	Area (sq. km.)		% Coverage	
		1971	2002	1971	2002
1	Settlement	24.67	96.08	2.24	8.73
2	Water Body	1.93	1.34	0.18	0.12
3	Agricultural Land	994.95	972.4	90.41	88.36
4	Wasteland	72.66	16.47	6.60	1.50
5	Plantation	6.3	14.22	0.57	1.29
	Total	1100.51	1100.51	100.00	100.00

A change detection analysis was attempted using two time periods. The available data reveals that the area under cultivation has marginally decreased from 90.41% to 88.36% during the period from 1971 to 2002. The area covered by wasteland during 1971 was 6.6% which has reduced to 1.5% in year 2002. It shows that some of the land is reclaimed for agricultural uses. The area occupied by settlements has increased from 2.24% to 8.73%. The same period has witnessed doubling of population from 1.8 to 3.54 million. These figures clearly indicate the alarming level of threat to the groundwater system of the area.

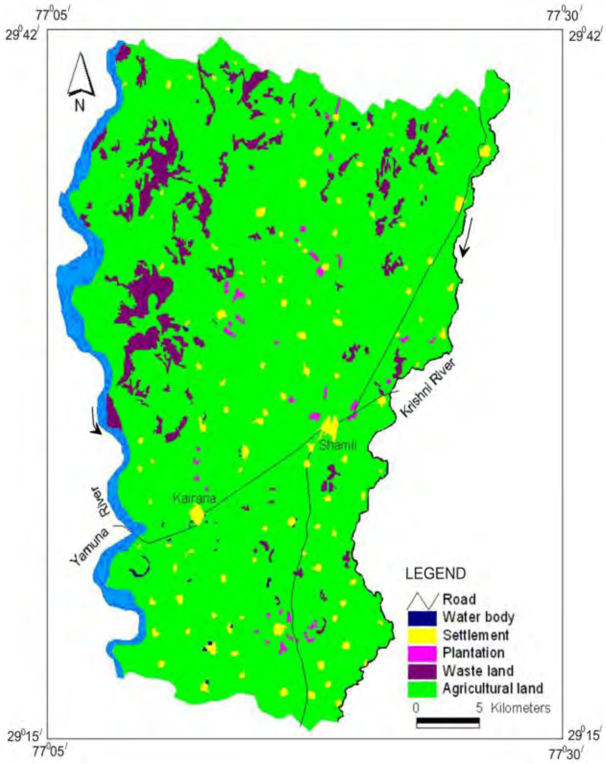


Fig.1.3a Landuse/Landcover pattern in the study area (1971).

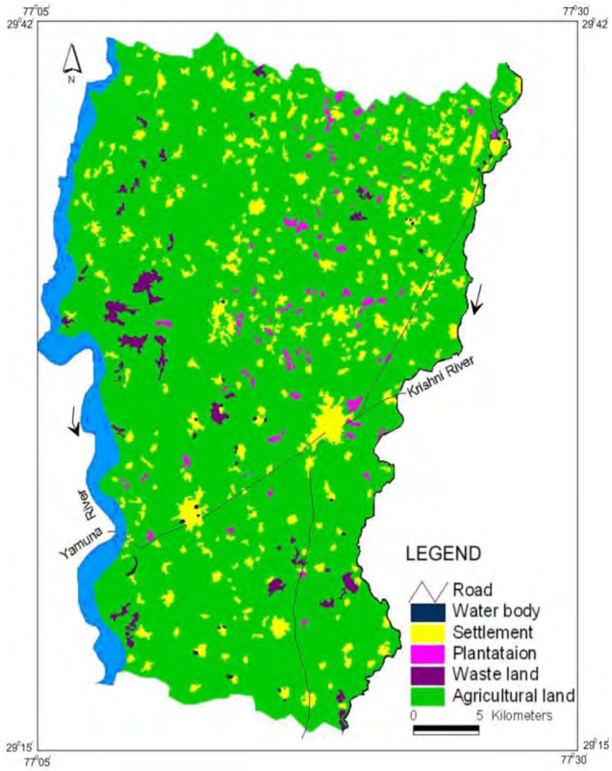


Figure 1.3b Landuse/Landcover pattern in the study area (2002)

1.6 Water Utilization Pattern

Out of total water resources of the Yamuna-Krishni sub-basin, only 8.1% is derived from the surface water sources and 91.9% from the groundwater. The Eastern Yamuna Canal and its distributaries are main source of surface water irrigation.

The block wise water utilization pattern is shown in figure 1.4. A perusal of figure shows that the blocks traversed by Eastern Yamuna Canal have maximum surface water utilization which range from 9 to 13% of total water use. In the rest of the blocks contribution from surface water is, on an average, is less than 5%. These figures clearly show stress on groundwater regime of the area.

1.7 Rainfall and its Temporal Variability

The available annual rainfall data of Kairana and Shamli raingauge stations for the period of 1990-2007 and 1990-2007 have been statistically analysed and results are tabulated in Table 1.2 , respectively.

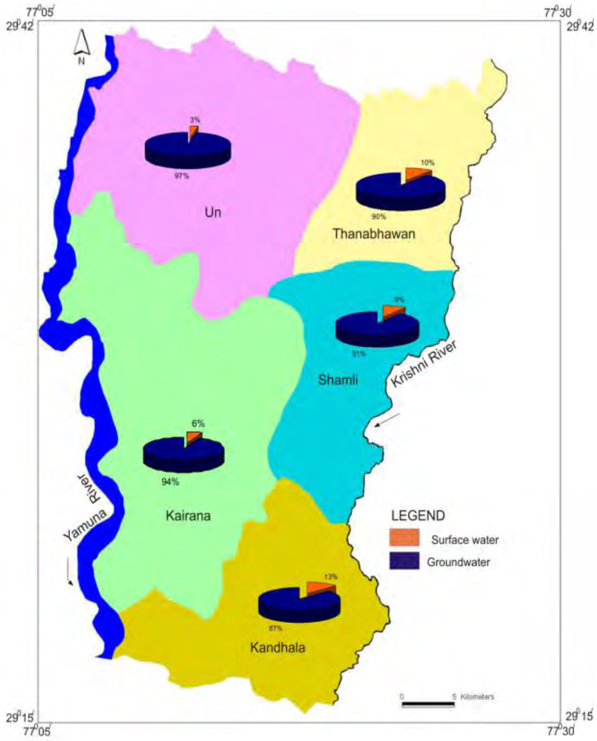


Fig.1.4 Block-wise water utilization pattern

It is observed that the highest rainfall at Kairana raingauge station is 1220 mm in the year 1990 whereas the lowest 415 mm (2007) showing a very wide range of variation. The mean annual rainfall is 664 mm. The highest rainfall at Shamli raingauge is 1099 mm in the year 1995 whereas the lowest is 206 mm in the year 1993 showing a wide range of variation. The mean annual rainfall is 697 mm. The results of Statistical analysis of rainfall data at Kairana and Shamli Raingauge Station is given in Appendix-IA and IB. The yearly rainfall distribution is shown in figure 1.5a and 1.5b.

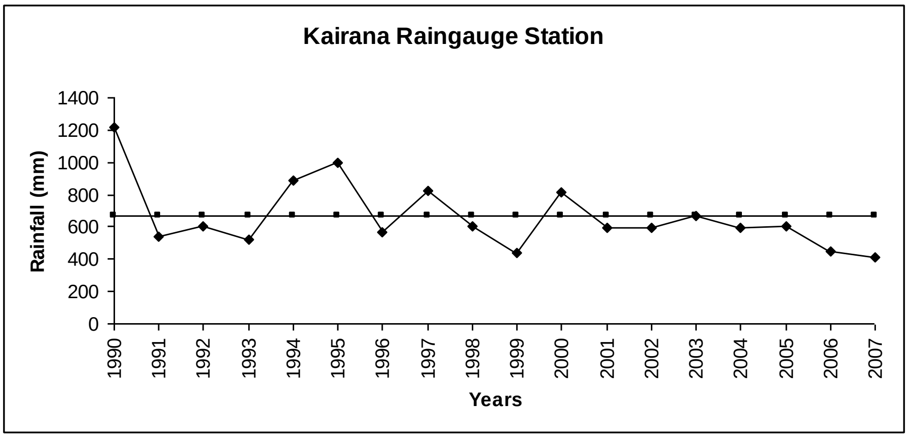


Fig.1.5a Yearly rainfall at Kairana Raingauge station(1990-2007)

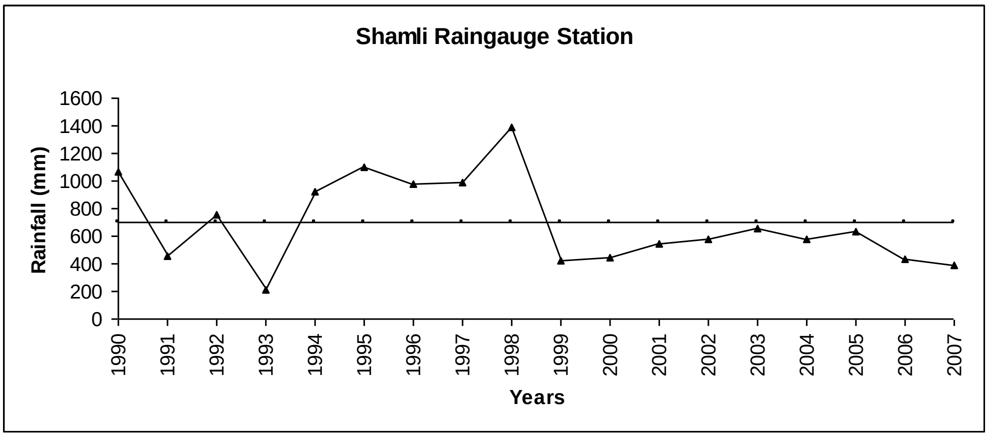


Fig.1.5b Yearly rainfall at Shamli Raingauge station (1990-2007).

Table 1.2 Results of Statistical Analysis of Annual Rainfall Data

Kairana Raingauge station	
Highest Rainfall (1990)	1220 mm
Lowest Rainfall(2007)	415 mm
Mean	664 mm
Std. Deviation	203.74
Coefficient of variation	30.67 %
Shamli Raingauge station	
Highest Rainfall (1995)	1099 mm
Lowest Rainfall(1993)	206 mm
Mean	697 mm
Std. Deviation	303
Coefficient of variation	43.5 %

1.7.1 Spatial Distribution of Rainfall

An isohyetal map using an average rainfall of 11 years period (1997-2007) for 5 raingauge station was prepared for district Muzaffarnagar. A perusal of isohyetal map (Fig.1.6) shows that intensity of rainfall decreases from east to west. A minimum of less than 500 mm of rainfall is received in south-western part which gradually increases to more than 1200 mm due east, proximal to river Ganga.

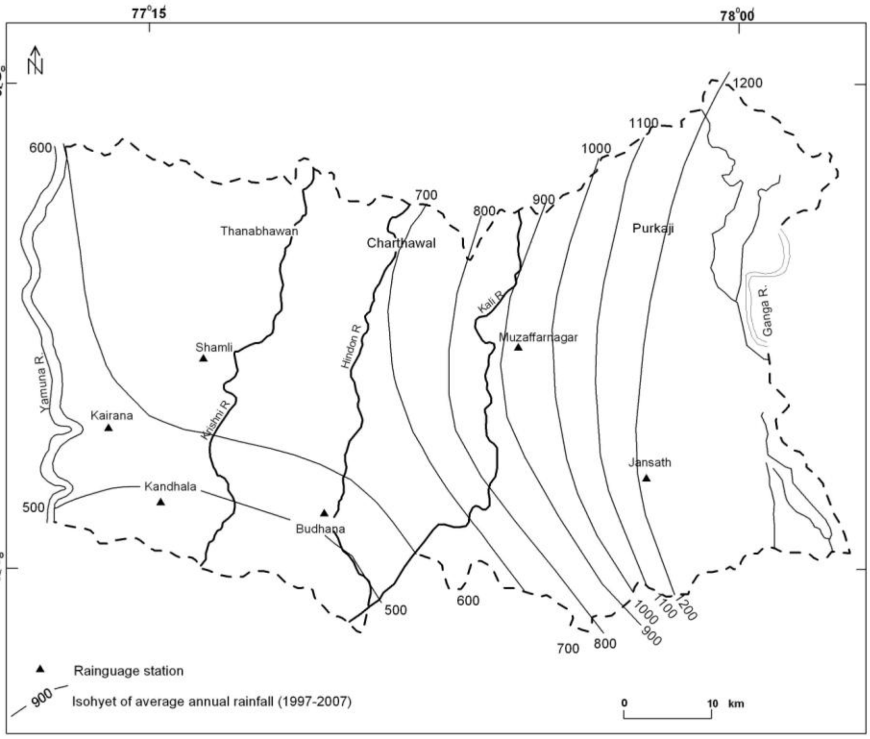


Fig.1.6 Isohyetal map showing distribution of average annual rainfall

1.8 Soil Types

The Indo-Gangetic Plains are formed by the periodic deposition of silt brought by rivers abounds in alluvial soil. The alluvial tracks of Ganga-Yamuna interfluve have got very fertile soil. The study area is characterized by three types of soils viz. (i) Loam (ii) Clay Loam and (iii) Sandy Loam (Survey of India, 2003). The distribution of the three soil types is shown in figure 1.7.

1.9 Regional Geological Set up

The study area forms a part of the Ganga basin. Morphologically, the Ganga plain is a shallow, asymmetrical depression with a gentle easterly slope. Along the piedmont zone, close to Himalaya, the altitude varies from 280 m in the west to 67 m in the east. Stratigraphically, it is built up of alternate layers of gravel, sand and clays of quaternary age. The Ganga plain exhibits asymmetrical sedimentary wedge, only few tens of meter thick towards peninsular craton and upto 5 km thick near Himalayan orogen (Singh, 2004).

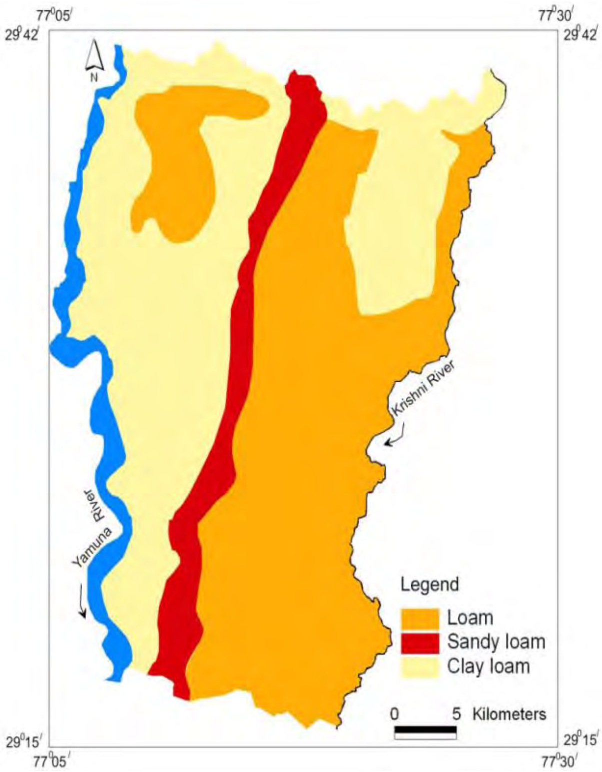


Fig.1.7 Soil map of the study area

The flexing lithosphere below the Ganga plain shows many inhomogenities in the form of ridges and basement faults (Sastri et al.,1971, Rao, 1973) which are (i) Monghyr-Saharsa Ridge, (ii) East Uttar Pradesh shelf, (iii) Gandak Depression, (iv) Faizabad Ridge, (v) West Uttar Pradesh Shelf, (vi) Kasganj-Tanakpur Spur, (vi) Ram Ganga Depression and (vii) Delhi-Hardwar Ridge.

These basement highs and faults have controlled the thickness of the alluvial fill (Bajpai, 1989, Singh, 1996) and have also affected the river channel on the surface.

The study area is at the fringe of Delhi-Hardwar Ridge, which represents a north-northeastward extension of the Delhi folded belt. The western limit of the Ganga basin is delimited by the Delhi-Hardwar Ridge and the oldest sedimentary sequence in the basin, namely, Upper Vindhyans, gradually thin out towards this ridge.

1.9.1 Geology

An extensive sub-surface data down to 450 m bgl have been generated under the Upper Yamuna projects of Central Ground Water Board (CGWB) with the objective of delineating the various aquifer system and their hydraulic parameters (Bhatnagar et al., 1982). On the basis of correlation of lithologs and electrical logs, four distinct groups of permeable granular zones (sand and gravel) were identified which are separated by three impermeable clay horizons. A map of the Ganga Plain showing sub-surface basement high and thickness of the foreland sediment is published by Singh 2004. This map shows that the study area lies between the contour of 1.5 and 1.0 km (Fig.1.8). Therefore the probable thickness of alluvium in the area is approximately 1.3 km.

Table 1.3 Probable Geological Succession of the study area.

Quaternary	Alternate bed of sand and clay with occasional beds of calcrete.	
------------------- Unconformity-----------------------		
Upper Proterozoic	Vindhyan Super Group	?
------------------- Unconformity-----------------------		
Middle Protoerozoic	Delhi Super Group	
------------------- Unconformity-----------------------		
Archean to Lower Proterozoic	Bundelkhand Granitoids	

It appears from the above sequence (Table 1.3) that the area is underlain by the Bundelkhand Granitoids which form the Basement Complex. It appears that a very long period of erosion preceded the deposition of the Delhi group of rocks on the eroded and upturned surface of the Bundelkhand Granitoids.

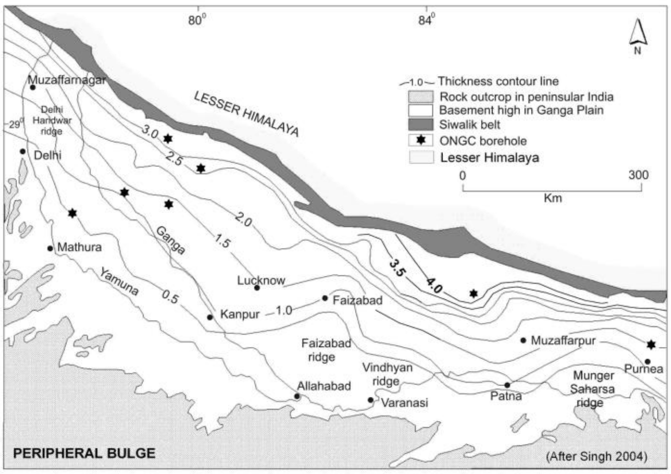


Fig.1.8 Map of the Ganga Plain showing sub-surface basement high and thickness of the foreland sediment (in kilometers) Compiled from various sources, namely Agarwal 1977, Karunakaran and RangaRao, 1979 and Singh 2004.

2 – HYDROGEOLOGY

2.1 Introduction

The study area is a part of Central Ganga plain. Geologically, the area is underlain by alluvial deposits of Quaternary age, approximately 1000 m in thickness. The alluvium is underlain by Middle Proterozoic Delhi quartzites. The quartzites, in turn, are underlain by Bundelkhand Granitoid (3000 Ma). The alluvium in Krishni-Yamuna interfluve region consists of alternate beds of sand and clay with occasional interbeds of calc-concretion (Kankar). The methodology of aquifer characterization are discussed in preceding sections.

2.2 Aquifer geometry

A Fence diagram based on lithological logs of borehole (Fig.2.1) drilled by State Tubewell Department has been prepared (Appendix III). The fence diagram (Fig.2.2) reveals the vertical and lateral disposition of aquifers, aquiclude and aquitard in the study area down 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 layer is persistent through out the area varying in thickness from 3 to 20 m bgl. 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 fine, medium to coarse sand. 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.

Granular zone composed of medium to coarse sand and gravel form about 80-90 % of total formation encountered, particularly in southeastern and southern part of the basin. This area being a down faulted area due to NE-SW Muzaffarnagar fault possibly became a dominant recipient of sand than the area north of the fault. Muzaffarnagar fault is an active transverse E-W running fault, with through to the south side and passing through the Muzaffarnagar city (Bhosle et al., 2007).

In addition to fence diagram three hydrogeological cross section A-B, C-D and E-F (Fig.2.1) are distributed across the entire area in which two sections run from west to east and the section E-F from north west to south east.

The section A-B (Fig.2.3) represent extreme north of the area. A perusal of the section A-B reveals the clay bed occurs in repeated alternation with in granular zone.

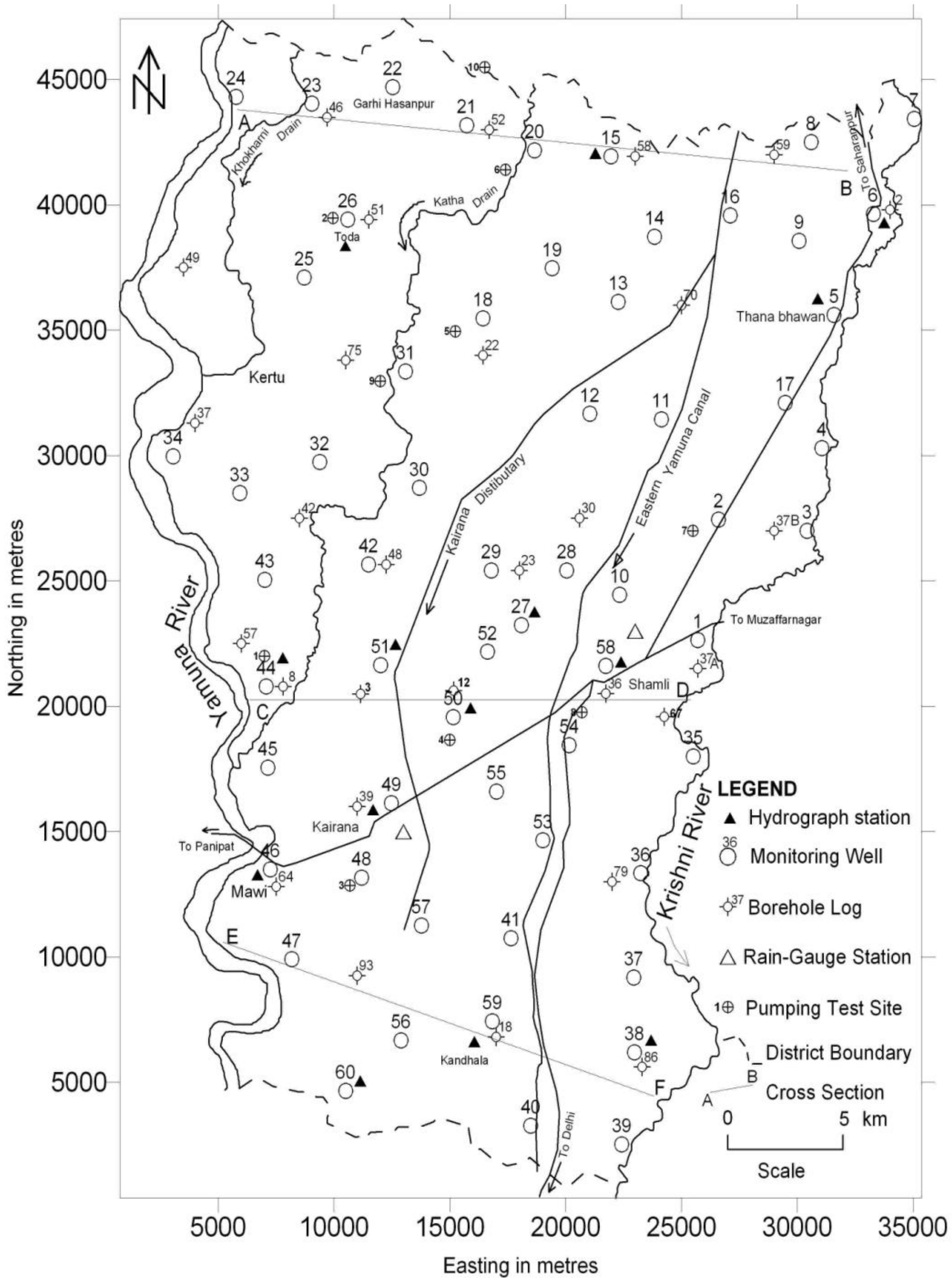


Fig.2.1 Base map of Yamuna-Krishni sub basin.

This section shows occurrence of three granular zones. There are also occurrences of minor clay lenses within the granular zones.

In section C-D (Fig.2.4), the top clay layer is thick in central part but gradually reduces in thickness in the eastern part. By and large, this section is marked by preponderance of alternate clay in the eastern part of the study area, proximal to meandering river Krishni.

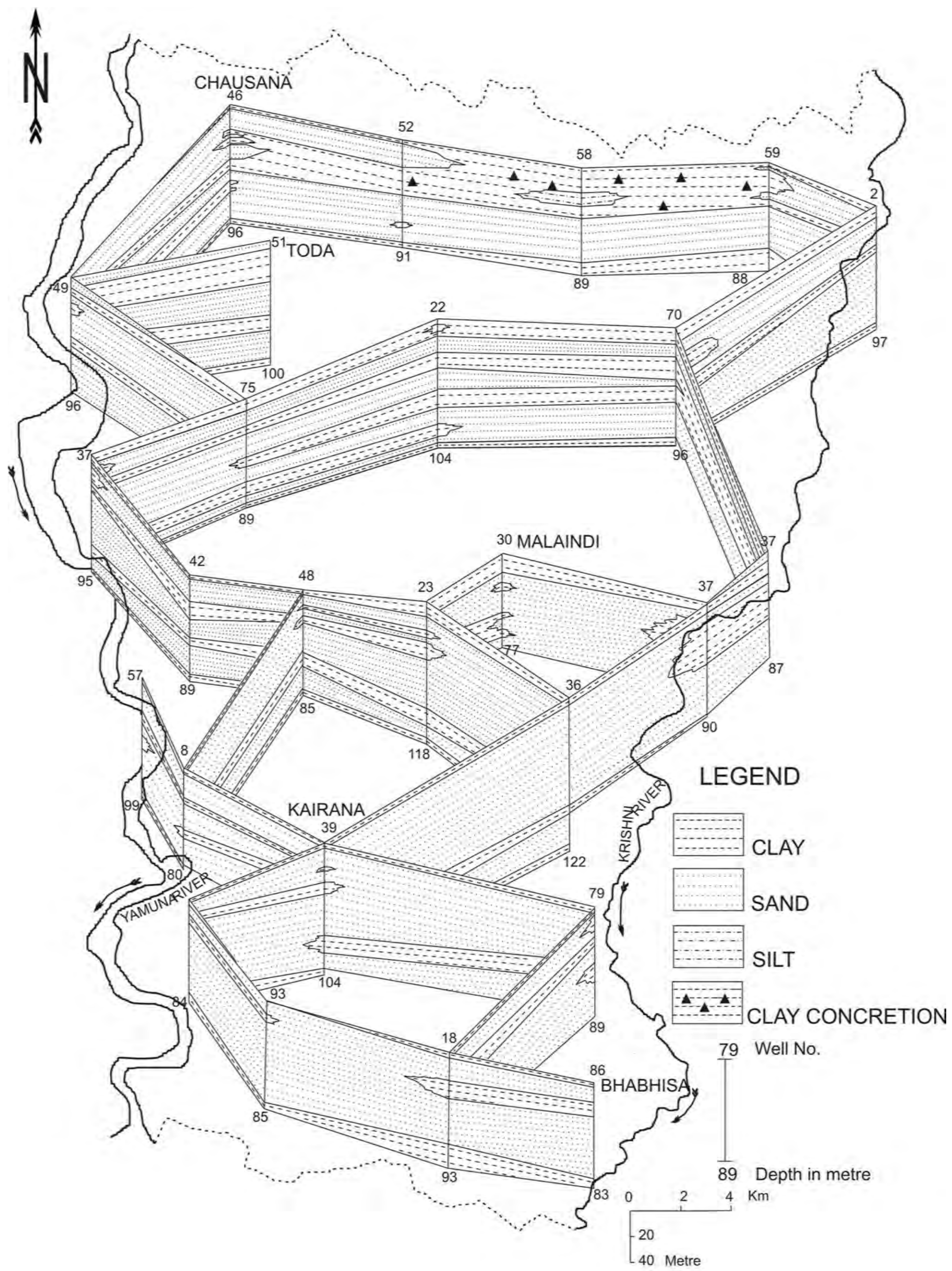


Fig.2.2 Fence diagram showing aquifer disposition in Yamuna-Krishni sub-basin.

The section E-F runs through the extreme NW to SE of the area (Fig.2.5). This section shows prominence of granular zone. The clay beds occur only as lenses. This fact is also substantiated by fence diagram and sand percent map.

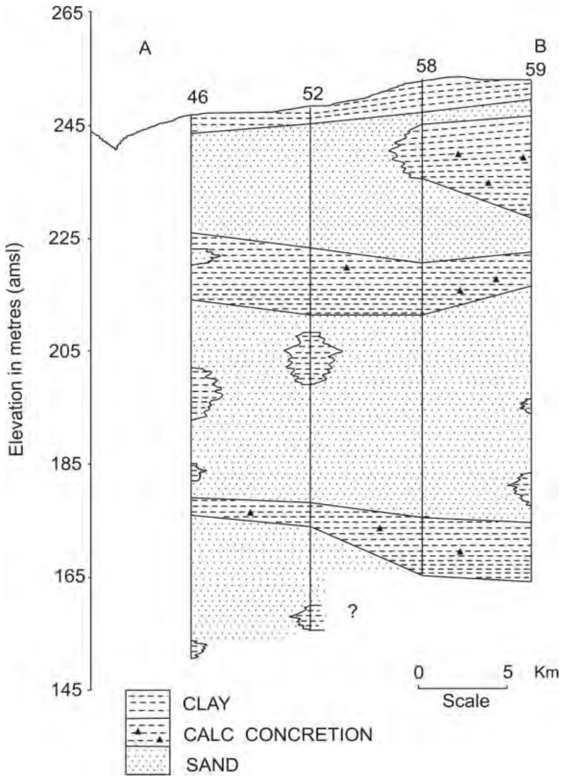


Fig.2.3 Hydrogeological cross section along the line A-B.

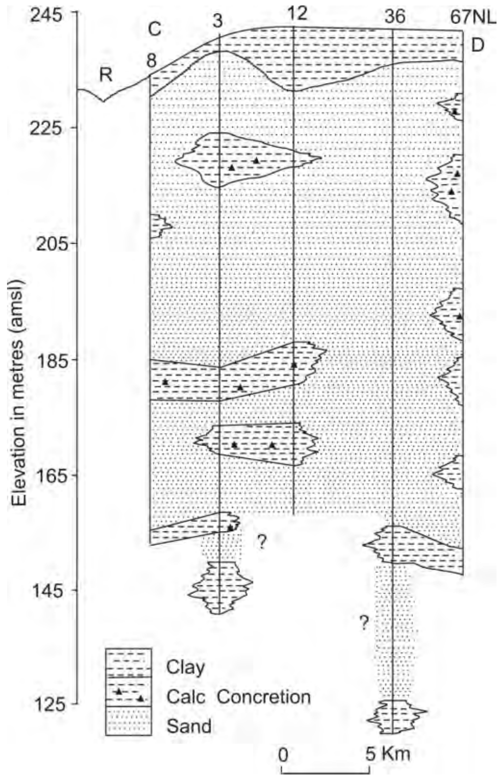


Fig.2.4 Hydrogeological cross section along the line C-D.

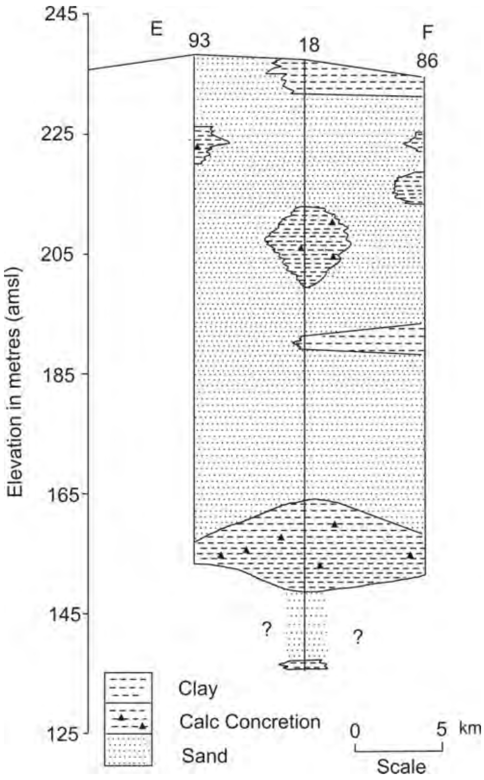


Fig.2.5 Hydrogeological cross section along the line E-F.

2.3 Sand percent map grain size related aspects

The granular zones encountered down to 100 m have been utilized in preparing the sand percent map (Fig.2.6, Plate 5). The sand percent map has been prepared on the basis of cumulative thickness of granular zones encountered in the boreholes. The area has been divided in to five sand percent zones viz. (i) <50 (ii) 50-60 (iii) 60-70 (iv) 70-80 (v) >80 percent. The sand percent map reveals that granular zone attain maximum thickness in southern part between Shamli and Kandhala village. The percentage of granular material decreases in the northern part of the area. The fence diagram also shows the same fact. It can also be infer that the variation in sand percent map is more along the course of river Krishni as compared to the river Yamuna. This may be explained by dominance of clay horizons along river Krishni which is also reflected by its highly meandering character.

The effectiveness of granular zones identified in the area of study as potential aquifer depend on size of constituent grain. The grain size analysis of aquifer material collected from available drilling sites were carried out and parameters like effective grain size (d_{10}) and uniformity coefficient (Cu) were calculated and are given in table 2.1.

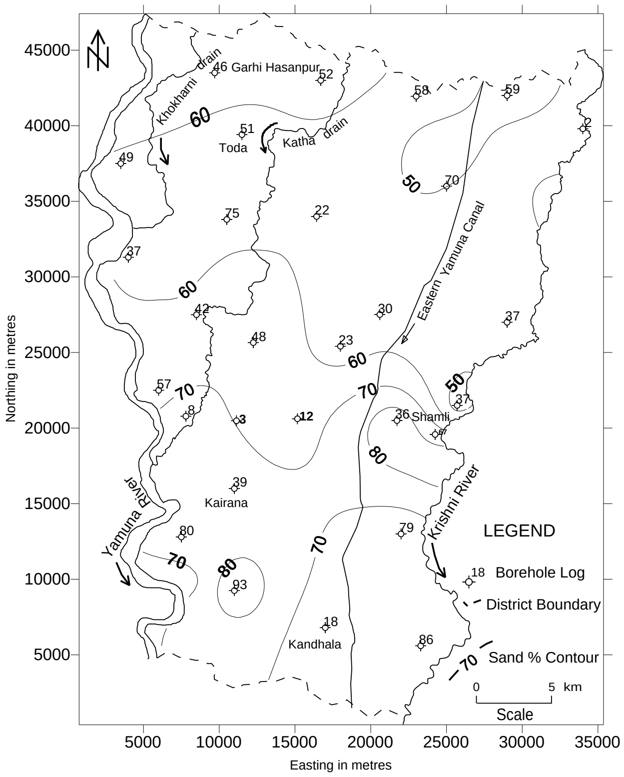


Fig.2.6 Sand percent map of the study area.

Table 2.1 Effective grain size and uniformity coefficient.

Sand sample No.	Location	Depth (m)	Effective grain size (d_{10})	Uniformity coefficient (Cu)	Typical sand type
1	Bhoora	25	0.19	1.36	Fine sand
2	Bhoora	45	0.14	1.78	Fine sand
3	Dulawa	25	0.15	1.66	Fine sand
4	Mundait	30	0.064	2.96	Silt
5	Kandhala	35	0.13	1.84	Fine sand
6	Issapurteel	30	0.15	1.66	Fine sand
7	Sikka	45	0.16	1.56	Fine sand

2.4 Groundwater level and its variations

It is well observed phenomena at least in northern part of India that water reaches to its shallowest level due to rainfall recharge in the month of November and it recedes to minimum in the month of June. Thus, keeping this in view water level monitoring was initially planed during these periods. Water level data was collected from observation wells with the help of steel tape. Due care was given for accurately measuring the water level data. Groundwater level in an unconfined aquifer is much sensitive to fluctuation. Thus error may introduce because of pumping influence in near by area, river stage and also because of groundwater movements. The data collected (Plate 4a, b & c) were used in interpretation of depth, slope, movement and fluctuation of water level.

2.4.1 Depth to water level

In pre-monsoon seasons i.e. June 2006 and June 2007 the depth to water level ranges from 5.76 - 21.96 metres (Fig.2.7) and 4.62 - 21.14 metres below ground level, respectively. The deeper water level viz. 16.95, 17.92 and 21.96 metre were recorded at Bhabhisa, Taprana and Pauti kalan, respectively (Appendix IV B & IV D). The deep water table conditions found to occur in the central part of the study area. The central tract between Katha drain and Eastern Yamuna Canal has high elevation above mean sea level. Moreover during the field survey it was observed that the pumpage of groundwater is high in this area, it also lacks surface water irrigation.

The depth to water levels is shallow along the River Yamuna (Fig.2.7). The area can be divided in to eight water level zones (i) 6-8 (ii) 8-10 (iii) 10-12 (iv) 12-14 (v) 14-16 (vi) 16-18 (vii) 18-20 (viii) >20 m bgl.

In post-monsoon seasons i.e. November 2005, November 2006 and November 2007 the depth to water level ranges from 5.16 - 21.96, 5.18 - 21.02 and 4.90 - 21.53 m bgl, respectively (Appendix IVA, IVC and IVE). Figure 2.8 show the depth to water in Post-monsoon season (Nov 2006). The post-monsoon depth to water level map (Nov 2006) shows significant rise in water level. As a result most of the contours shows moderate shift in their position. For example, the 14 m zone in the down reaches of Eastern Yamuna Canal (EYC) has changed to 12 m zone.

Moreover, the contour pattern is changed all along the EYC, which nonetheless shows combined effect of rainfall and seepage through canal beds. It was observed during field survey that flow in EYC and its various irrigation channels was more during post monsoon period. In the central part, the area occupied by 18-20 m zone has decreased considerably. The 16 m zone in the extreme north of the area is covered by 14 m zone in the post monsoon map.

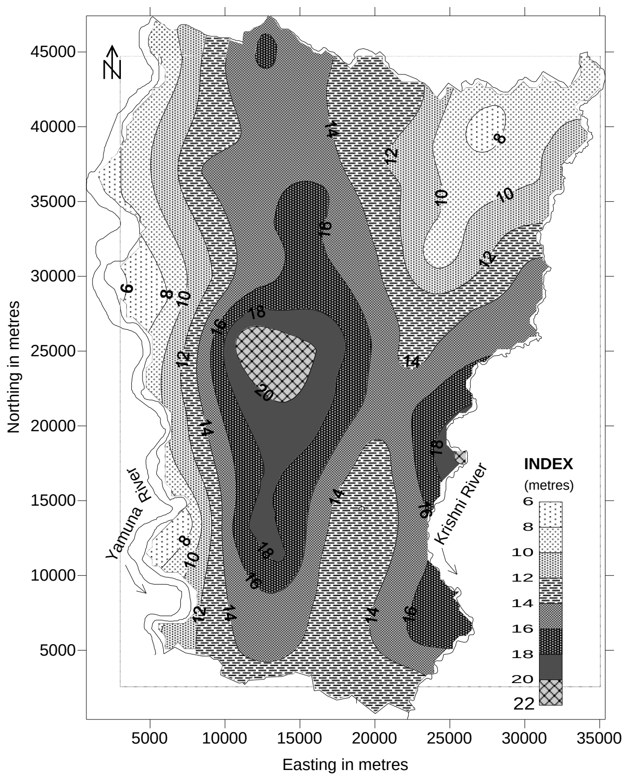


Fig.2.7 Pre-monsoon depth to water level map (June 2006)

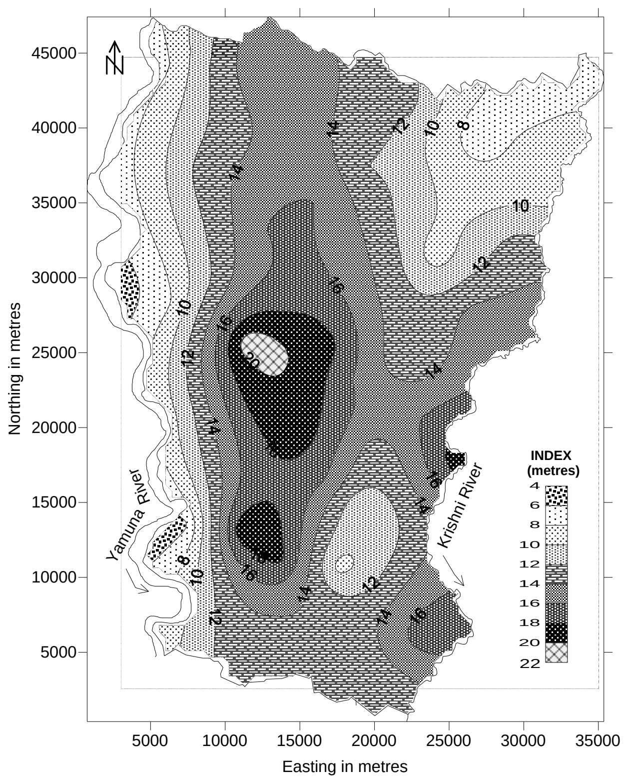


Fig.2.8 Post-monsoon depth to water level map (Nov 2006)

The change in contour pattern in command and non-command area is, in all likelihood, infer that the increase in groundwater storage is because of rainfall recharge, irrigation return and through canal seepage as well.

2.4.2 Water Table Fluctuation Maps

The measurement of water level fluctuations in observation wells is an important facet of groundwater studies (Freeze and Cherry, 1979). The difference between successive rise and fall in the water level in observation wells during a year is called fluctuation, where rise is due to the recharge and fall because of the discharge.

The water level fluctuation in the study area is of both type i.e. positive and negative fluctuations. Positive fluctuations are those which show rise in water level during post-monsoon. Negative fluctuation shows further decline in post-monsoon season. Positive and negative groundwater fluctuation would pertain to the conditions where groundwater recharge components exceeds the groundwater discharge and vice versa. Figure 2.9a and 2.9b shows water level fluctuation in the area. The fluctuations are represented by differences in pre-monsoon and post-monsoon water levels.

A perusal of fluctuation map of 2006 (Fig.2.9a) shows that the area has been divided in to five fluctuation zones viz. (i) 0-0.5 (ii) 0.5-1.0 (iii) 1.0-1.5 (iv) 1.5-2.0 and (v) >2.0 m. The area in the vicinity of Eastern Yamuna Canal and its network of small distributaries has got maximum fluctuation which is combined effect of recharge from rainfall and canal seepages. The area lying between river Yamuna and EYC shows very low fluctuation. This is because of below average rainfall for the last three years and also this part of the area lack surface water irrigation and hence ultimate stress is upon groundwater. This vary fact has emerged in the form of negative groundwater fluctuation at Kairana township, though the area covered by negative fluctuation is very small.

Owing to below average rainfall and continued groundwater abstraction throughout the year has lead the Yamuna-Krishni sub-basin in to a complex situation where the discharge is exceeding the groundwater recharge. A perusal of water level fluctuation map of 2007 (Fig.2.9b) shows that the area can be divided in to five fluctuation zones viz. (i) -1.0 to -0.5 (ii) -0.5 to 0 (iii) 0 to 0.5 (iv) 0.5 to 1.0 and (v) 1.0 to 1.5 m. The most part of the area is characterized by -0.5 to 0 m fluctuation zone.

The maximum negative fluctuation zone i.e. -1.0 to -0.5 is restricted to a smaller part in the vicinity of river Krishni.

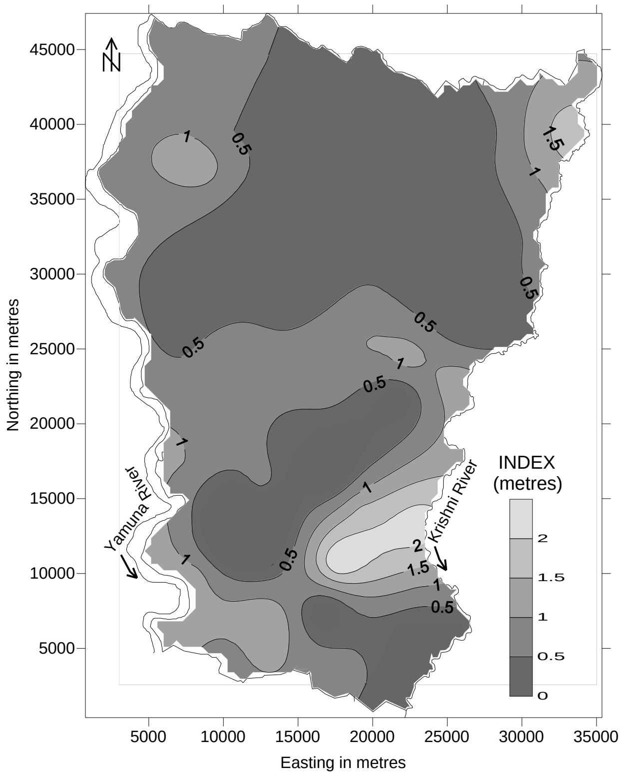


Fig.2.9a Water level fluctuation map (Nov 2006)

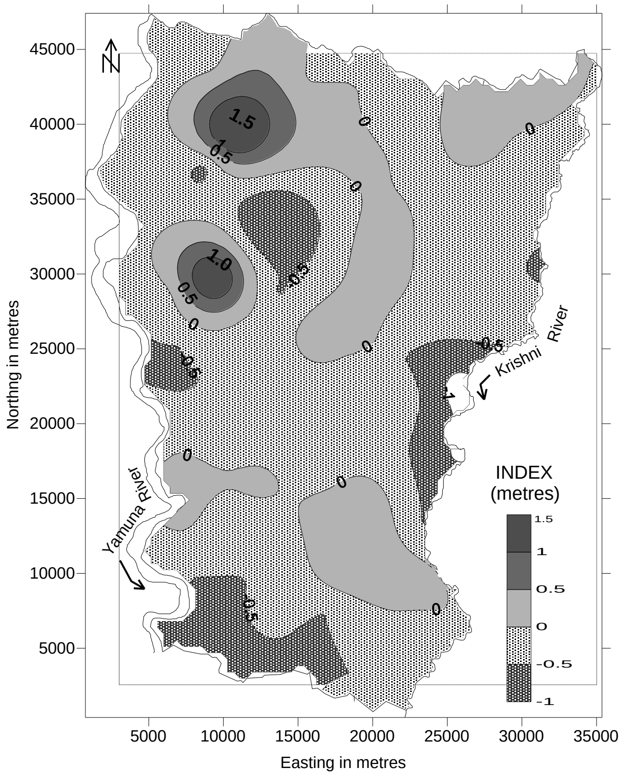


Fig.2.9b Water table fluctuation map (Nov 2007)

The statistical analysis of the water level fluctuation data shows that 53% of the wells are falling in -0.5 to 0 zone. Zone -1.0 to -0.5 is characterized by 13% wells. The zone of maximum negative declination is characterized by 3 wells which constitute only 5% of the total wells. This negative fluctuation is explained by the fact that the area is receiving below average rainfall since last three years. The deviation in rainfall is in the order of 16 to 33%.

However, the abstraction scenario is same or slightly higher than previous years. This has lead a situation of negative fluctuation which is nonetheless is overexploitation of the aquifer. The positive groundwater fluctuation is characterized by 29 % of the total wells which constitute 17 wells. The positive fluctuation at the North West part of the area may be attributed to some local factors.

2.5 Water table contour map and groundwater movement

Water level data of wells collected were analysed and altitude of water level with reference to the mean sea level were worked out. The reduced level of water with reference to mean sea level was plotted and water table contour map was prepared, with contour interval of one metre.

2.5.1 Form and Slope of Water table

A perusal of pre-monsoon 3-D water table contour map (Fig.2.10) show that the elevation of water table ranges from 246 metre above mean sea level (m amsl) in the north east to 219 m amsl in the south east. It shows that the regional groundwater flow direction is from NNE to SSW. Besides varied local flow directions were also observed which may be attributed to some local factors. Eastern Yamuna Canal (EYC) acts like a groundwater divide, almost throughout the area. The groundwater flow direction at the left bank of canal is towards the Krishni river with an average hydraulic gradient of 1.25 m/km. While from its right bank the groundwater flows from NE-SW direction. The groundwater flow direction is very conspicuous and scattered away from the right bank of EYC. This distorted pattern of flow direction in all likelihood is the out come of overdrafting in these areas. The track between river Yamuna and EYC occupies greater area therefore the recharging due to this canal is not very pronounce and restricted only to the close proximity of Eastern Yamuna Canal.

In general the gradient varies from 2.2 m/km in the NE region to 0.4 m/km at SW region in premonsoon 2006 (Fig.2.11). In the NW direction of the area, there occur two

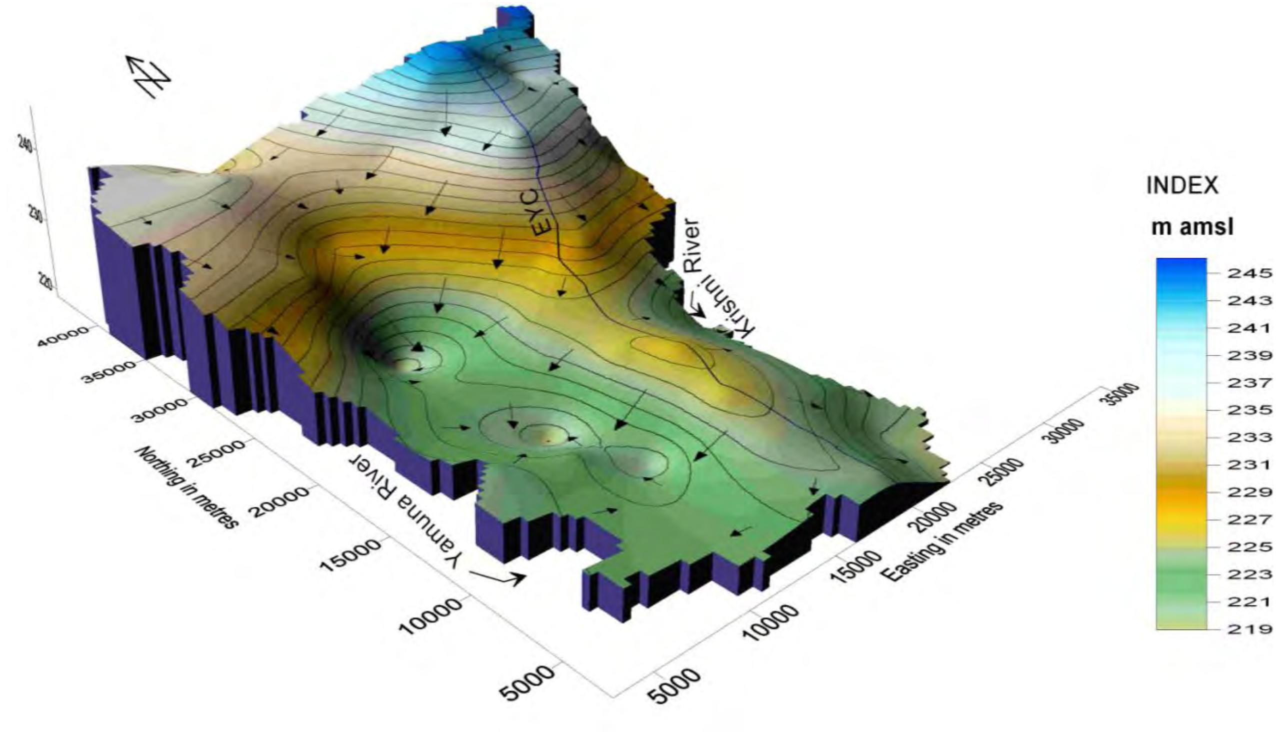


Fig.2.10. 3-D water table contour map of the study area of June 2006.

groundwater troughs at locations Kairana and Bipur. The possible reasons for these troughs are indiscriminate pumping of groundwater for agricultural uses.

The groundwater trough at Bipur is much prominent than the trough beneath the Kairana township. The hydraulic gradient is 1.95 m/km at Bipur and 1m/km at Kairana. Close spacing of contour at Bipur trough is indicative of two factors viz. (i) Heavy withdrawal of groundwater, (ii) Low permeability of aquifer material. During field investigation it was observed that the area is excessively pumped moreover the hydraulic conductivity of this region is comparatively low from the rest of the area. These two factors seem to be possible reason for steep gradient.

A mound has formed over the Eastern Yamuna Canal at the lower reaches. This mound is shedding water from its eastern flank to the river Krishni and from its western flank towards Kairana township. The contour behaviour shows that the river Yamuna is contributing the aquifer system and hence influent through out the area. The groundwater flow direction is towards the river Krishni hence it is effluent in nature.

Figure 2.12 shows the post-monsoon water table contours for the period 2006. The post-monsoon water table contour map remains essentially the same as that of the pre-monsoon water table contour map. However during post-monsoon 2006 (Fig.2.12) few changes are noted in the contour behaviour owing to groundwater storage increase during

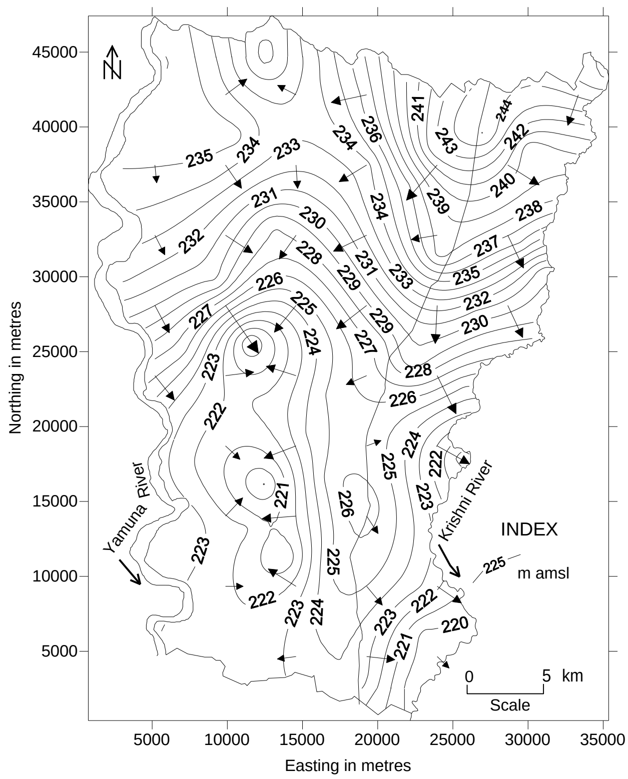


Fig.2.11 Pre-monsoon water table contour map (June 2006)

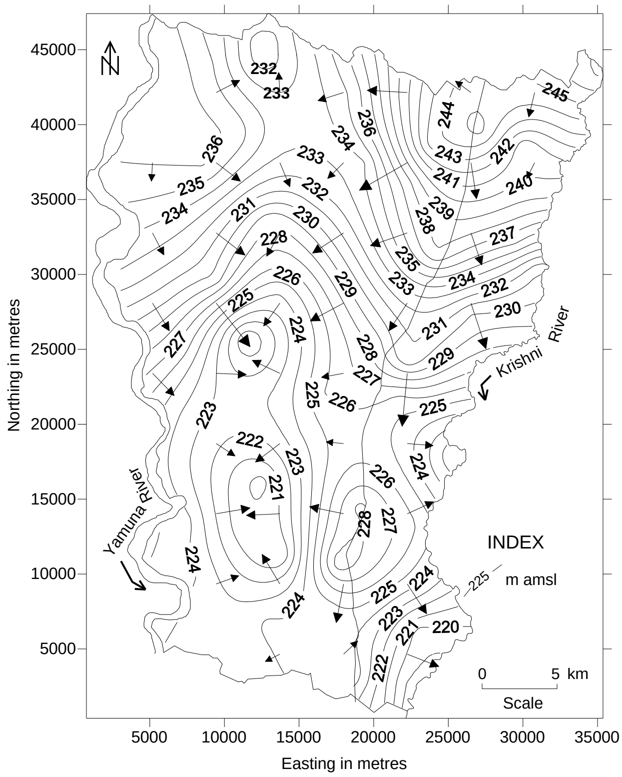


Fig.2.12 Post-monsoon water table contour map (November 2006)

post-monsoon period which are discussed below few changes are brought about in shape of the contours and are somewhat displaced by higher contour values. The groundwater troughs at the location Pauti and Kairana is present in both the season for year 2006 and hence seems to be permanent in nature.

2.6 Long term behaviour of water levels

2.6.1 Biannually water level monitoring

Historical water level data of fourteen permanent hydrograph stations were collected from Central Ground Water Board (CGWB) and State Groundwater Department (UPSGWD). The data were utilized to prepare hydrograph with a view to study their behaviour with respect to time and space and their dependence on natural phenomenon. The water levels in unconfined aquifers are affected by direct recharge from precipitation, evapotranspiration, withdrawals from the wells, discharge to streams, and sometimes changes in atmospheric pressure. From the above discussion it has been inferred that the water level has a rising and declining trend with respect to time and a function which causes such rises in water levels *i.e.* availability of rainfall.

Perusals of hydrographs (Fig.2.13a, b, c, d, e, f, & g) indicate that the water level variation is cyclic and sinusoidal as a function of time and space. For a year, the water level is deepest during the month of June and shallowest during the month of November. It is observed that the water level starts rising by last week of June and attains shallowest level in November. In overdeveloped areas a downward trend of water levels may continue for many years because of continual increases in pumpage or withdrawals in excess of recharge, or both.

It is seen from the hydrographs that there is progressive decline in the water level trend with in the study area, especially for last three-four years, the decline trend seems pronounced and persistent. A trend line was fitted on the graphs using t-statistic for testing significance of observed regression coefficient, the values of r-square and r for the given data set shows 95% level of confidence. The average annual decline in command and non-command area is given in Table 2.2 & 2.3. The hydrograph data for non-command and command area is given in Appendix V A and V B, respectively.

Table 2.2 Average annual decline during (1999-2007) in command area

Hydrograph station	Average annual Decline (m)
Thanabhawan	0.32
Jalalabad	0.46
Shamli	1.1
Titoli	1.12
Bhabhisa	1.53
Garhi Abdullah	1.27

Table 2.3 Average annual decline during (1999-2007) in non-command area

Hydrograph station	Average annual Decline (m)
Toda	0.62
Bhoora	1.3
Kandela	1.08
Kairana	0.87
Khurgyan	0.464
Kandhala	1.07
Mawi	0.408
Gangeru	0.7

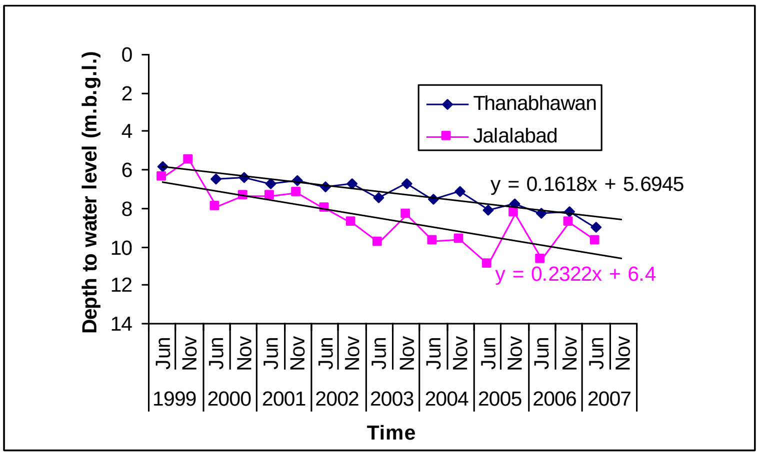


Fig.2.13a Long term water level fluctuation trends at Thanabhawan and Jalalabad.

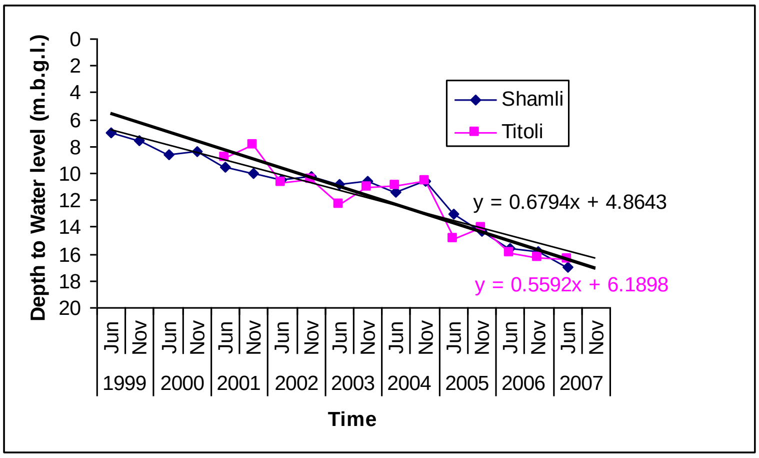


Fig.2.13b Long term water level fluctuation trends at Shamli and Titoli.

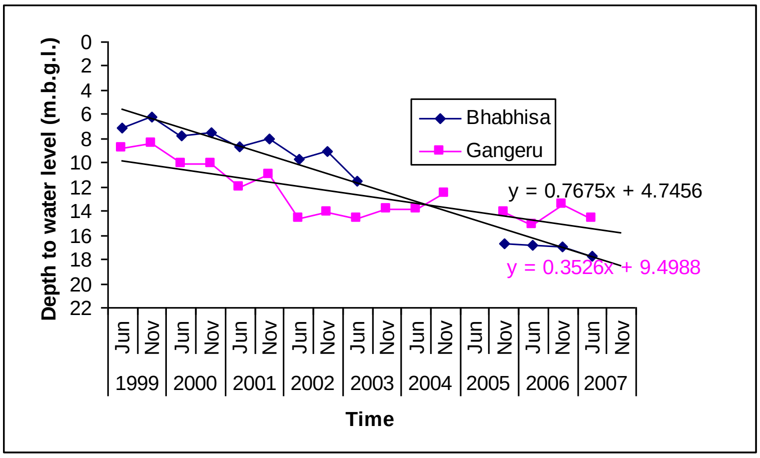


Fig.2.13c Long term water level fluctuation trends at Bhabhisa and Gangeru.

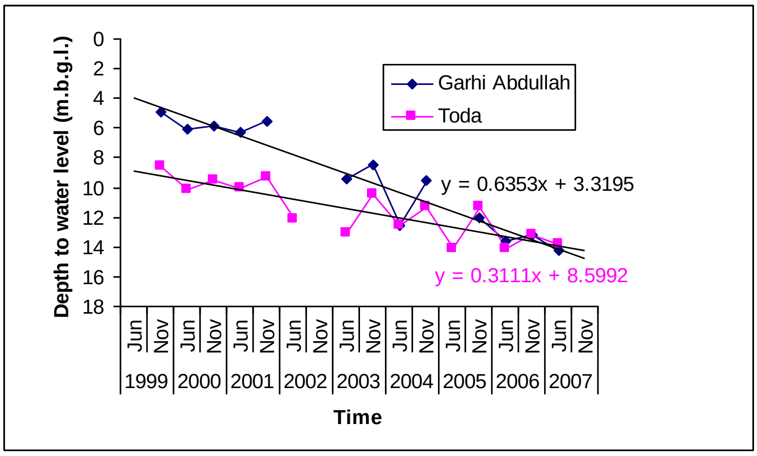


Fig.2.13d Long term water level fluctuation trends at Garhi Abdullah and Toda.

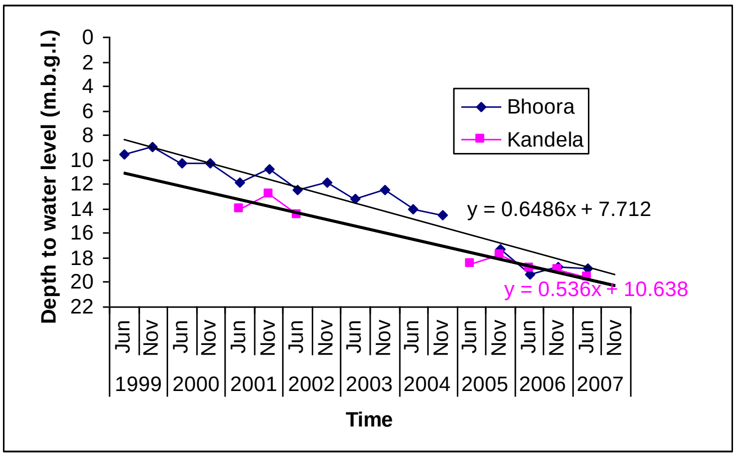


Fig.2.13e Long term water level fluctuation trends at Bhoora and Kandela.

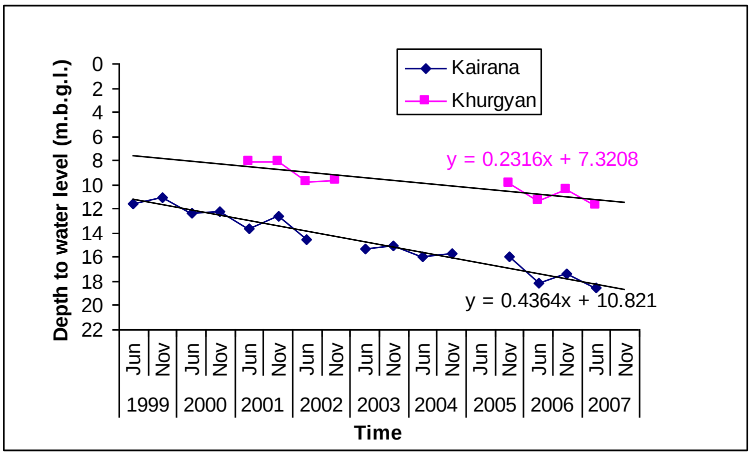


Fig.2.13f Long term water level fluctuation trends at Kairana and Khurgyan.

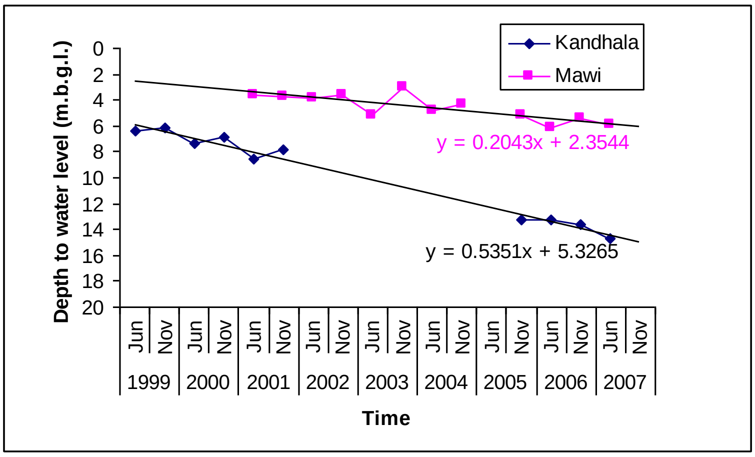
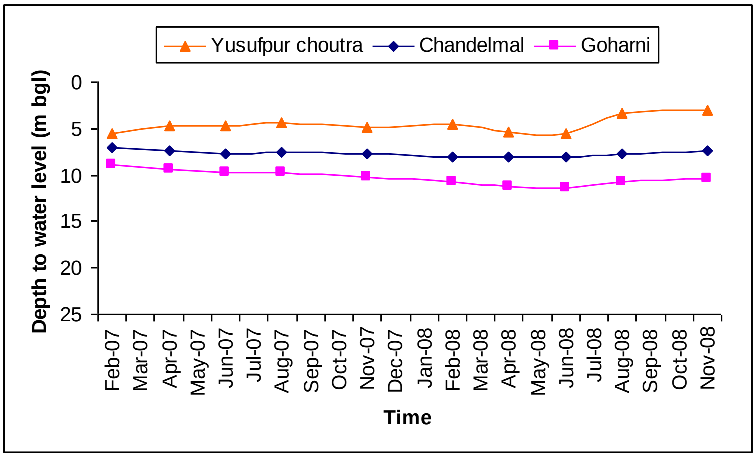


Fig.2.13g Long term water level fluctuation trends at Kandhala and Mawi.

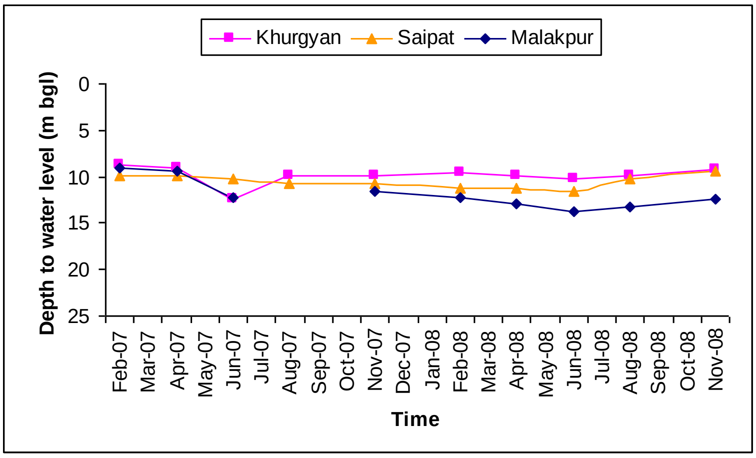
2.6.2 Bimonthly Water Level Monitoring

Attempts have been made to analyse the groundwater fluctuation trends in response to utilization pattern. Thus, 14 observation wells were selected to measure the water level at bimonthly time interval (Appendix-VI). Most of the observation wells show gradual decline in water level from the month of Feb-07 to June-07 (Fig.2.14a, b, c, d & e). 8 out of 14 observation wells show rise in water level in the period June-07 to Aug-07. The rise in general attributed to rainfall recharge. The significant rise at the locations Kairana and Todda may be attributed to some local recharge factors. It is also evident that the water level rising trend does not continue for the period from Aug-07-Nov-07.

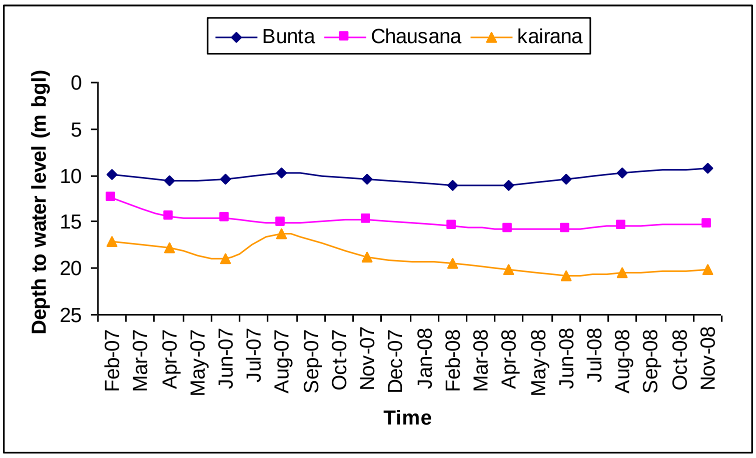
It can also be inferred from the graphs that the groundwater fluctuation trend is not uniform through out the study area.



(a)



(b)



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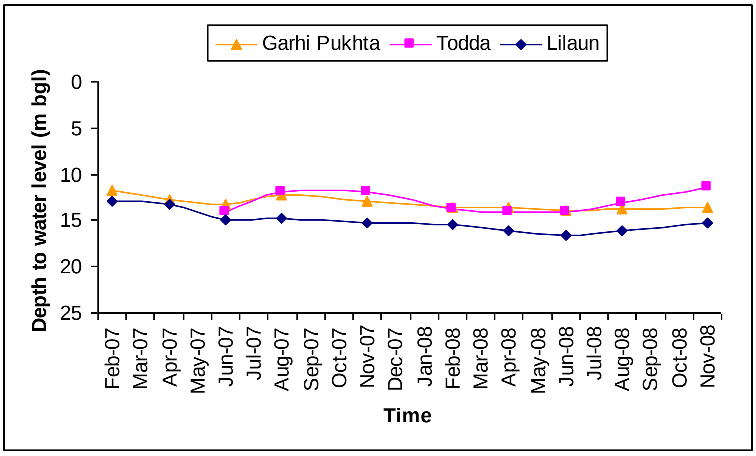
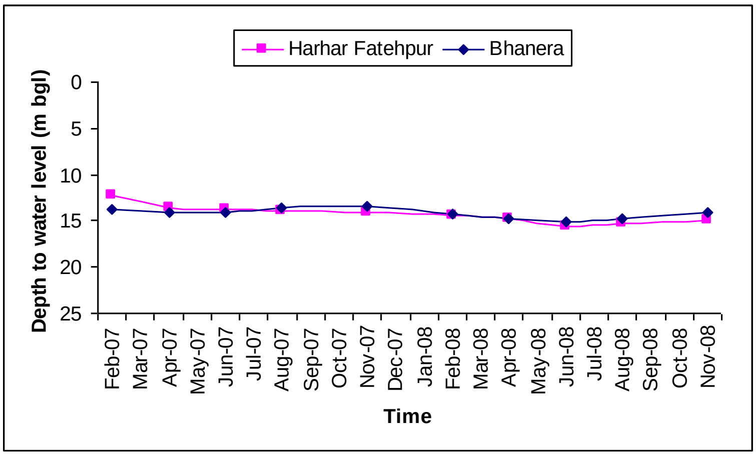


(d)



(e)

Fig 2.14a, b, c, d & e Bimonthly water level fluctuation trend

The Sharp decline (>2 m) was observed at Malakpur and Khurgyan, both location are fairly apart, indicate that the local recharge-discharge factors are influential in determining fluctuation trend.

2.6.3 Temporal Variation in Water Table and Monthly Rainfall

The monthly rainfall data collected from two raingauge stations i.e. from Kairana and Shamli. The fact that the rainfall is the main source of groundwater recharge necessitates the plotting of rainfall against water level or change in groundwater storage. The close analysis of the graph shows that rainfall seems to be a source groundwater recharge. This is envisaged in rising of water level at the end of monsoon period. Groundwater recharge is greatest in monsoon months and is least in summer and dry years.

Extended dry periods have pronounced adverse effects on water levels; groundwater storage is considerably reduced during these periods. In areas of heavy pumping the hydrographs often shows the seasonal and secular fluctuation not because of natural phenomena but also because of seasonal fluctuation in pumping rates.

The scanty and below average rainfall in the last seven and nine years at Kairana and Shamli respectively, has affected the groundwater regime and is clearly depicted in both the figures 2.15a & 2.15b. The rainfall in the year 2007 is decreased by 33% of the average at Kairana raingauge station and 16% at the Shamli raingauge station. This has given rise to almost flat trend of water level which was earlier characterized by sharp rise in the month of November and decline in the month of June.

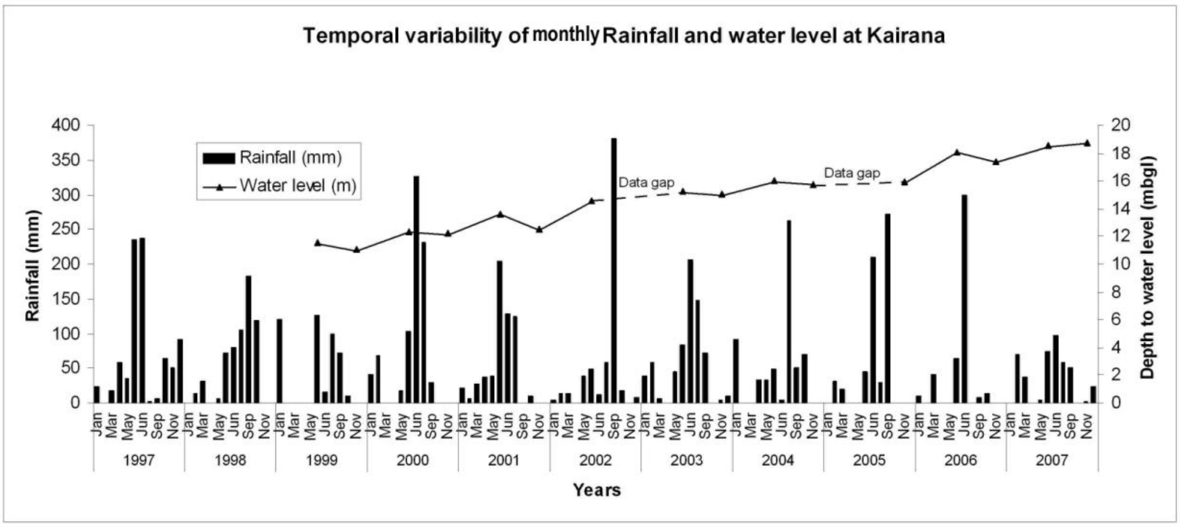


Fig.2.15a Temporal variability of monthly rainfall and water level at Kairana.

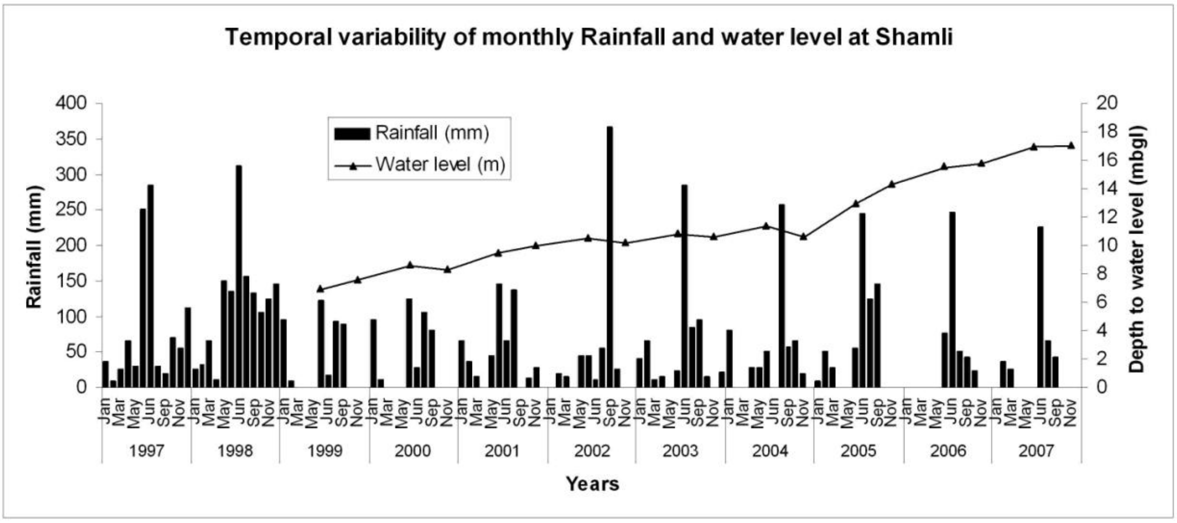


Fig.2.15b Temporal variability of monthly rainfall and water level at Shamli.

A critical study of hydrographs indicates that the ascent of level is also affected by the intensity and distribution of rainfall.

2.7 Aquifer parameters

The aquifer Parameters discussed here includes isopermeability map derived from Logan's approximate method and hydraulic conductivity as determined in laboratory. In addition, there is a discussion on parameters assessed using the pump test.

2.7.1 Isopermeability Map

Logan (1964) reasoned that if a well is pumped for such a long period that flow is in steady state, then an approximate estimation of the order of magnitude of the transmissivity can be made using the Theim's formula for a confined aquifer which can be written as

$$T = \frac{2.3Q\log\left(r_{max}/r_w\right)}{2\Pi S_{max}} \qquad (1)$$

where,

r = Radius of pumped well in metres

r_{max} = radius of influence in metres

S_{mw} = Max. drawdown in the pumped well in metres

Logan further stated that the accuracy of the calculation depends only on the accuracy of measurement of S_{mw} (on which well losses may have substantial influence) and on the accuracy of the ratio r_{max}/r_w. As r_{max}/r_w can not be accurately determined generally, Logan opined that although the variation in r_{max} and r_w may be substantial, the variation in the logarithm of their ratio is much smaller. Hence, assuming average condition of ratio, he suggested a value of 3.33 for log ratio which may be taken as rough approximation.

Substituting the value in the Eqn (1), we get the Logan's formula

$$T = \frac{1.22Q}{S_{mw}} \qquad (2)$$

where, S_{mw} is the max. drawdown in a pumped well. Accordingly to Kruseman and Rider (1970), Logan's formula in above form gives erroneous results of the order of 50% or more. However, based on Logan's formula, an isopermeability map of the area was prepared. For the purpose, specific capacity and drawdown data of various tube wells were collected and utilized for the determination of transmissivity and permeability.

A perusal of the Isopermeability map (Fig.2.16) of the area of investigation shows that there are six permeability zones viz. (i) 20-30, (iii) 30-40, (iv) 40-50, (v) 50-60 m/day.

The Upland area between river Yamuna and Katha drain has the permeability value <30 m/day. This is also substantiated by the fact that the sub surface lithology in this track is characterized by sand and thick clay lenses. However, most of the area has permeability range in between 30-40 m/day. In the left half region the permeability values, in general, increases southward.

The permeability values at the upper reaches of river Krishni is as high as >50 m/day which decreases gradually towards south. The area in the middle of Krishni-Yamuna Interfluve particularly at village Shamli and Kaserwa has low permeability value i.e. <30 m/day, although the area has got very high sand percent (>80%). This may possibly be attributed to the subtle variation in the grain size, sorting characteristics that control porosity and permeability, and thus fluid flow characteristic.

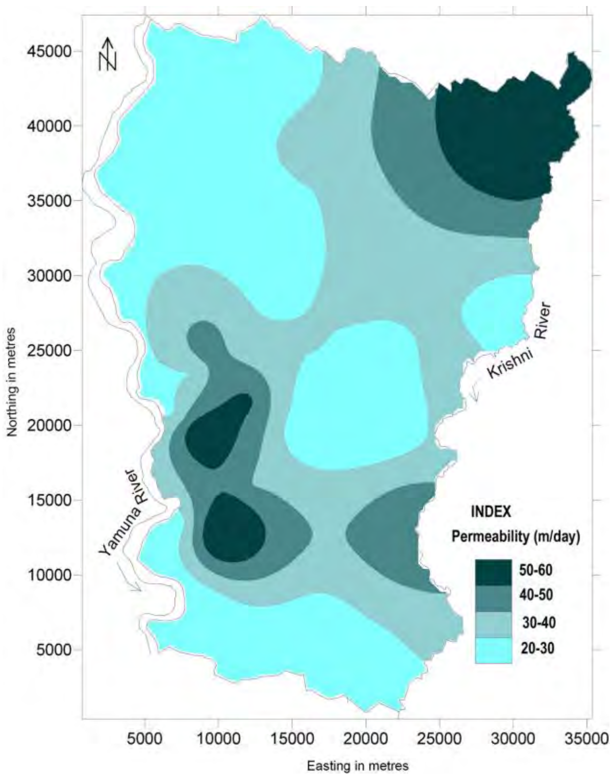


Fig.2.16 Logan's Isopermeability map

2.7.2 Laboratory Estimation of Hydraulic Conductivity

Hydraulic conductivity (K) of an aquifer is known to depend both upon the fluid properties and properties of transmitting medium. For the present study, seven aquifer material (sand samples) were collected from drilling sites and their permeability was determined using constant head Permeameter. Permeability can be obtained by measuring the volume of water percolated through the sample of cross-sectional area A and length L in given time t under a constant head h

From Darcy's Law,

$$K=VL/hAt$$

at the laboratory temperature. The hydraulic conductivity obtained by Permeameter ranges from 1.01 to 7.7 m/day which corresponds to typical conductivity value for fine to medium grained sand. These values are lower than the pumping test value by several orders. The depth range of the sand sample collected varies from 25-45 m which is less than the aquifer tapped for pumping tests. The Pump tests were conducted at an average depth of 143 m. The permeability of various aquifer materials is tabulated in Table 2.4.

Table 2.4 Results of Laboratory Hydraulic Conductivity (m/day).

S.No	**Location**	**Depth (m)**	**K(m/day)**
1	Kandhala	35	2.22
2	Bhoora	25	1.01
3	Bhoora	45	7.7
4	Sikka	45	6.17
5	Issapurteel	30	5.06
6	Dulawa	25	5.95
7	Mundait	30	2.00

The permeability values obtained by Permeameter represent the samples from shallow depth. The size of sand tested varies from very fine to fine. Therefore, the values obtained are at lower side.

2.7.3 Pump Test

A number of pumping test were conducted by Central Ground Water Board (CGWB) and State Groundwater Departments (UPSGWD) in the study area. Out of these a long duration test was conducted at Kheri village ($77^0\ 16^{/}\ /29^0\ 25^{/}\ 30^{//}$) at a discharge rate of 6.64×10^3 m^3/day. The t vs s data was analysed using Theis and Boulten's method. The result of the pumping test is tabulated in Table 2.5.

Table 2.5 Results of the long duration pump test

S.No.	Method	Plot	Data used	T (m^2/day)	S_A	S_Y	Remarks
1.	Boulton	T vs. s	OW-II	1790	2.3×10^{-3}		Early match
				1510		5.9×10^{-2}	Late match
2.	Theis	T vs. s	PZS	3520	1.9×10^{-3}		First segment data used

The result of 8 short duration pumping test conducted at different site in the area by UPSGWD are tabulated in table 2.6. The pumping rate of these wells varies 265 m^3/day to 3941 m^3/day.

Table 2.6 Result of the short duration Pump test

S. No.	Location	Aquifer Group tested (mbgl)	Discharge (m^3/day)	Non-pumping water level	Draw down in (m)	Corrected T (m^2/day)	Kr (m/day)
1.	Khurgyan	125	3940.83	3.947	9.32	1265	10.1
2.	Jharkheri	120	3207.65	10.06	2.77	3190	26.6
3.	Dhanwa	160	4994.78	6.69	6.76	2028	12.7
4.	Mundait	162	3207.65	4.14	4.13	2018	14.4
5.	Todda	152	2284.64	6.40	4.92	1492	9.8
6.	Jaganpur	143	2651.22	7.85	2.94	1941	13.6
7.	Un	154	2847.6	7.02	4.16	4003	26
8.	Jamalpur	143	3469.5	7.24	3.63	3303	23.1

Specific yield of 0.15-0.23 is used in and adjoining part of the study area by several workers (Gupta et al., 1985, Raja et al., 1989, Khan, 1992). However, for the present study specific yield of 0.16 is taken.

3 - ESTIMATION OF DYNAMIC GROUNDWATER RESOURCE

3.1 Introduction

Quantification of the groundwater resource is a basic prerequisite for efficient groundwater resource development and this is particularly vital for India with widely prevalent semi-arid climate. The basic objective of groundwater resource evaluation is to estimate the total quantity of groundwater resources available, and their future supply potential to predict possible conflicts between supply and demand and to provide a scientific database for rational water resources utilization (Earth Summit, 1992).

The effective groundwater budgets of an alluvial area require proper understanding of the hydrodynamics of the basin. The heavy demand of groundwater sometime leads to excessive withdrawals and indiscriminate utilization which is often reflected in serious imbalance of hydrogeological situations at later date. It is therefore, imperative to identify various recharges and discharge components of groundwater regime and their effect on its variation with time.

3.2 Methodology

In the present study GEC 1997 methodology have been adopted with few modifications, like subsurface flows and river-aquifer interaction have been estimated with the help of groundwater flow model. The study area is divided in to canal command area and non-command area for the assessment purpose (Fig.3.1). Command area is the area which comes under major or medium surface water irrigation. Contrarily, non-command areas lack any major or medium surface water scheme. The groundwater fluctuation method is used for recharge assessment in the monsoon season. The monsoon season is taken from June to October. The Kharif crops (paddy, maize, fodder) are cultivated during this period. The rainfall recharge in non-monsoon season is small component and hence estimated empirically. The non-monsoon season is taken from November to May. The Rabi and Zaid (Wheat, oilseeds, pulses etc.) crops are cultivated during this season. The value of specific yield is taken from pumping test data, irrigation return flow, canal seepage and surface water irrigation is estimated with the help of statistical data, field data and recommended values for seepage etc. by GEC'97.

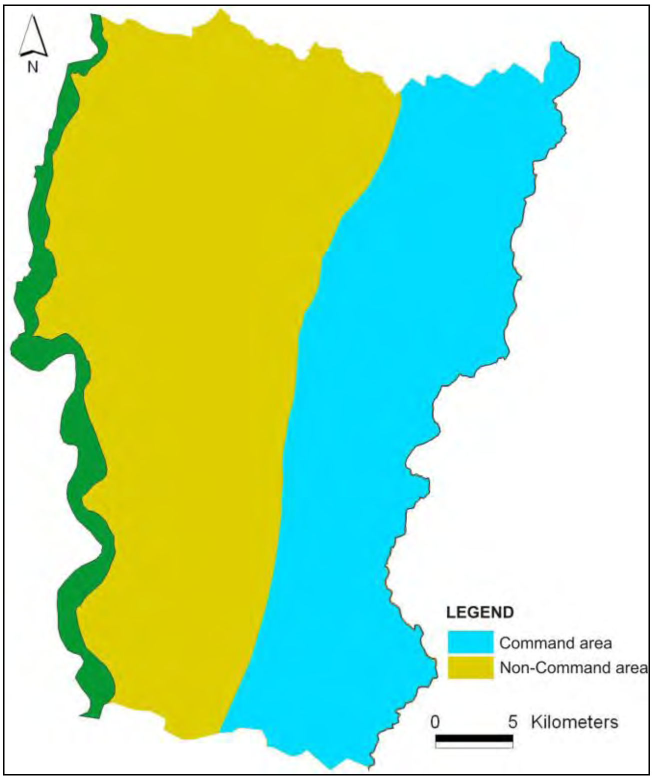


Fig.3.1 Command and non-command area

3.2.1 Estimation of Groundwater Recharge for the monsoon season in Non-Command area

The water level fluctuation method is applied for the monsoon season to estimate the recharge. The groundwater balance equation for the monsoon season in non-command area is given by

$$R_G - D_G - B + I_S + I = S \qquad (2)$$

where,

R_G = gross recharge due to rainfall and other sources including recycled water

D_G = gross groundwater draft

B = base flow into streams from the area

I_S = recharge from streams into groundwater body

I = net groundwater inflow into the area across the boundary (inflow-outflow)

S = groundwater storage increase

All quantities in eqn.2 refer to the monsoon season only.

To signify the total recharge eqn.2 can be rewritten as

$$R = S + D_G + B - I_S - I \quad (3)$$

where

R = possible recharge, which is gross recharge minus the natural discharge in the area in the monsoon season

Substituting the expression for storage increase S in terms of water level fluctuation and specific yield, eqn.3 becomes,

$$R = h x S_y x A + D_G + B - I_s - I \quad (4)$$

Where,

h = rise in water level in the monsoon season = 0.338 m

A = area for computation of recharge = 662.94 Sq.Km

S_y = specific yield =0.16

I_S = recharge from streams into groundwater body = 6.39 MCM

I = net groundwater inflow into the area across the boundary (inflow-outflow) = 2.86 MCM

B = base flow into streams from the area = 0.52 MCM

R = 0.388 x 0.16 x 662.94+100.52+0.52-6.39-2.86

R = 132.94 MCM

The recharge calculated from eqn.4 gives the available recharge from rainfall and other sources for the particular monsoon season.

For non-command areas, the recharge from other sources may be recharge from recycled water from groundwater irrigation, recharge from tanks and ponds and recharge from water conservation structures, if any. The rainfall recharge is given by,

$$R_{rf} = R - R_{gw} - R_{wc} - R_t \quad (5)$$

where, R_{rf} = recharge from rainfall

R_{gw} = recharge from groundwater irrigation in the area = 69.2 MCM

R_{wc} = recharge from water conservation structures = Nil

R_t = Recharge from tank and ponds =Nil

R_{rf} = 132.94-69.2-0-0 (Since, $R_{wc} = R_t = 0$)

R_{rf} = 63.74 MCM

3.2.2 Estimation of Groundwater Recharge for the monsoon season in the command area

For command areas, recharge from other sources include recharge due to seepage from canals, recharge due to return flow from surface water irrigation and groundwater irrigation, recharge from storage tanks and ponds, and recharge from water conservation structures. The recharge from rainfall is given by,

$R_{rf} = hxS_yxA + D_G - R_C - R_{gw} - R_{sw} - R_t - R_{wc}$ (6)

where,

R_{rf} = recharge from rainfall

R_C=recharge due to seepage from canals = 20.00 MCM

A = area for computation of recharge = 437.50 Sq.Km

R_{sw}=recharge from surface water irrigation = 12.82 MCM

R_{gw} = recharge from groundwater irrigation in the area = 74.14 MCM

R_{wc} = recharge from water conservation structures = Nil

R_t = Recharge from tank and ponds = Nil

D_G=gross draft in the command area = 88.52 MCM

h = rise in ground water level in the command area = 0.708 m

S_y=specific yield = 0.16

R_{rf}= 0.708x0.16x437.5+88.52-20-74.14-12.82-0-0

R_{rf}=49.56+88.52-20-74.14-12.82

R_{rf}=31.12 MCM

R_{wc} & R_t are not applicable in the present study area.

3.2.3 Recharge through Rainfall

The recharge from rainfall during the non-monsoon season may be estimated based on the rainfall infiltration factor, provided the normal rainfall in the non-monsoon season is greater than 10% of the normal annual rainfall. If the rainfall is less than this threshold value, the recharge due to rainfall in the non-monsoon may be taken as zero (GEC 97).

Rainfall recharge in the non-monsoon season may be estimated based on the rainfall infiltration factors. The infiltration factor is taken as 22% of total rainfall. The estimates of non-monsoon rainfall recharge are given in Table 3.1.

Table 3.1 Non-monsoon rainfall recharge

	Rainfall (mm)	Infiltration factor	Total area (km^2)	Rainfall recharge (MCM)
Command Area	115	0.22	437.5	11.06
Non-command Area	109	0.22	663	15.89

3.2.4 Recharge through Irrigation returns

Since groundwater is the major source of irrigation in the study area, a large part of it can return to the aquifer by direct infiltration. The infiltration factor is dependent upon several factors including soil types and texture, depth to water table, types of crop and method of application of water. It varies widely (0.15-0.45) for the prevailing three crops pattern i.e. Rabi, Kharif and Zaid (GEC 1997). The recharge through irrigation returns for command and non-command areas are given in Table 3.2 and Table 3.3, respectively.

Table 3.2 Seasonal (crop wise) irrigation return in command area

Depth to water table	Crop Type	Area Irrigated (km^2)	Average wetted Depth (m)	Irrigation Water applied (MCM)	Seepage Factor	Seepage (MCM)
<10 m	Rabi	95.35	0.4	38.14	0.25	9.54
	Kharif	180.43	0.4	72.17	0.45	32.48
	Zaid	25.1	0.4	10.04	0.25	2.51
>10 m	Rabi	170.8	0.4	68.33	0.15	10.25
	Kharif	297.55	0.4	119.02	0.35	41.66
	Zaid	28.55	0.4	11.42	0.15	1.71

Table 3.3 Seasonal (crop wise) irrigation return in non-command area

Depth to water table	Crop type	Area Irrigated (km^2)	Average wetted Depth (m)	Irrigation Water applied (MCM)	Seepage Factor	Seepage (MCM)
<10 m	Rabi	50.0	0.4	20	0.25	5.00
	Kharif	85.4	0.4	34.16	0.45	15.37
	Zaid	14.32	0.4	5.73	0.25	1.43
>10 m	Rabi	240.32	0.4	96.13	0.15	14.42
	Kharif	384.47	0.4	153.79	0.35	53.83
	Zaid	36.8	0.4	14.72	0.15	2.21

3.2.5 Recharge through Canal Seepages

Recharge through percolation from canals depends on the infiltration capacity of the canal sub-surface lithology, extent of wetted perimeter, length of canal etc. (Karanth,1987). The wetted perimeter and total length of different canals was determined. Data of total numbers of running days were collected from the District Irrigation Department. The recharge through canal seepage is tabulated in Table 3.4.

Canal seepage = length × wetted perimeter × total running days x specific loss

Table 3.4 Recharge through canal seepage

Type of canal	Total length of canal (m)	Average wetted peri-meter (m)	Average running days		Seepage (MCM)	
			Non Monsoon	Monsoon	Non monsoon [Col. 2 x col. 3 x col. 4 x 20x10^{-2}]	Monsoon [Col. 2 x col. 3 x col. 5 x 20x10^{-2}]
1	2	3	4	5	6	7
Branch	45000	14.25	180	120	23.08	15.39
Distributary	141000	6.13	68	60	11.75	10.37
Minor	50000	3.30	100	80	3.30	2.64

Total seepage through canal in monsoon season is 28.4 MCM. Out of this 20.0 MCM is taken for command area.

3.2.6 Recharge through Surface Water Application

Recharge is also takes place through surface water irrigation. The surface irrigation water applied is taken out by multiplying irrigated area with applied water depth. Seepage factor ($0.3<S_f<0.4$) is used which is same as recommended by GEC' 97 for alluvial areas. Recharge through surface water irrigation is given in Table 3.5.

Table 3.5 Recharge through surface water irrigation (MCM)

	Depth to water table	Area Irrigated (km^2)	Average wetted depth (m)	Irrigation water applied (MCM)	Seepage factor (S_f)	Seepage (MCM)
Command Area	<10 m zone	33.66	0.4	13.46	.40	5.39
	>10 m zone	61.90	0.4	24.76	.30	7.43
Non-command Area	>10 m zone	34.44	0.4	13.76	0.30	4.13

3.2.7 Estimation of Horizontal Inflows

Horizontal Inflows was computed using a finite difference model (MODFLOW) with hydrodynamic and geometry acquired on the basin, in order to obtain a spatial distribution of flows on the grid of square cells (Fig 3.2). Table 3.6 shows the estimates of horizontal inflows.

Table 3.6 Subsurface horizontal inflows across the sub-basin.

	Inflows (MCM)	
	Monsoon	Non-monsoon
Command	3.6	6.1
Non-command	3.98	6.9

3.2.8 River-aquifer interaction

Two-dimensional x–z (profile) steady-state numerical model solutions were used to explore the interaction between the river and aquifer and a variety of boundary conditions were considered, including recharge to the water table. The altitudes of river stage and river bed bottom are measured accurately. The river boundary package was employed for both rivers. In the zone budget package, both the rivers were treated as individual zones and subsequently their flux was calculated by model itself. The quantitative river–aquifer interaction is reported in table 3.7.

Table 3.7 River aquifer interaction

River	Inflow* (MCM)	Baseflow** (MCM)
Yamuna	6.39	0.52
Krishni	5.12	0.68

* Inflow to study area, ** Baseflow to river.

3.2.9 Total Annual Recharge

The total annual recharge is obtained as the sum of recharge in the monsoon season and recharge in the non-monsoon season, where in each season, the recharge comprises of recharge from rainfall and recharge from other sources. Table 3.8 shows the estimates of total annual recharge.

Table 3.8 Annual groundwater recharge in the study area (MCM)

Area	Rainfall recharge	Irrigation returns	Canal seepage	Recharge through surface water irrigation	HIF	River-aquifer interaction	Total (MCM)
Command	42.18	98.15	50.00	12.82	9.70	5.12*	217.97
Non-command	79.63	92.26	16.53	4.13	10.88	6.39**	209.82

* Krishni river, ** Yamuna river

3.2.10 Estimation of Groundwater Discharges

The groundwater discharges from the sub-basin includes draft through pumpage, evaporation from water table and subsurface horizontal outflows.

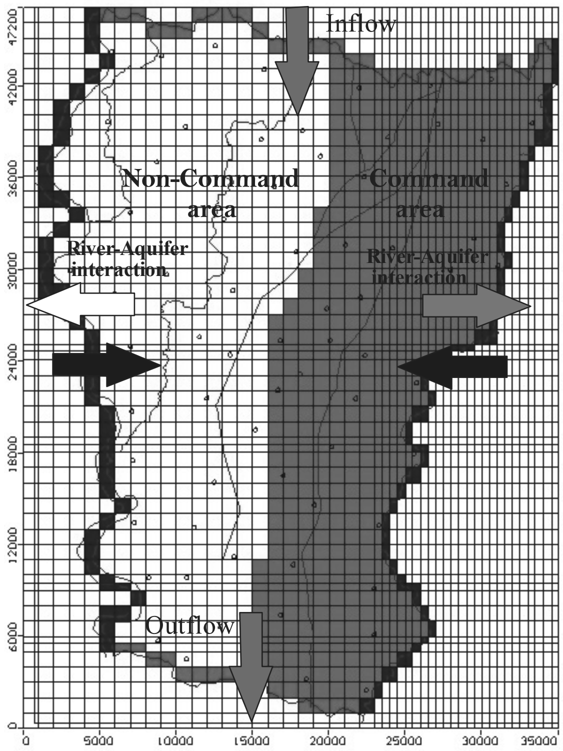


Fig.3.2 Horizontal flows across the Yamuna-Krishni sub-basin.

3.2.10.1 Estimation of Groundwater Draft through Pumpage

The database on number of groundwater structures existing in area were collected from well inventoried during several field visits. The data of bore well census from District statistical Department is also used for this purpose (Table 3.9). Three types of borewells were categorized on the basis of their yield. The state borewells, governed by state groundwater department have a discharge rate of 1500 l/m. The private (electric) and private (diesel) borewells have discharge rate of the order of 250 l/m and 60 l/m, respectively (Plate 6).

Table 3.9 Borewell census in the study area.

	Block	State Tubewell	Private(Electric)	Private (Diesel)
Command Area	Thanabhawan	9	1041	1838
	Shamli	6	1850	592
	Kandhala	17	2274	377
Non-Command Area	Un	59	2649	9117
	Kairana	17	1674	2444

The duration of pumping mainly depends on electric power supply, borewell maintenance and time (season) of the year. The unit yearly draft for the above groundwater structures has been fixed by GEC 1997. The unit draft for state tubewell, private (electric) and private (diesel) tubewells is 0.2, 0.037 and 0.0075 MCM, respectively.

The annual unit draft is used to calculate groundwater draft for different season. Season-wise draft through pumpage for monsoon period (152 days) and non-monsoon period (213 days) is estimated separately and given in Table 3.10.

Table 3.10 Groundwater draft through pumpage (MCM)

		State tubewells	Private (Electric)	Private (Diesel)
Monsoon Season	Command	2.62	77.47	8.42
	Non-command	6.23	64.8	34.68
Non-monsoon Season	Command	3.77	113.63	11.23
	Non-command	8.97	95.11	46.24

3.2.10.2 Evaporation from water table (EVAP)

This component is evaluated using the relation developed by Coudrain et al., (1998). Evaporation flux is expressed as an inverse power function of the piezometric depth below the soil surface, independently of the soil characteristics. The EVAP component is calculated for the area having shallow water table.

$$EVAP = 71.9(Z)^{-1.49}$$

where, Z = Water depth from soil (m)

The EVAP component comes out to be 1.77 mm. The groundwater discharge through EVAP for command and non-command areas is given in Table 3.11.

Table 3.11 Discharge through EVAP in the study area (MCM)

	Area (Km^2)	EVAP (mm)	EVAP (MCM)
Command	90.3	1.77	0.16
Non-command	114.9	1.77	0.20

3.2.10.3 Estimation of Horizontal Outflows

The subsurface flows leaving the study area are termed as horizontal outflows. Groundwater flow model gives very precise account of the horizontal outflows from every possible direction. These are given in Table 3.12.

Table 3.12 Subsurface horizontal outflow

	Outflows (MCM)		Baseflow (MCM)
	Monsoon	Non-monsoon	
Command	0.78	0.76	0.68*
Non-command	1.12	1.09	0.52**

* Krishni river, ** Yamuna river

3.2.11 Total Discharges

The total discharge is the sum of groundwater draft through pumpage, evaporation from water table and groundwater outflows. The estimates of groundwater discharge are given in Table 3.13.

Table 3.13 Total discharge in the study area (MCM)

	Draft through pumpage	Evap	Outflow	Baseflow	Total discharge
Command	217.14	0.16	1.54	0.68	219.52
Non-command	256.03	0.20	2.21	0.52	258.96

3.2.12 Stage of Groundwater Development in the Study Area

The stage of groundwater development (%) = (Existing gross groundwater draft for all uses/Net annual groundwater availability) X 100

The stage of groundwater development for command and non-command area is worked out separately and is given in Table 3.14.

Table 3.14 Stages of groundwater development (June 06– May 07)

	Gross groundwater draft (MCM)	Net annual groundwater availability (MCM)	Change in groundwater storage (±ΔS)	Stage of Groundwater development (%)
Command area	219.52	217.97	-1.55	100%
Non-command area	258.96	209.82	-49.14	123%
Total	478.48	427.79	-50.69	111%

The results of groundwater budget show that change in groundwater storage in command and non-command area is – 1.55 MCM and - 49.14 MCM, respectively. The deficit balance implies that groundwater in both types of area is excessively pumped. The stage of groundwater development in command and non-command areas is 100% and 123 %, respectively. Thus, stage of groundwater development has reached to its maximum and sub-basin is categorized under dark category.

Using the above methodology groundwater balance is also calculated for the period from June 2007 to May 2008.The results are tabulated in table 3.15.

Table: 3.15 Stages of groundwater development (June 07– May 08)

	Gross groundwater draft (MCM)	Net annual groundwater availability (MCM)	Change in groundwater storage (±ΔS)	Stage of Groundwater development (%)
Command area	218.53	185.48	-33.05	117 %
Non-command area	274.60	208.17	-66.43	132 %
Total	493.13	393.65	-99.48	125 %

3.2.13 Long Term Groundwater Fluctuation Trend

The stage of groundwater development is considered as the index of balance between groundwater available and utilization. As the stage of development approaches 100%, it indicates that potential for future development is meager. However, the assessment based on the stage of groundwater development has inherent uncertainties. The uncertainties lie with the estimations of groundwater draft and gross groundwater recharge, owing to the limitations in the assessment methodology, as well as uncertainties in the data.

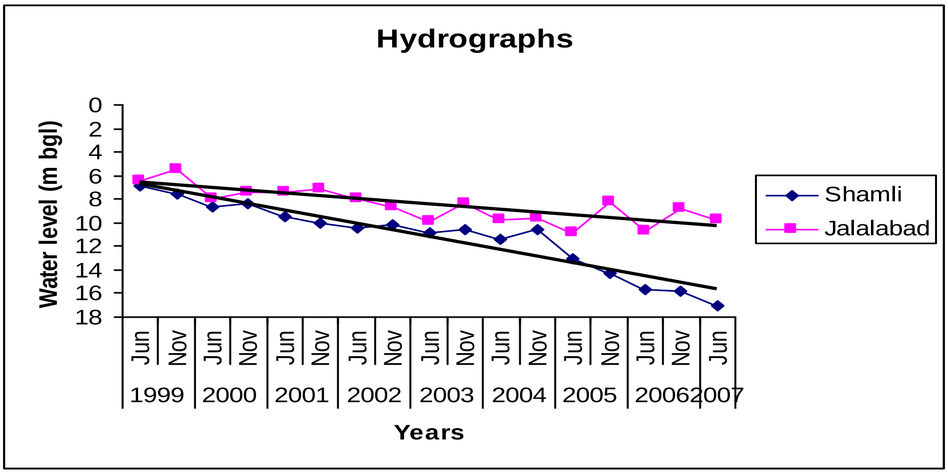


Fig. 3.3a Hydrograph showing significant decline in command area

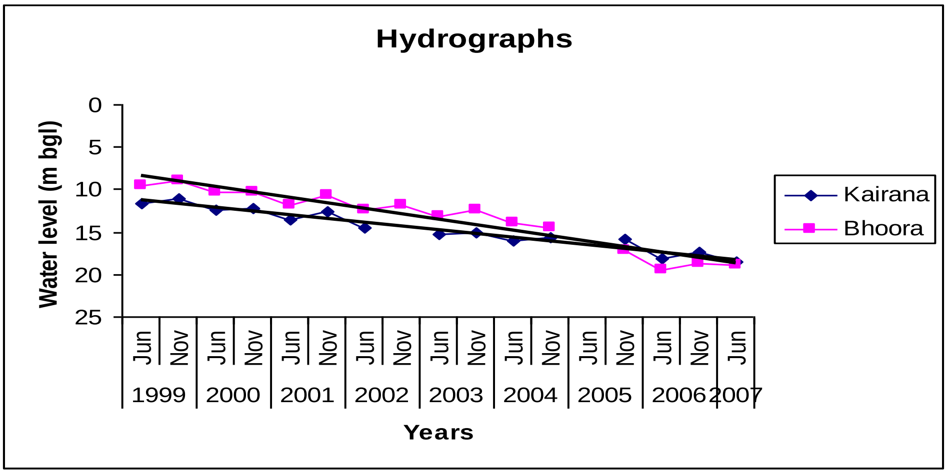


Fig.3.3b Hydrograph showing significant decline in non-command area

The long term groundwater level trend of the area must be correlated with the water balance results. The long term water level behaviour of the groundwater regime has been studied for four permanent hydrograph stations. Out of these four stations Jalalabad and Shamli hydrographs represent command area and Kairana and Bhoora represent non-command area. A perusal of Figure 3.3a & 3.3b shows long term declining trend in the study area which is in accordance with water balance results.

4 - GROUNDWATER FLOW MODELLING

4.1 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 modelling 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 soft ware (McDonald & Harbaugh,1988).

4.2 Finite Difference Approximation

In finite difference method (FDM), a continuous medium is replaced by a descrete 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

$$T_x \frac{\partial^2 h}{\partial x^2} + T_y \frac{\partial^2 h}{\partial y^2} = S_y \frac{\partial h}{\partial t} \pm q \qquad (1)$$

When eqn (1) is applied to an unconfined aquifer, the Dupuit assumptions are used: (1) flow lines are horizonatal 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.

$$K_x \frac{\partial^2 h}{\partial x^2} + K_y \frac{\partial^2 h}{\partial y^2} + K_z \frac{\partial^2 h}{\partial z^2} = S_s \frac{\partial h}{\partial t} - R \qquad (2)$$

Where K_x, K_y and K_z are components of the hydraulic conductivity tensor. S_s is the Specific storage, R is 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.

4.3 Model conceptualization and data acquisition

The purpose of building a conceptual model is to simplify the field problem and organize the associated field data so that the system can be analyzed more readily (Anderson and Woessner, 2002). The conceptualization include synthesis and framing up of data pertaining to geology, hydrogeology, hydrology, and meteorology.

4.3.1 Groundwater Level Data

A network of 60 existing observation wells were selected for water level monitoring. The water level monitoring programme was initiated in November 2005. The depth of monitoring wells ranged between 10-30 m and these tap the first layer of the aquifer. Water levels were recorded from November 2005 to November 2007 at all observation points. Care was taken to try and obtain static groundwater levels however errors may have been introduced because practically it was impossible to stop all pumping in an extensively cultivated area where concentration of groundwater abstraction structures are so high.

4.3.2 Aquifer geometry

Geologic information including geologic maps, cross sections and well logs were combined with information on hydrogeologic properties to define hydrostratigraphic units for the conceptual model (Anderson and Woessner, 2002).

The present study was confined to the first group of aquifers. Lithological data of 27 boreholes were utilized for sketching horizontal and vertical disposition of aquifers and aquitards in the study area to a depth of 122 m bgl. The nature of the alluvial sediments is generally complex and is composed of a rapid alternation of sand and clay layers. The top clay bed is underlain by a granular zone, which extends downward to different depths varying up to a maximum of 122 m bgl. The granular zone is subdivided in places into two to three sub-groups by the occurrence of sub-regional clay beds. Local clay lenses are also common throughout the area. By and large the aquifers down to a depth 122 m appear to merge with each other as the clay layers do not extend laterally to the entire area (Fig.2.2).

A three layer model was chosen over a single layer model to account for the presence of clay lenses and the inability of the software to recognize lenses. The top sandy layer contains the water table and is of variable thickness ranging from 15-84 m bgl. The simulation of aquifer geometry was done accordingly and clay lenses are presented as semi permeable layers. The absence of clay horizon in a particular area was achieved by assigning a value of hydraulic conductivity equivalent to overlying and underlying aquifers. The second layer i.e. clay layer was assigned hydraulic conductivity values similar to the overlying and underlying layers at places where the clay layer was discontinuous as revealed by hydrogeological cross sections and fence diagram.

4.3.3 Aquifer Parameters

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.

The various aquifer parameters, such as hydraulic conductivity and specific yield/specific storage, were estimated and assigned to different layers, using data derived from previous studies (e.g. Bhatnagar et al., 1982). The hydraulic conductivity values assigned to the model ranged between 9.8 to 26.6 m/day. A specific yield of 0.16 was applied uniformly to the entire area. Hydraulic conductivity values were obtained from seven pump tests (Fig.2.1) and were assigned to seven distinct zones using the Thiessen Polygon method (Fig.4.1a and 4.1b), which involves the construction of polygon around

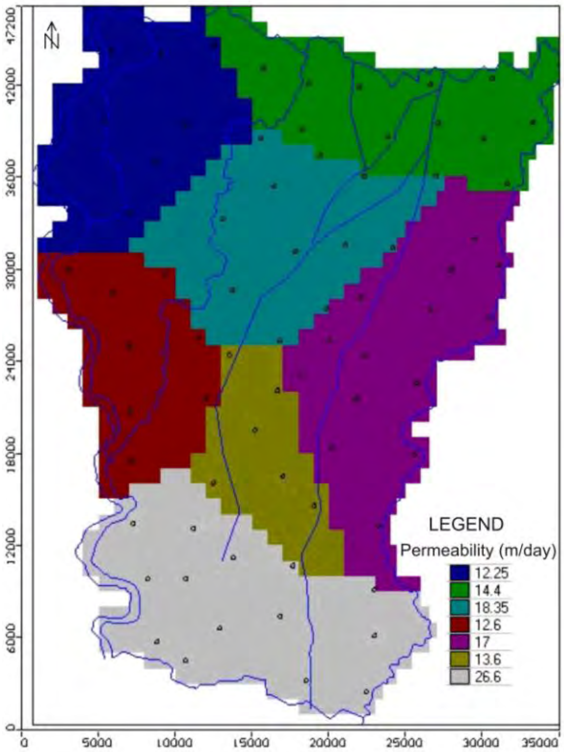


Fig.4.1a Zone wise permeability distribution in first and third layer.

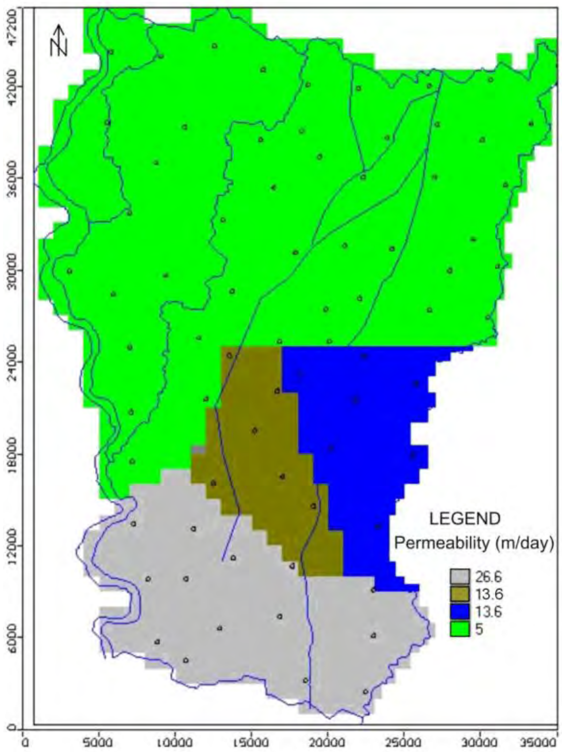


Fig.4.1b Zone wise permeability distribution in second layer.

the stations. This method is preferred over contouring where data points are sparse. The conductivity values for the first and third layer remained the same as the both the layers are essentially similar. The second layer, being an aquitard, was given a conductivity value of 5 m/day. The second layer was also given similar conductivity values at places where clay layer was discontinuous. The higher conductivity zones in the second layer were used to maintain the interconnectivity between the first and third layers. This assumption is based on the fact that clay layer is not a continuous layer and laterally pinched out and at places the first and third layer merge with each other to present a single bodied aquifer.

4.3.4 Recharge

Recharge from rainfall, irrigation return water and canal seepage was estimated using methodology given by the Groundwater Estimation Committee (1997). The details are describe in chapter 3.

The estimation of recharge and discharge parameters were done for monsoon and non-monsoon periods. The estimated values were then applied to the respective grids in the model using recharge boundaries (Fig.4.2). The total recharge estimated was in accordance with water table fluctuation method and GEC 1997 methodology for groundwater resource estimation. Recharge through irrigation returns and seepage through unlined canals was estimated using standard norms recommended by GEC-97.

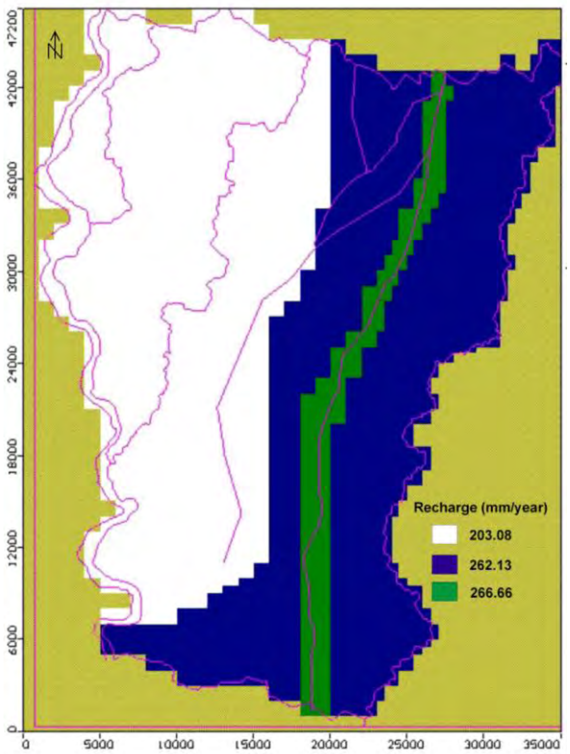


Fig.4.2 Zone wise recharge distribution in Yamuna-Krishni model.

Site specific recharge data are often used purely as fitting parameters during model calibration (Varni and Usunoff, 1999) where site specific information is available, and an assumed fraction of this is commonly assigned as the recharge boundary condition (Kennett-Smith et al., 1996, Hsu et al., 2007). Such assumptions are adequate for the long term simulation of regional groundwater flow system (Jyrkama et al., 2002) and was used during the present study.

4.3.5 Groundwater Draft through pumping

A database of existing borewells in the study area was created from several field visits over the period November 2005 to November 2007. A borewells census from the Statistical Department was also used for the same purpose. Three types of wells were categorized on the basis of their yield (Fig.4.3). The state tubewells, governed by State Tubewell Department, have a discharge rate of 1500 L/min. Private electric motor and private diesel engine borewells have discharge rates in the order of 250 L/min and 60 L/min, respectively. The duration of pumping mainly depends on electric power supply, tubewell maintenance and season of the year.

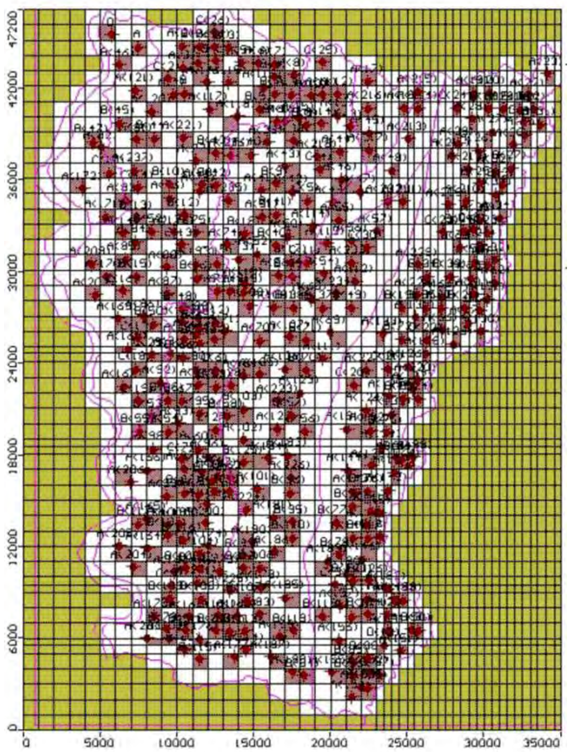


Fig.4.3 Simulated groundwater pumping centres in Yamuna-Krishni Model.

Simulated pumping rates of 500 m^3/day, 1000 m^3/day, 1500 m^3/day, 2000 m^3/day and 2500 m^3/day were used in the pumping well package. The actual pump rate varies from 25-400 m^3/day for a single groundwater draft structures. Since it was nearly impossible to import all the wells which may exceeds more than 10,000 in number. Therefore, simulated rate of 1000 to 2500 m^3/day were applied, assuming that one simulated pumping well represent several actual pumps.

4.3.6 Boundary Conditions

Every model requires an appropriate set of boundary conditions to represent the system's relationship with the surrounding area. The western and eastern boundaries representing the Yamuna and Krishni Rivers, respectively, were assigned as river boundaries (Fig.4.4). For these boundaries, river head and river bed bottom elevations were assigned to appropriate grids after carrying out several field visits. The river head and bed bottom elevations at the initial and final point of River Yamuna are 235 and 234 m amsl and 224 and 223.5 m amsl, respectively. For River Krishni the river head and bed bottom elevations at the initial and end point are 240 and 239 m amsl and 220.8 and 220.6 m amsl, respectively. River bed conductance varies between 150 to 100 and 50 to 30 m^2/day for the Yamuna and Krishni Rivers, respectively.

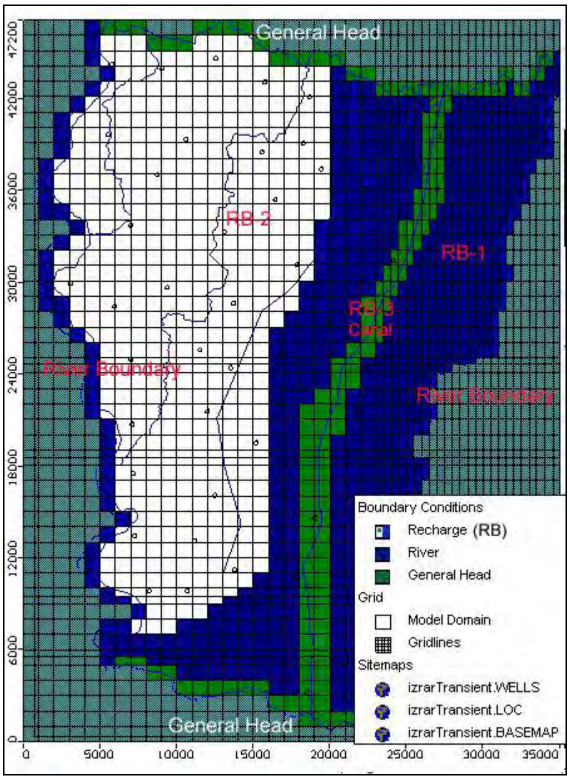


Fig.4.4 Map showing Boundary conditions in the study area

General head boundaries (GHB) were assigned at the northern and southern edges of the model. Heads were assigned to the GHB with the help of historical water level data.

4.4 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 modelling. 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 modelling. 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.

4.4.1 Model conceptualization

I. The Yamuna-Krishni sub-basin is interfluve region, bounded by river Yamuna and river Krishni from western and eastern side respectively.

II. The aquifer model in Yamuna-Krishni interstream region consists of 47 rows and 40 columns.

III. The model has three layers with a uniform grid of 1000m x 1000m (Fig. 4.5). All the layers are interconnected through vertical conductivity and water level is same for all layers.

IV. 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 (Fig. 4.1a and 4.1b).

V. The simulated three layer model extends up to maximum thickness of 122m with an average thickness of 95 m below ground level (Fig.4.6a and 4.6b).

VI. 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.

VII. 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.

VIII. The recharges values to command, non-command and seepage value for individual canal has been worked out and assigned to respective grids (Fig.4.2) using recharge boundary package.

IX. The pumping rates vary from 25-400m^3/day. The simulation of the pumping rate is done accordingly and representative pumping of simulated pumping rates like 1000, 1500, 2000 and 2500 m^3/day is used (Fig.4.3).

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

XI. The river boundary condition was applied to the rivers Yamuna and Krishni. Heads are prescribed to all the boundary conditions.

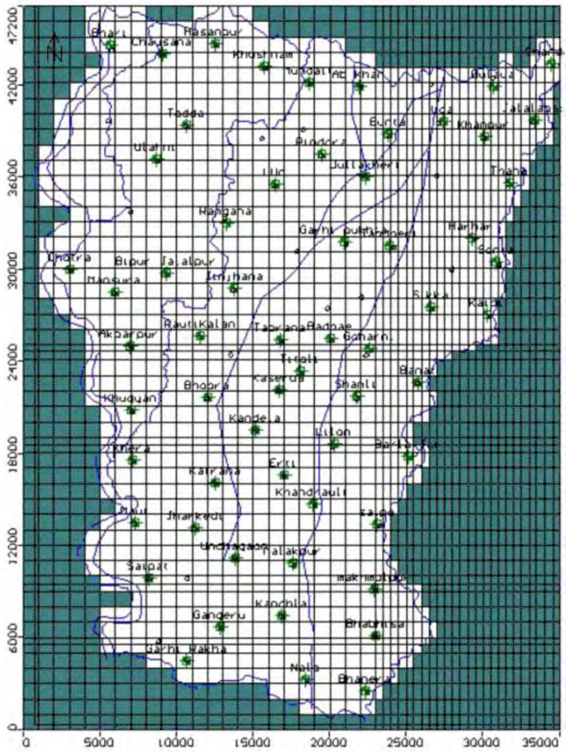


Fig.4.5 Grid pattern and location of observation wells in Yamuna-Krishni sub-basin.

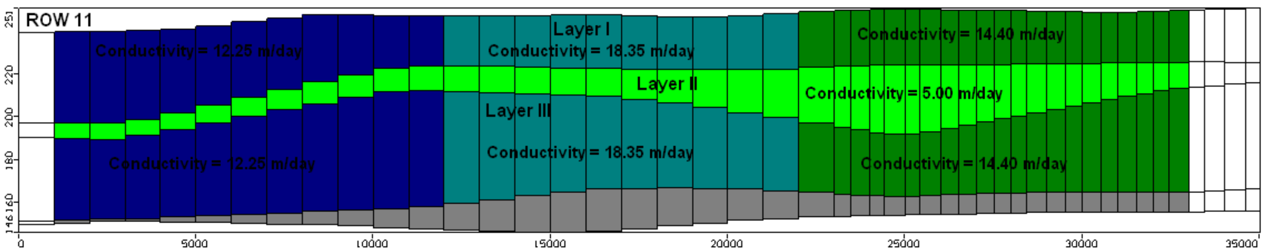


Fig.4.6a Hydrogeological cross section along row 11 showing three layer system.

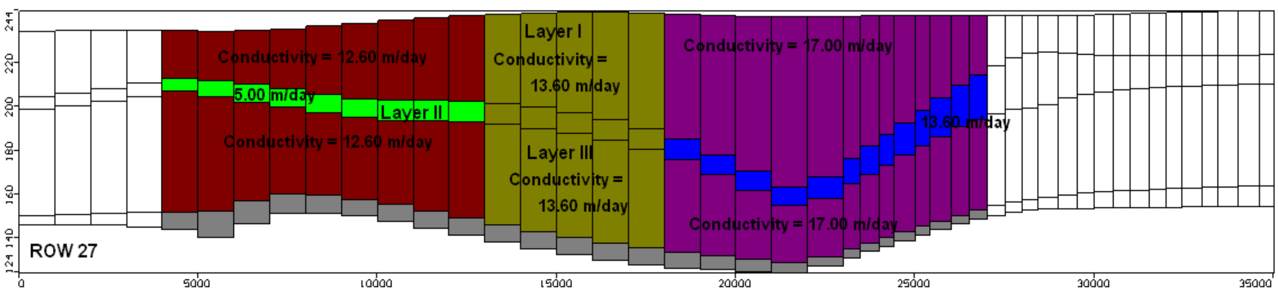


Fig.4.6b Hydrogeological cross section along row 27 showing three layer system.

4.5 Visual 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.

The finite-difference groundwater model Visual MODFLOW 4.1 Pro was used in the present study. MODFLOW is a computer program that numerically solves the three-dimensional ground-water flow equation for a porous medium by using a finite-difference method (Waterloo Hydrogeologic Inc. 2005). In the 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.

4.6 Model Calibration

The purpose of model calibration is to establish that the model can reproduce field measured heads and flows. Calibration is carried out by trial and error adjustment of parameters or by using an automated parameter estimation code.

4.6.1 Steady State Calibration

Steady state conditions are usually taken to be historic conditions that existed in the aquifer before significant development has occurred (i.e. inflows are equal to outflows and there is no change in aquifer storage). In this model, quasi-steady state calibration comprised the matching of observed heads in the aquifer with hydraulic heads simulated by MODFLOW during a period of unusually high recharge. The calibration was made using 60 observation wells monitored during November 2006. Hydraulic conductivities estimated from pumping tests were used as initial values for the steady state simulation. By trial and error calibration, the conductivity values for zone 1 and 4 were increased by 25 % and the conductivity for other zones represent actual pumping test values. The recharge value were reduced by <10% from original calculated values during many sequential runs until the match between the observed and simulated water level contours were obtained (Fig. 4.7a and 4.7b).

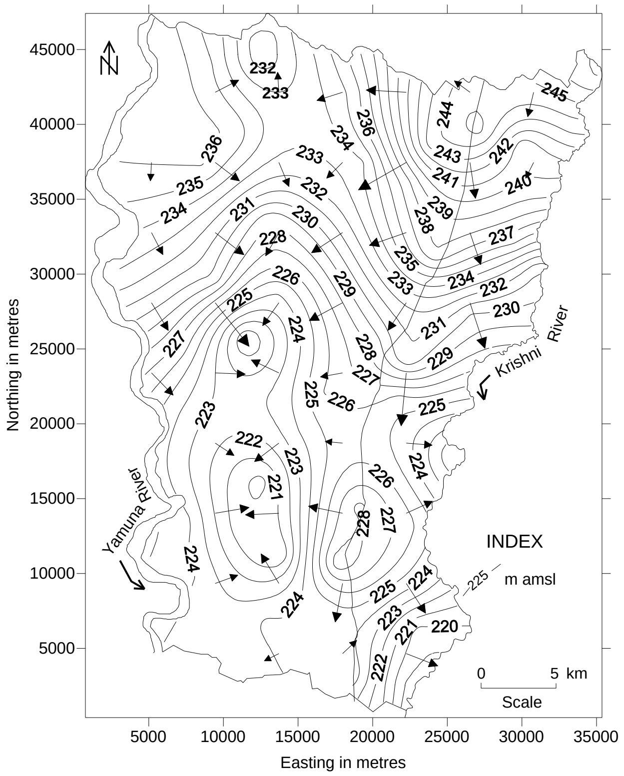


Fig.4.7a Observed water table contour map (November 2006).

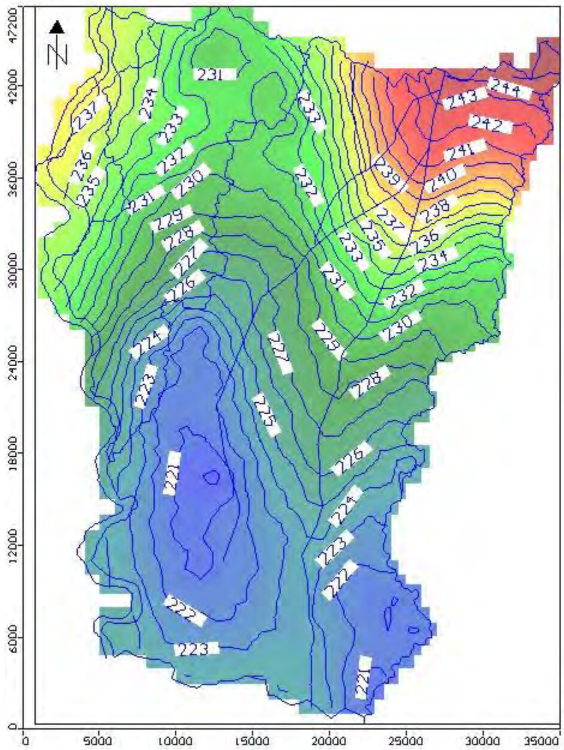


Fig.4.7b Simulated water table contour map (November 2006).

The computed water level accuracy was judged by comparing the mean error, mean absolute and root mean squared error calculated (Anderson and Woessner, 1992). Mean error is -0.066 m. 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 wells, which in the present simulation is 1.8 m (Fig. 4.8). The absolute residual mean is 1.5 m. The absolute residual mean $|\overline{R}|$ is similar to the residual mean except that it is a measure of the average absolute residual value defined by the equation:

$$|\overline{R}| = \frac{1}{n}\sum_{i=1}^{n}|R_i|$$

The absolute residual mean measures the average magnitude of the residuals, and therefore provides a better indication of calibration than the residual mean (Waterloo Hydrogeologic Inc, 2005).

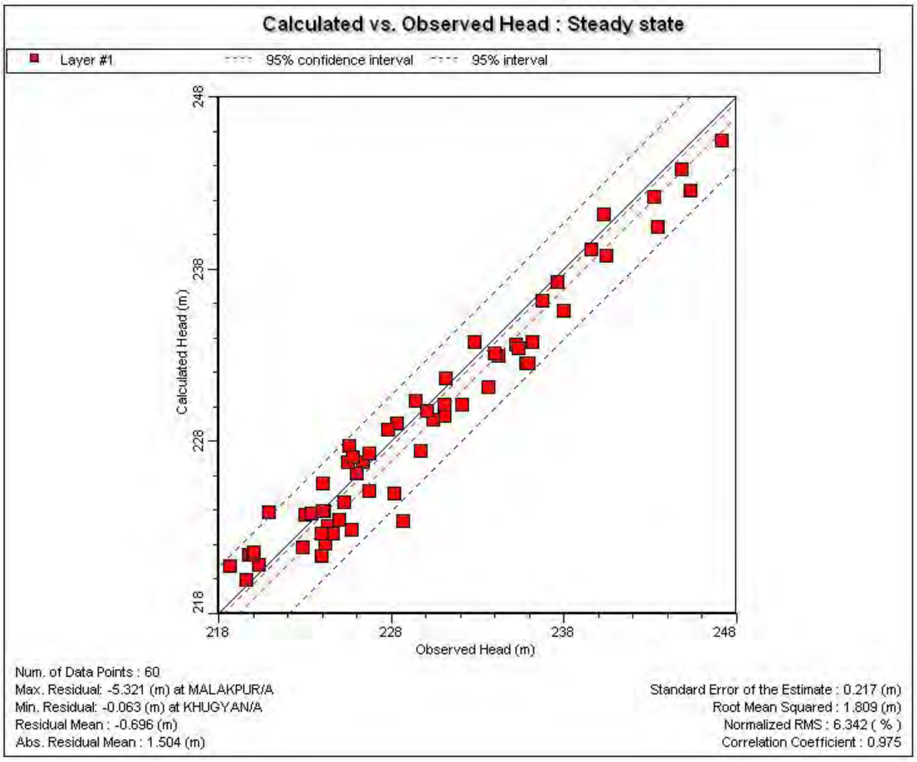


Fig. 4.8 Calculated versus observed heads (Nov 2006).

4.6.2 Transient State Calibration

It is quite possible that the aquifer system may attain steady state conditions at more than one time period as at any time period if the flows get balanced and the water levels do not change over that period, the system remains in the steady state condition. However, in practice and moreover in India where in most cases, over-exploitation are common, it is very difficult to get the aquifer in the steady state condition unless we go much beyond in time in the past which limits the data availability. Thus in this case, the aquifer system was found to be in near steady state during November 2006, it was chosen to run and calibrate the model under steady state for this period and the calibrated hydraulic conductivity distribution was obtained. Subsequently, the model was calibrated to transient state from June 1999 to June 2007. The time steps in transient simulations run from November 1999 to June 2007 were divided in to 18 time steps. Each year was also divided in to two stress periods of 152 days (monsoon period) and 213 days (non-monsoon period), respectively. Recharge boundaries were initially set using a 30-day stress period, which was gradually increased to 152 and 213 days. The actual amount of recharge was calculated for each year using GEC'97 methodology. Recharge through irrigation return flows and canal seepage was calculated using specific norms. Visual MODFLOW uses boundary conditions imposed by the user to determine the length of each stress period. The initial hydraulic conductivity values of the steady state model were used as the values for the transient state model. Initial recharge for command and non command area was used as a 248.8 and 264.6 mm/year. The initial specific yield was taken 0.16 which was increased to 0.20 during successive runs.

After a number of trial runs, where the input/output stress were varied, computed water levels were matched fairly reasonably to observed values. The RMS for the transient model is 1.58 m (Fig.4.9). Also it was assured that the model water levels during November 2006 reasonably matched with the observed water levels during that period.

The computed water level of November 2006 indicates a prevailing trend of groundwater flow in the interstream region.The observed pre and post monsoon water levels for selected observation wells for the period 1999-2007 were used for the transient state calibration. It should be noted that estimation of recharge, as a fraction of annual rainfall, was a first approximation: actual recharge depends upon total precipitation, its frequency and other inputs such as irrigation returns and canal seepage. A comparison of observed and computed heads at different observation wells is shown in figure 4.10a, b, c and d.

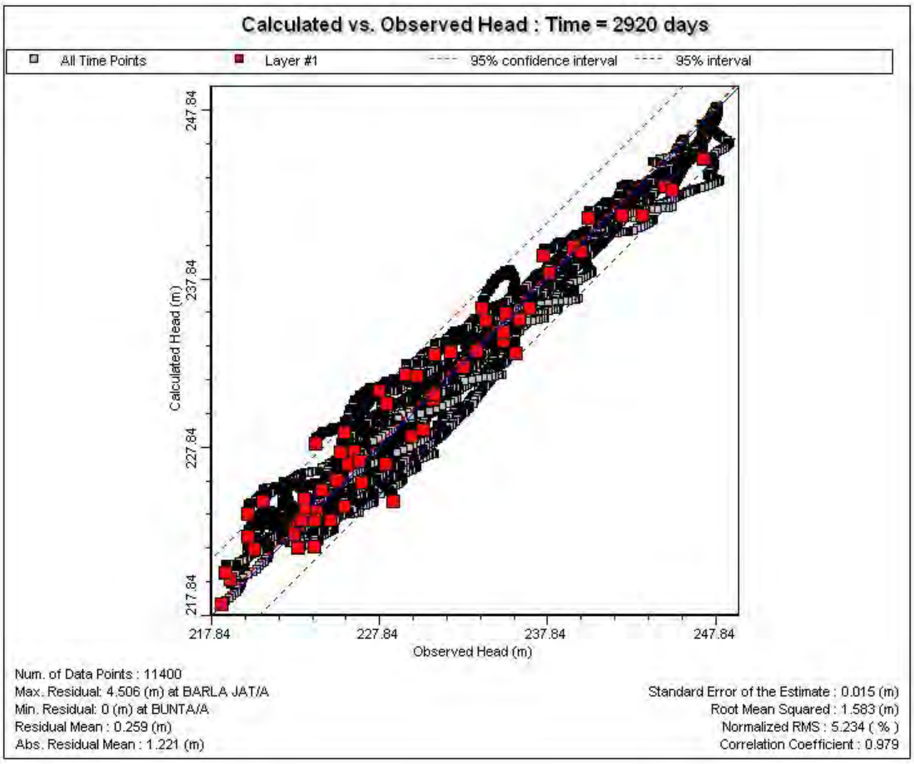


Fig.4.9 Calculated versus observed heads (June 1999-June 2007).

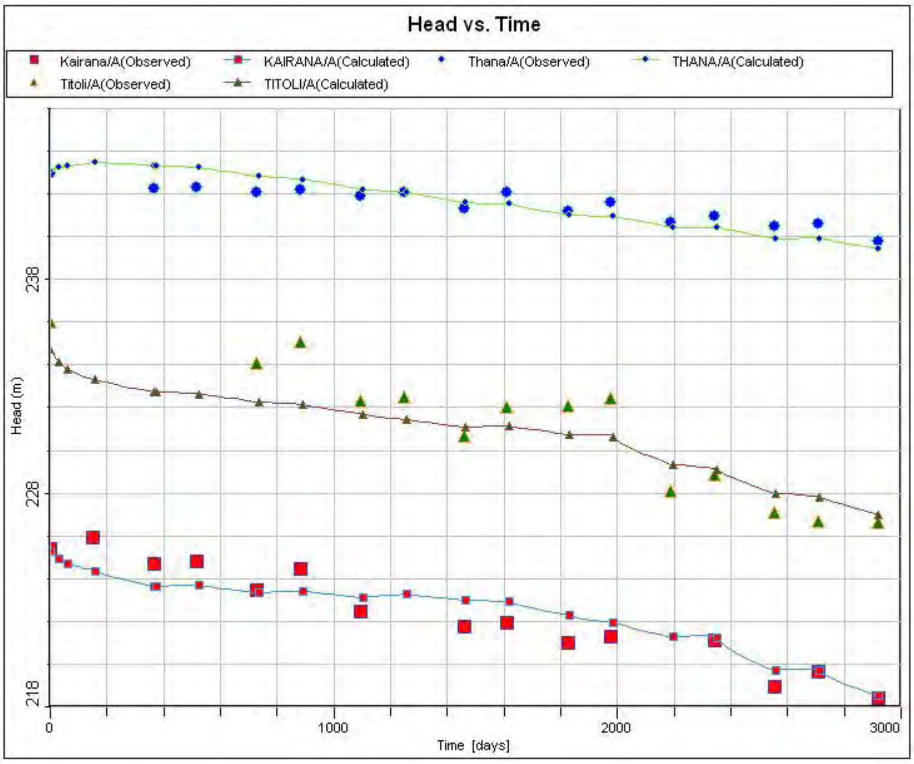


Fig.4.10a Observed and simulated heads at Kairana, Titoli and Thanabhawan.

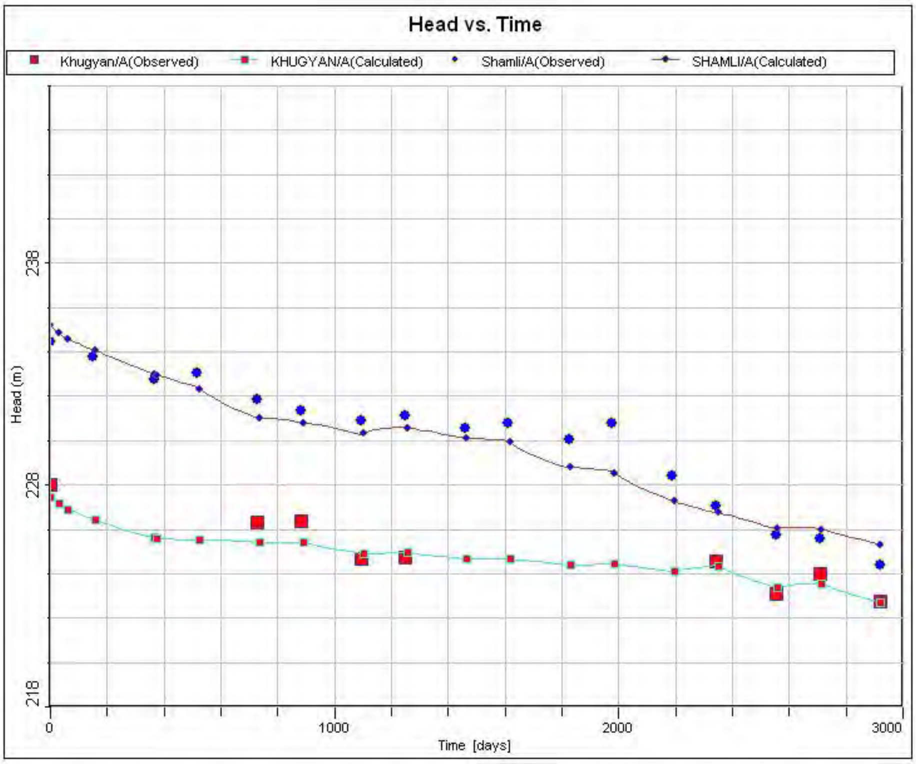


Fig.4.10b Observed and simulated heads at Shamli and Khurgyan.

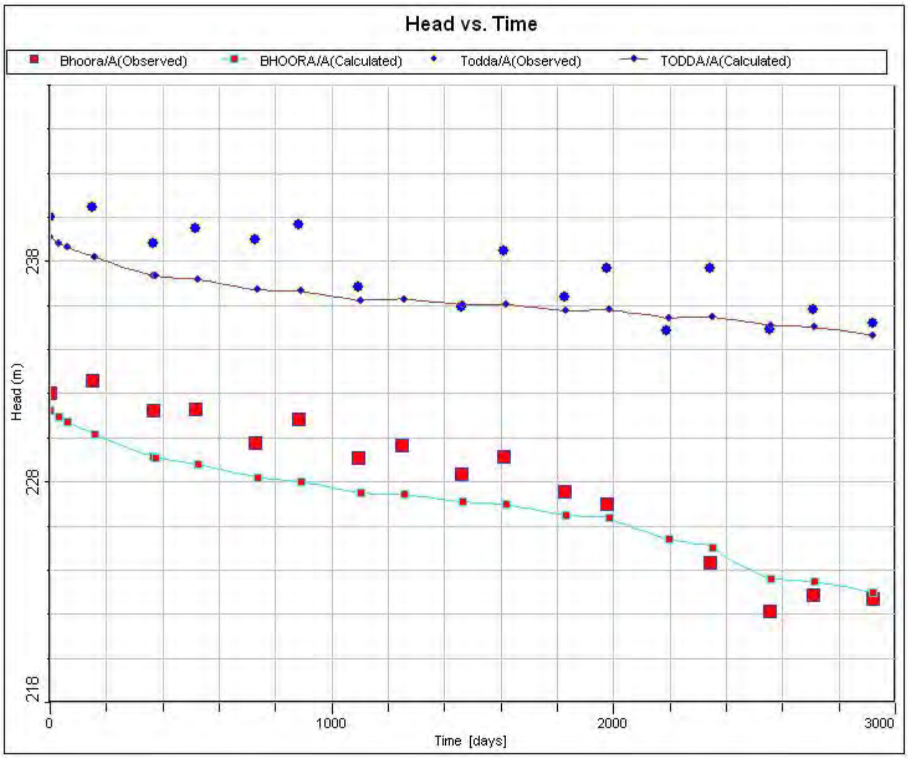


Fig.4.10c Observed and simulated heads at Bhoora and Todda.

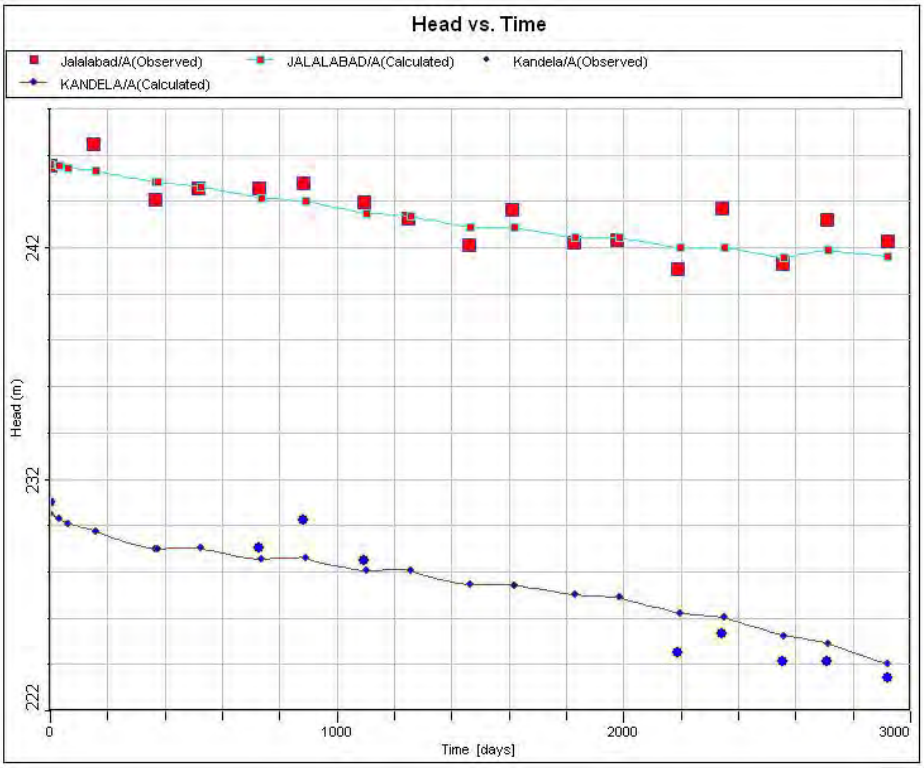


Fig.4.10d Observed and simulated heads at Jalalabad and Kandela.

4.7 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). During the sensitivity analysis, calibrated values for the hydraulic conductivity, storage parameters, recharge and boundary condition are systematically changed with in 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 modelling exercise the sensitivity of hydraulic conductivity and recharge was examined. The conductivity 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 the first sensitivity analysis the conductivity values were increased by 10%, which increased the RMS error to 1.703 m. Second and third runs were made with 20% and 50% increases in the conductivity values, which again increased the RMS error. A fourth run was made such that the minimum values of conductivity (i.e. 9.8 and 10.1 m/day), encompassing an area close to River Yamuna, were raised by 25%. The forth run provided a better match of observed and simulated heads with a RMS error of 1.58 m. Thus the initial permeability of 9.8 and 10.1 m/day were increased to 12.25 and 12.6 m/day along the River Yamuna. The rest of the values represent actual conductivity values taken from the pumping tests.

The recharge parameter was changed during the next sensitivity analysis run. It represents the recharge due to rainfall and irrigation return flows and canal seepages. Initially, the estimated recharge values were calculated separately for command, non-command and canal tracks and applied to their respective grids. The recharge sensitivity of the model was tested for a 1% increase and decrease in this parameter and these showed RMS errors of 1.64 and 2.03 m, respectively. Thus, the model was more sensitive to recharge than conductivity.

4.8 Results

4.8.1 River-aquifer interaction

In an unconfined aquifer river-aquifer interactions are sensitive and need to be handled with care. Interactions between an alluvial aquifer system and river are influenced by the spatial arrangement of hydrofacies at the interface between the river and the underlying aquifer (Woessner, 2000). Modelling studies that include river aquifer interactions need to be focused on the impacts of regional scale, water management and conjunctive use issues (Onta et al., 1991; Reichard, 1995; Wang et al., 1995). For instance, the accuracy of groundwater inflow or outflow estimates, made from the difference in river flows at the beginning and the end of a reach, is limited because flow differences are often small compared to the total river flow (Rushton, 2006). Also, regional average streambed thickness and hydraulic conductivities used in large scale models affect stream-aquifer interactions (Anderson and Woessner, 1992).

The Yamuna and Krishni Rivers forms western and eastern boundaries of the area and actively participate in groundwater dynamics. For modelling purposes, both rivers were divided in to five segments such that each segment had representively uniform river stage, bed bottom and conductance. The effect of groundwater extractions (pumping) in the flood plains of River Yamuna, which have a strong influence on the rivers characteristics, also had to be considered. The rivers were assumed to be between 3 and 25 m wide with a depth of water between 0.4 and 1.0 m. Two-dimensional x–z (profile) steady-state numerical model solutions were used to explore the interaction between the river and aquifer and a variety of boundary conditions were considered, including recharge to the water table. The altitudes of river stage and river bed bottom are measured accurately. The river boundary package was employed for both rivers. In the zone budget package, both the rivers were treated as individual zones and subsequently their flux was calculated by model itself. The quantitative river-aquifer interaction is reported in Table 4.1.

Table 4.1: River-aquifer interaction

River	Inflow* (Mcum)	Baseflow** (Mcum)
Yamuna	**6.39**	**0.52**
Krishni	**5.12**	**0.68**

Inflow to study area*, Baseflow to river**

4.8.2 Zone budget

The Zone Budget package calculates sub-regional water budgets using the results from the MODFLOW simulation. The estimated recharge values were initially used in the recharge boundaries to command, non-command and canal tracks. The heads were assigned to river stage by applying the river boundary package.

The water balance of the model for June 2006 to June 2007 is as follows: the total recharge to the Yamuna-Krishni sub-basin is 139.61 Mcum. The total annual draft through pumpage is 229.83 Mcum. The subsurface horizontal inflows and outflows are 9.09 and 2.53 Mcum, respectively. The result shows a deficit balance of 73.35 Mcum. The various components of groundwater balance are tabulated in Table 4.2.

Table 4.2: Components of groundwater balance using MODFLOW.

Components of groundwater balance	Monsoon (Mcum)	Non-monsoon (Mcum)
Direct recharge	93.00	46.61
Subsurface inflows	3.05	6.04
Draft through pumpage	111.23	118.6
Subsurface outflows	1.39	1.14

4.8.3 Predictions and assessment (2007-2014)

Three different scenarios were considered to predict the behaviour of the groundwater regime in the Yamuna-Krishni sub basin during the period 2007-2014. These scenarios are explained below:

4.8.3.1 Scenario 1: Increase in current withdrawal rate

During this prediction scenario, the ongoing abstraction rate was increased by 20% from 2007 to 2014, over a period of 8 years. This increase is in line with present rate of consumption. The initial recharge of November 2006 was kept constant throughout the prediction period. It was observed during this prediction run that the area in the vicinity of river Krishni was drastically affected and four observation wells i.e. Bhabhisa, Bhanera, Kaidi and Sonta went dry in the 2014 time period. A maximum drawdown of 10 m was observed around Makhmulpur village. The minimum drawdown were observed at locations close to the River Yamuna e.g. Khurgyan, Chontra and Bhari observation wells where the drawdown was <2 m (Fig.4.11a)).

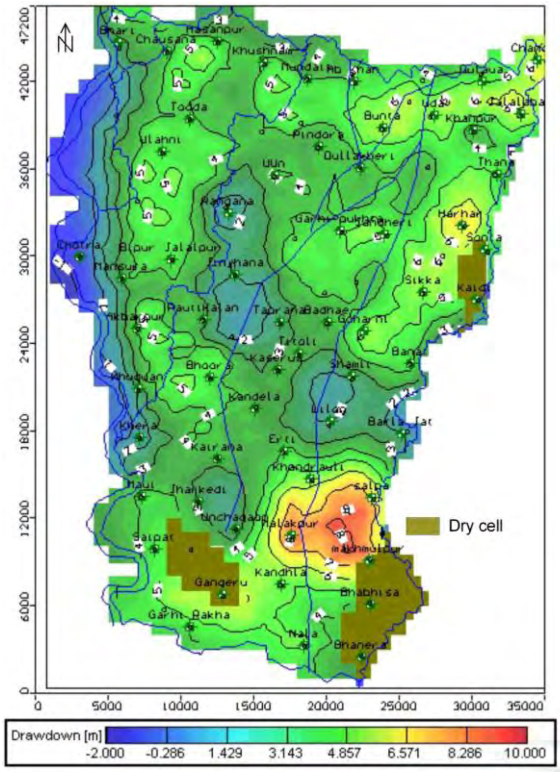


Fig.4.11a Drawdown in prediction scenario 1.

4.8.3.2 Scenario 2: Decrease in recharge

In this prediction scenario the combined effect of increasing abstraction rates by 20% and reducing rainfall by 20% was examined. The combined impact of both theses factors showed a maximum drawdown of 10 m occurring in wells locationed at Makhmulpur, Malakpur and Salpa, close to River Krishni. The minimum drawdown of <2 m was observed at Chontra and Bhari observation wells. In this scenario five observation wells (i.e. Gangeru, Bhabhisa, Bhanera, Kaidi and Sonta) went dry by 2014. The extent of dry cells is large in comparison to scenario 1 (Fig.4.11b).

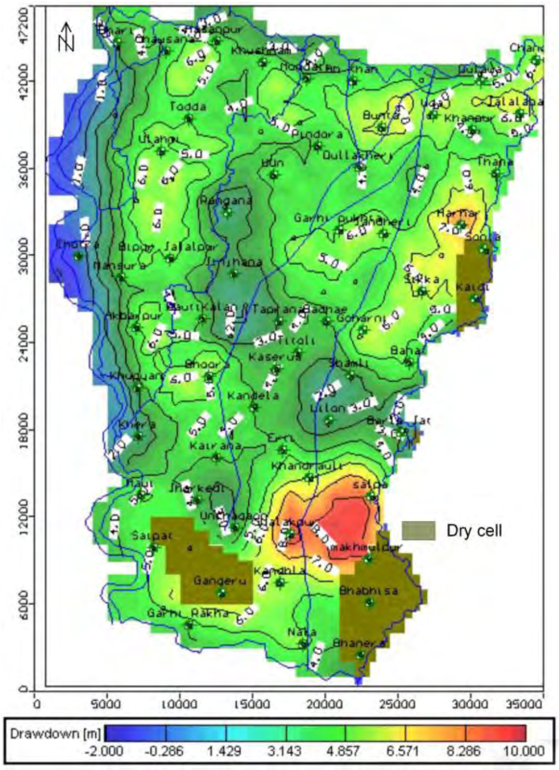


Fig.4.11b Drawdown in prediction scenario 2.

4.8.3.3 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 in the study area, additional recharge of 300 mm/year was applied to the dry Kairana distributary and to its irrigation channels. This is again a practically possible scenario. The extent of dry cells was reduced after introducing this additional recharge (Fig.4.11c).

Thus recharge through surface water structures and through water harvesting can positively help affected areas.

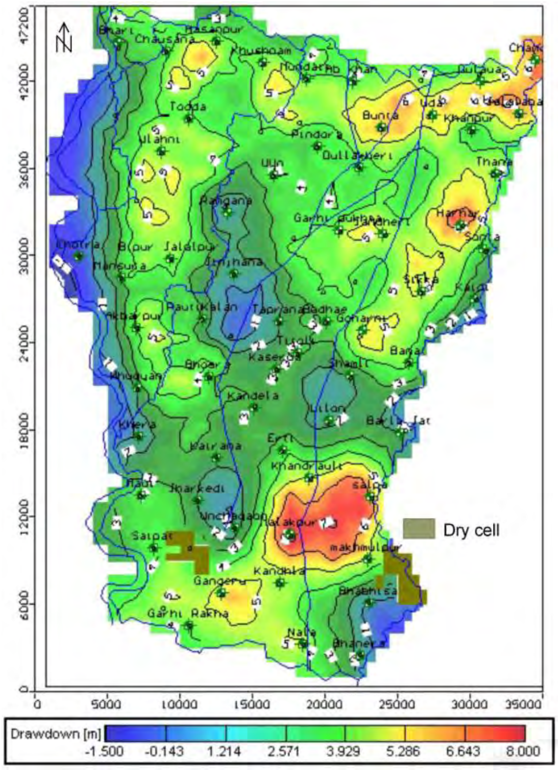


Fig.4.11c Drawdown in prediction scenario 3.

5 - GROUNDWATER VULNERABILITY ASSESSMENT

5.1 Introduction

In the past few decades groundwater contamination has become one of the most serious problems in the world. Once polluted, remediation of aquifers would be very difficult, and even sometimes it becomes impossible to restore to its original quality (Qinghai et al., 2007). Alluvial areas like Central Ganga Plain (CGP), where groundwater is easily accessible from shallow water table aquifers, need proper protection of groundwater regime from contamination. The groundwater utilization has increased manifold due to advancement in agrarian sector together with rapid industrialization. The groundwater abstraction from shallow aquifers is continuously on the rise which could be related to multifarious problems, like overexploitation, and quality deterioration, thus posing threats to the sustainability of this precious resource.

Vulnerability assessment of groundwater, as used in many methods, is not a characteristic that can be directly measured in the field. It is an idea based on the fundamental concept “that some land areas are more vulnerable to groundwater contamination than others” (Vrba and Zaporozec., 1994).

Vulnerability mapping involves combining several thematic maps of selected physical resource factors into a groundwater vulnerability map that identifies different areas of the sensitivity of groundwater to natural and human impacts. The original concept of groundwater vulnerability was based on assumption that the physical environment may provide some degree of protection to groundwater with regard to contaminants entering the sub-surface. The earth materials may act as natural filter to screen out some contaminants. Water infiltrating at the land surface may be contaminated but is naturally purified to some degree as it percolates through the soil and other fine grained material in the unsaturated zone.

In recent years, groundwater vulnerability assessment has become very useful tool for planning and decision making of groundwater protection (Vias et al., 2005). However, it is important to note that vulnerability maps are not panacea. They are simply just one of the many tools available for groundwater protection programmes. The main value of vulnerability maps is that they can be used as an effective preliminary tool for the planning, policy and operational levels of the decision making process concerning groundwater management and protection (Vrba and Zeporozec, 1994).

The groundwater is the major contributor for agriculture, domestic and industrial uses in the study area. The first group of aquifer which is mostly unconfined through out the study area is very potential for various contaminants through agriculture, industrial and domestic uses. Therefore a groundwater vulnerability map is prepared using modified DRASTIC approach.

5.2. DRASTIC Model

DRASTIC is a methodology proposed by Aller et al. (1987) which allows the pollution potential of any area to be systematically evaluated. This methodology is based on weighting and rating method that assesses vulnerability by means of seven parameters like *D*epth to water, *N*et recharge, *A*quifer media, *S*oil media, *T*opography, *I*mpact of vadose zone and *H*ydraulic conductivity. In the present study the DRASTIC methodology with few modifications is adopted which is described below.

The landuse pattern having a strong bearing on groundwater regime is included as new parameter in the DRASTIC approach. An account of a uniform parameter would not impart any distinctness in vulnerability mapping. Therefore, owing to little variation in topography of Yamuna-Krishni sub-basin and consequently the contribution of topography to the groundwater vulnerability being negligible in the study area. These factors have been rearranged to form the acronym, DRASIC-LU for ease of reference. The stepwise methodology is shown in flow chart (Fig.5.1)

5.2.1 Depth to Water

The depth to water is important, as it determines the depth of material through which a contaminant travels before reaching the aquifer. It may help to determine the likely duration of contact of the pollutants with the surrounding media. In general, there is greater chance for attenuation to occur as depth to water increases thereby allowing longer travel times (Aller et al., 1987). The depth to water is also important, because it provides the maximum opportunity for oxidation by atmospheric oxygen (Herlinger and Viero, 2007). Therefore, the depth to groundwater is assigned the maximum weight of 5 in determining the vulnerability using DRASTIC method (Table 5.1).

The depth to water ranges from 4.90-21.53 m below ground level (bgl) during November 2007 (Fig.5.2). The area close to river Yamuna and the north east part is characterized by shallow depth. The depth to water table is assigned the variable ratings of 7, 5 and 3.

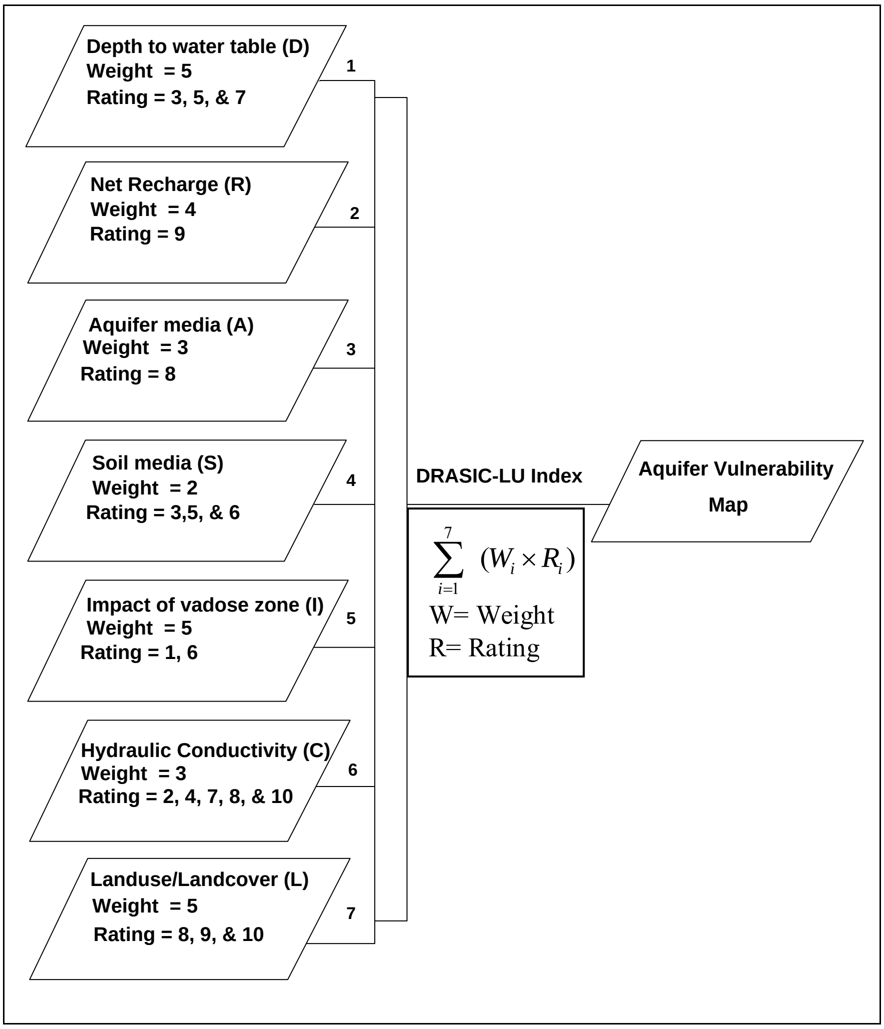


Fig.5.1 Procedure for the construction of the aquifer vulnerability map

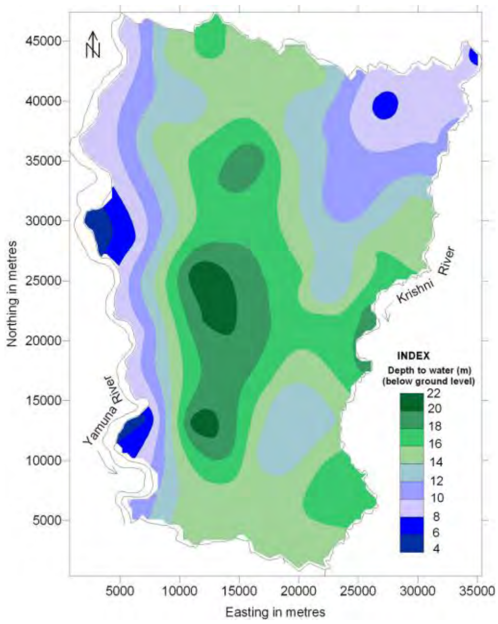


Fig.5.2 Depth to water level map (November 2007)

5.2.2 Net Recharge

The primary source of groundwater recharge in the study area is precipitation, which infiltrates through the surface of the ground and percolates to the water table. Recharge through irrigation return water is also an additional source of groundwater recharge. Net recharge indicates the amount of water per unit area of the land, which penetrates the ground surface and adds to the water table. This recharge water is thus available to transport a contaminant vertically to the water table and horizontally within the aquifer. The more water that leaks through, the greater the potential for recharge to carry pollution into the aquifer (Aller et al., 1987). The net recharge in the study area is >254 mm and assigned uniformly a rating of 9.

Table 5.1 Assigned weight for DRASTIC parameters (Aller et al., 1987).

Parameters	**Ratings (*R*)**	**Weight Scale (*W*)**
Depth to water table (D)	3, 5 & 7	5
Net Recharge of aquifer (R)	9	4
Aquifer media (A)	8	3
Soil media (S)	3, 5, & 6	2
Topography (T)	NA	1
Impact of vadose zone (I)	1 & 6	5
Hydraulic Conductivity (C)	2, 4, 7, 8 & 10	3
LULC (L)	8, 9 & 10	5

5.2.3 Aquifer Media

The aquifer media exerts the major control over the route and path length which a contaminant must follow. The path length is an important control along with hydraulic conductivity and gradient in determining the time available for attenuation processes such as sorption, reactivity, dispersion and also the amount of effective surface area of materials contacted in the aquifer (Aller et al., 1987). In general, the larger the grain size and the more fractures or openings within the aquifer, the higher the permeability and the lower the attenuation capacity, consequently the greater the pollution potential.

In the study area aquifer material is almost homogeneous which is sand mixed with gravel and assigned a uniform rating of 8.

5.2.4 Soil Media

Soil is commonly considered the upper weathered zone of the earth which averages 1.8 m or less. It has a significant impact on the amount of recharge water which can infiltrate into the ground and hence, influence the ability of a contaminant to move vertically into the vadose zone. In general, the pollution potential of a soil is largely affected by the type of clay present and the grain size of the soil. The study area is characterized by three types of soil viz. loam, clay loam and sandy loam (Fig. 5.3), which correspond to ratings of 5, 3 and 6 respectively.

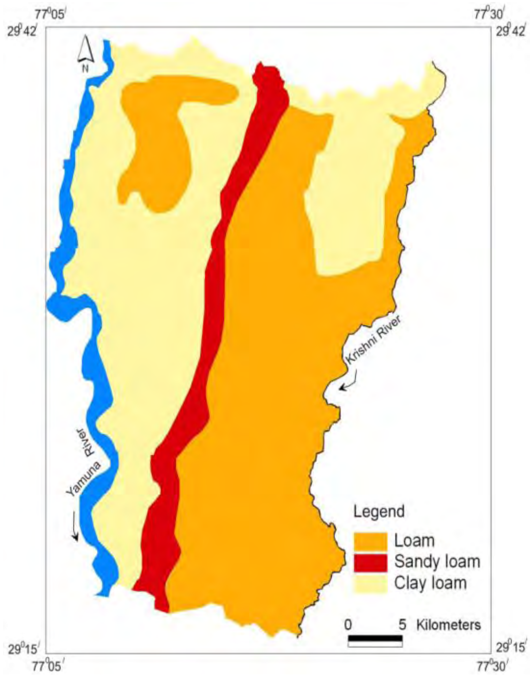


Fig.5.3 Soil map of the study area

5.2.5 Impact of Vadose Zone

The vadose zone media determines the attenuation characteristics of the material below the typical soil horizon and above the water table. The media also controls the path length and routing, thus affecting the time available for attenuation and the quality of material encountered. The materials forming the vadose zone in the study area are clay, silt and fine sand which are corresponding to the ratings 1 and 6. The assigned weight for vadose zone is 5.

It was observed that the characterization of vadose zone is significant due to alternation between clay and fine sand, both possessing distinct hydrological character. The initial ratings of 1 and 6 for clay and fine sand do not sufficiently incorporate their impact on aquifer vulnerability map. Thus, to sort out the problem, harmonic mean approach (Hussain et al., 2006) has been applied to calculate the precise rating values at each location. Using following equation

$$I_r = \frac{T}{\sum_{i=1}^{n} \frac{T_i}{Ir_i}} \qquad (1)$$

where, Ir = the weighted harmonic mean of the vadose zone

T = total thickness of the vadose zone

T_i = thickness of the layer i

Ir_i = rating of layer i.

The lithologs of the boreholes were utilized for the calculation of thickness of layers in vadose zone. Thickness of the top clay layer is crucial in determining the behaviour of particular location in terms susceptibility to contamination.

5.2.6 Hydraulic Conductivity

Hydraulic conductivity is controlled by the amount and interconnection of void spaces within the aquifer. The rate at which the groundwater flows also controls the rate at which a contaminant will move within the aquifer. The highest range of hydraulic conductivity i.e.>25 m/day, is assigned a rating of 10. However, in the study area, the hydraulic conductivity values have been observed to range from 12.3 m/day to 26.6 m/day (Fig. 5.4). Thus, adoption of the original rating would not sufficiently reflect the variation of hydraulic conductivity and its impact while estimating the aquifer vulnerability. A new rating proposed by Qinghai et al., (2007) in similar area is applied in the present study (Table 5.2).

Table 5.2 Hydraulic conductivity ranges and their rating. (After Aller et al., 1987 and Qinghai et al., 2007)

Hydraulic conductivity (m/day) (Original range)	**Hydraulic conductivity (m/day) (New range)**	**Rating**
0.005-0.5	0-5	1
0.5-1.5	5-10	2
1.5-3.5	10-15	4
3.5-5.0	15-20	7
5.0-10.0	20-25	8
>10.0	>25	10

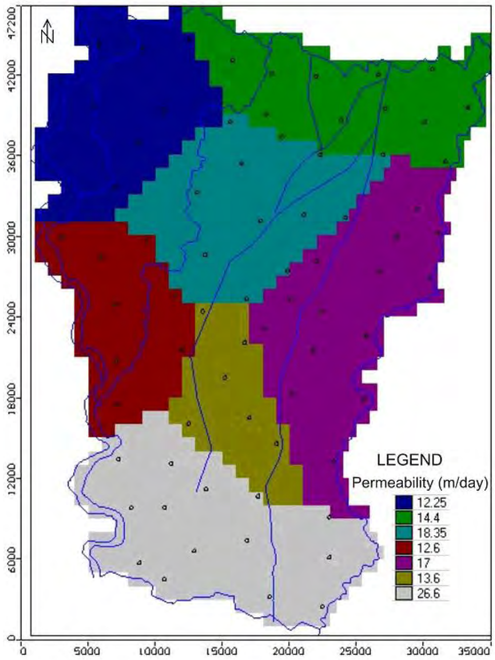


Fig.5.4 Zone-wise hydraulic conductivity distribution

5.2.7 Landuse Pattern

Groundwater quality in Yamuna-Krishni sub-basin is deteriorating due to industrial and sewage pollution (Umar and Ahmed, 2007). The land use pattern has strong bearing on groundwater quality. Therefore, land use pattern is taken into account in vulnerability mapping. In the present study, analysis of groundwater, surface water and trace elements, and subsequent interpretation indicate that urban land use (industrial and sewage pollution) has maximum impact followed by rural land use. Based on these observations, qualitative ratings were proposed for the different types of land use categories. The assigned weight of this parameter is 5. Based on this, following ratings were used to categorize land use in the study area as given in Table 5.3.

Table 5.3 Land use categories ratings

Land use Category	Ratings
Urban and Industrial	10
Rural and Industrial	9
Rural and Agriculture	8

The DRASIC Index, a measure of the pollution potential, is computed by summation of the products of rating and weights for each factor as follows:

DRASIC-LU Index = D r D w + R r R w + A r A w + S r S w + I r I w + C r C w + L r Lw

Where

Dr = Ratings to the depth to water table

Dw = Weights assigned to the depth to water table.

Rr = Ratings for ranges of aquifer recharge

Rw = Weights for the aquifer recharge

Ar = Ratings assigned to aquifer media

Aw = Weights assigned to aquifer media

Sr = Ratings for the soil media

Sw = Weights for soil media

Ir = Ratings assigned to vadose zone

Iw = Weights assigned to vadose zone

Cr = Ratings assigned of hydraulic conductivity

Cw = Weights given to hydraulic conductivity

Lr = Ratings assigned of Land use

Lw = Weights assigned of Land use

The vulnerability index is computed as the sum of the products of weights and ratings assigned to each of the input considered as above. The vulnerability index ranges from 140 to 180 and is classified into four groups i.e. 140-150, 150-160, 160-170 and 170-180 corresponding to low, medium, high and very high vulnerability zones, respectively. Using this classification a groundwater vulnerability potential map (Fig.5.5) was generated which shows that 7% area falls in low vulnerability zone and 40% falls in medium vulnerability zone. About 30% of the study area falls in high vulnerability zones and 23% of the study area is characterized by very high vulnerability zone. A perusal of vulnerability map shows that the southern part and in upper reaches of river Krishni has got very high vulnerability zone and therefore more susceptible to groundwater pollution.

The fact which readily emerges out from the study is that the depth to water level, hydraulic conductivity and impact of vadose zone and land use pattern serve as the major influential parameters in mapping the vulnerability. However, the impact of remaining parameters can not be ruled out.

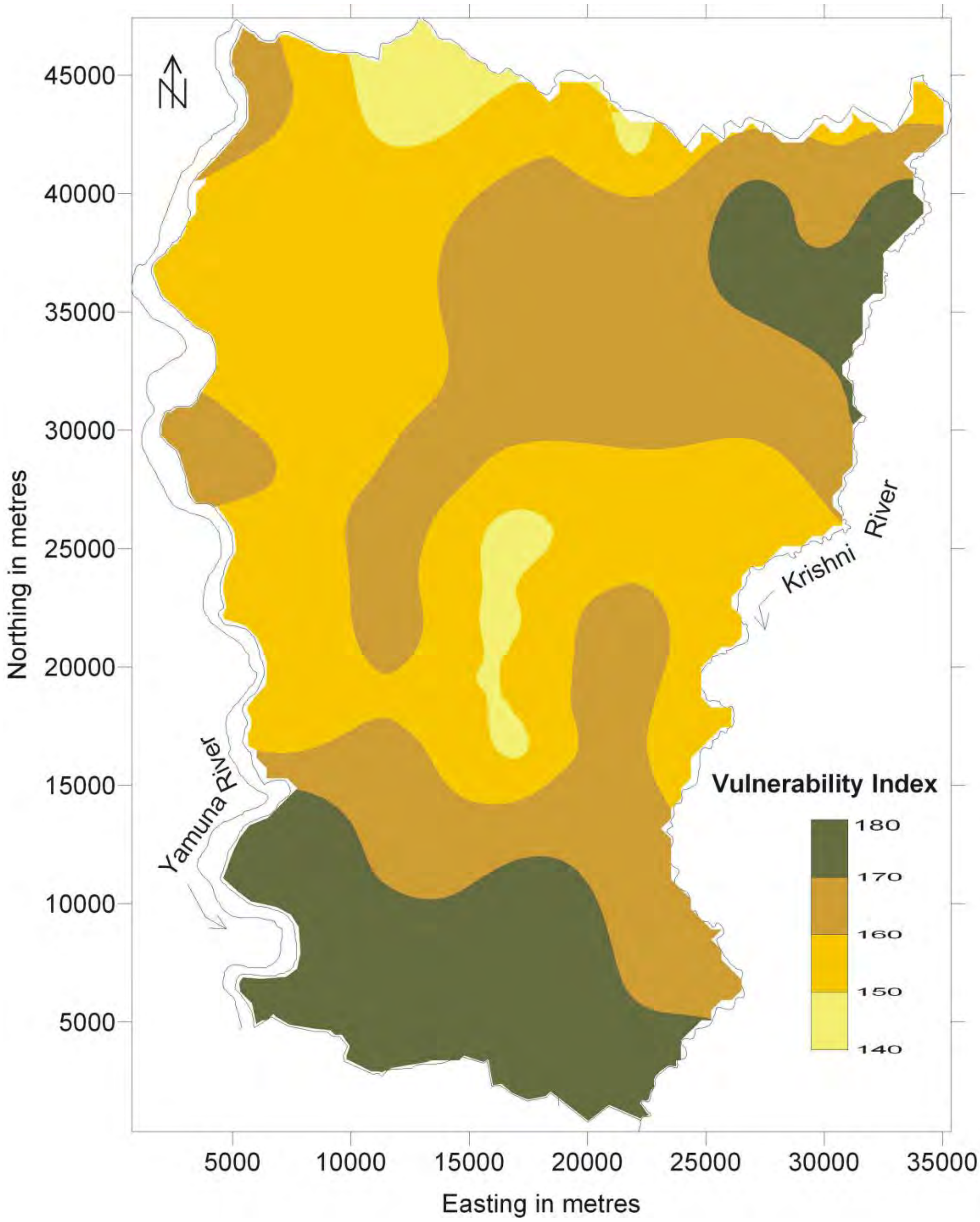


Fig. 5.5 Aquifer vulnerability map of the Yamuna-Krishni sub-basin.

The southern part is characterized by very high vulnerability index which is attributed to high values of hydraulic conductivity and aquifer thickness. The few patches in the vicinity of the river Yamuna constituting the Yamuna Flood Plain (YFP) are characterized by high vulnerability index, which in turn is attributed to shallow water level (5-7 m bgl) and thin vadose zone.

The area just east of Yamuna flood plain is the zone of medium vulnerability. The moderate risk to groundwater contamination is mainly attributed to the presence of thick vadose zone containing clay layers and comparatively of low hydraulic conductivity, particularly in the northern part. The presence or absence of clay layer affects the pollution attenuation capacity. The clay is abundant in the northern part and gradually decreases due south and serves as the most variable parameter with ratings of 1 and 6.

The groundwater vulnerability potential map shows that bulk of the area is covered by high to very high vulnerable zone followed by medium and low vulnerable zones. Ironically, all major townships like Shamli, Kairana and Kandhala are located in high to very high vulnerability zones. The vulnerability map thus generated helps in identifying areas which are more likely to be susceptible to groundwater contamination relative to one another.

6 - HYDROGEOCHEMISTRY

6.1 Introduction

Water is frequently referred as universal solvent, because it has the ability to dissolve at least some amount of all substance that comes in contact. Rainfall and snow melt percolating through the soil zone and unsaturated material chemically reacts with the gases, minerals and organic compounds that occur naturally within the subsurface. These reactions continue below the water table as the water flows through the aquifer. The result is that the characteristics and composition of the water evolve as it flows through the ground in response to the types of solids and gas phases that the solution encounters and the geochemical reactions that occur between these phases (Deutsch, 1997). Therefore, each groundwater system has its own characteristic chemical signature produced as a result of chemical alteration of the meteoric water recharging the system (Drever, 1982).

The study of a relatively large group of samples from a given area offers clues to various possible trends of chemical alteration which the meteoric water undergoes before acquiring distinct chemical characteristics and attaining a chemical steady state in the aquifer. These identified trends in turn may be related to natural and anthropogenic causative factors (Umar and Absar, 2003). With this simple objective in sight systematic sampling was carried out in the study area from the point of view of understanding various possible sources of dissolved ions and to assess the seasonal variation in groundwater quality with respect to drinking and irrigational uses.

6.2 Methodology

6.2.1 Sample Collection

Due to probable seasonal variation in the water quality. One forty four groundwater samples were collected for physico-chemical analysis in four successive season's viz. post-monsoon and pre-monsoon period corresponding November 2005, June 2006, November 2006 and June 2007 respectively (Fig. 6.1). In November 2005 and June 2007, seven and 9 surface water samples were also collected (Appendix VIIIA, B) from river Yamuna and Krishni respectively (Plate-7a and 7b). In addition four samples were also collected from Nala/Drain (Appendix VIIIC) for major ion analysis (Plate-8a and 8b). The water samples were collected and stored in 1 litre capacity clean plastic bottles.

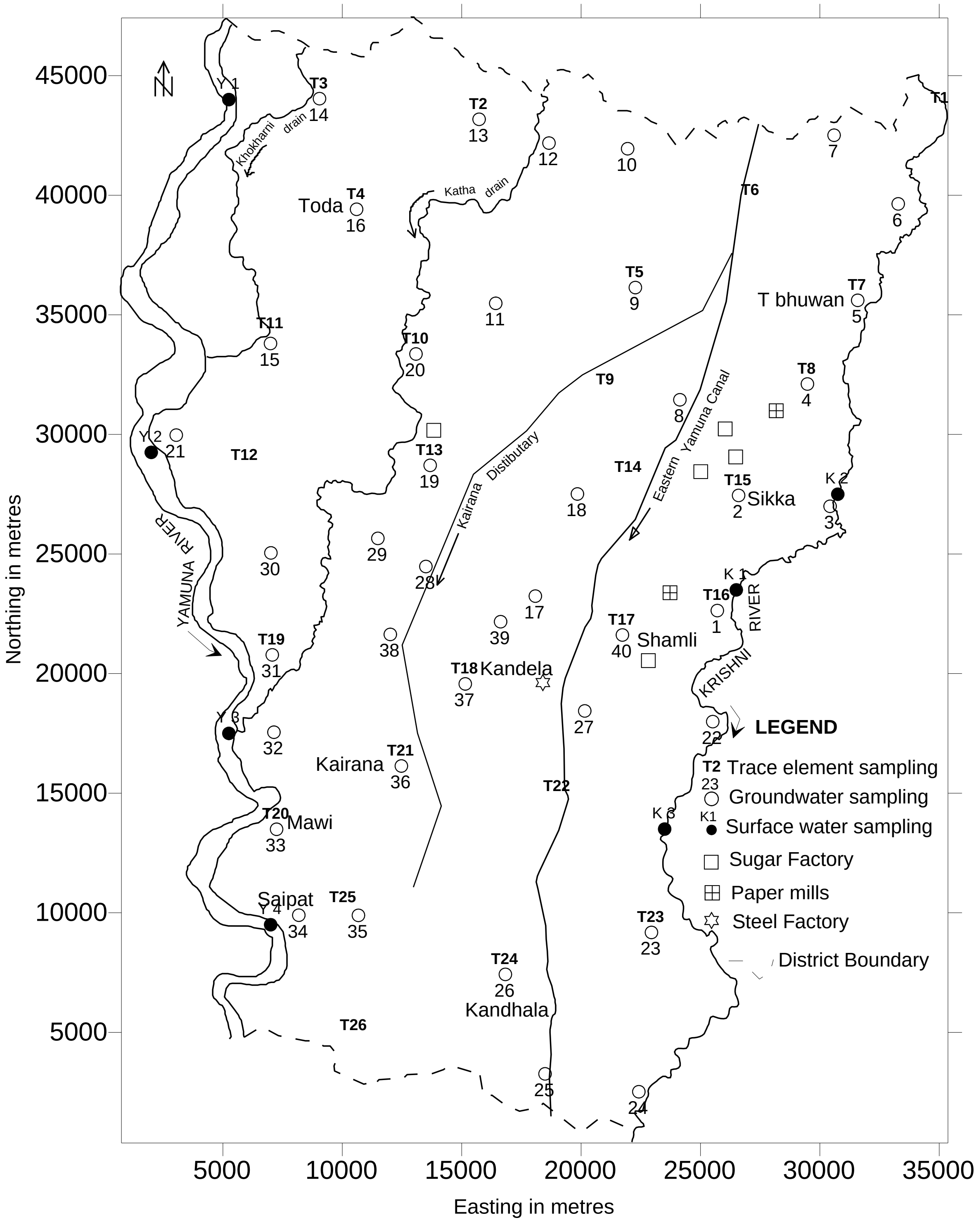


Fig.6.1 Sampling location map of the study area.

Before collection the bottles were carefully washed. In order to avoid any impurity, the wells were duly pumped so that the stagnant water is completely removed from storage with in the well assembly. Besides major ions, 26 groundwater samples were collected for trace element analysis in June 2006 (Appendix IXA).Six surface water and a drain samples were collected from Yamuna and Krishni rivers for trace element analysis in June 2007(Appendix IXC).Three groundwater samples also repeated in June 2007 (Appendix IXB)which were showing high values. The trace element samples were treated with 0.6N HNO_3.

The major ion analysis was carried out in the Geochemical Laboratory, Department of Geology, Aligarh Muslim University, Aligarh. Trace elements analysis was carried out at National Geophysical Research Institute, Hyderabad.

6.2.2 Analytical Techniques

The physico-chemical characteristics of water samples were determined according to the standard methods of APHA (1992). Temperature, Electrical Conductivity (EC) and pH were determined in the field. Temperature was determined by a laboratory thermometer with an accuracy of 0.1^0C and pH by a portable digital pH meter. The EC was measured with the help of portable kit with electrodes.

The concentrations of Ca^{++}, Mg^{++}, HCO_3^-, Cl^- and total hardness were determined by titrimetric method. Ca^{++} and Mg^{++} were determined by EDTA titration, for HCO_3^-, HCl titration to a methyl orange point was used. Chloride was also determined by titration with $AgNO_3$ solution. Flame emission photometry was used for the determination of Na^+ and K^+. In this method water sample is atomized and sprayed in to a burner. The intensity of the light emitted by a particular spectral line is measured with the help of a photoelectric cell and a galvanometer. Sulphate was analysed by gravimetric method. The concentrations of NO_3^- and F^- were determined with the help of nitrate and fluoride digital meters which worked on principle of colorimetry.

A set of 26 trace elements were determined by ICP-MS at NGRI, Hyderabad. However the trace elements like Fe, Al, Mn, Cu, Zn, Ni, As, Pb, Cd, Cr, Co and Se were described here because of their relevance in drinking water.

6.3 Physical and chemical properties of groundwater

Data collected at a site are the primary information used to characterize a natural system and evaluate contaminant level, distribution and mobility as part of a human health or ecological risk assessment. Parameters like pH, Temperature and EC were measured at the well head site. These parameters are individually described in the preceding sections.

6.3.1 Hydrogen Ion Activity (pH)

The pH was measured at well site and it ranges in between 6.7 to 7.7 during November 2005 (Appendix VII A) and 6.8 to 7.6 during the field survey conducted in June 2006 (Appendix VII B), respectively. There is mild increase in pH during June 2006. The groundwater is slightly alkaline in nature. From the point of view of human consumption all the samples may be considered suitable as they are neither acidic nor strongly alkaline.

6.3.2 Total Dissolved Solids (TDS)

Total Dissolved Solids have been calculated by summing all the major Cations and Anions (Appendix VIIA & VIIB). The TDS values ranged in between 491-1575 mg/l during November 2005. 14 samples shows TDS >1000 mg/l during Nov 2005. The TDS values <600 mg/l is generally considered to be good. Drinking water becomes significantly unpalatable at TDS value >1000 mg/l. The TDS value during June 2006 ranged in between 497 to 1922 mg/l. During this season 19 groundwater samples contain TDS>1000 mg/l. Sample 35 show abnormally higher TDS value ($\approx$2000 mg/l).

The TDS concentration contour map for pre-monsoon 2006 season was prepared (Fig.6.2). A perusal of figure shows two distinct highs, one in the eastern part between river Krishni and Eastern Yamuna Canal and other in the southwestern sector on the left bank of river Yamuna. Interestingly, the former is located within the zone with high density of industries. The southwestern high, however does not seem to have any explicit relationship with anthropogenic influences.

6.3.3 Hardness

Hardness of water is mainly due to the presence of calcium and magnesium ions in the water. Other cations such as iron, manganese, aluminium, zinc, strontium also react to the hardness but not significantly. The degree of hardness in water is commonly based on the classification given by Sawyer and Mc Carty, 1967 (Table 6.1).

Table 6.1 Hardness classification of water

Hardness (mg/l) of $CaCO_3$	Water class
0 – 75	Soft
75 – 150	Moderately hard
150-300	Hard
> 300	Very hard

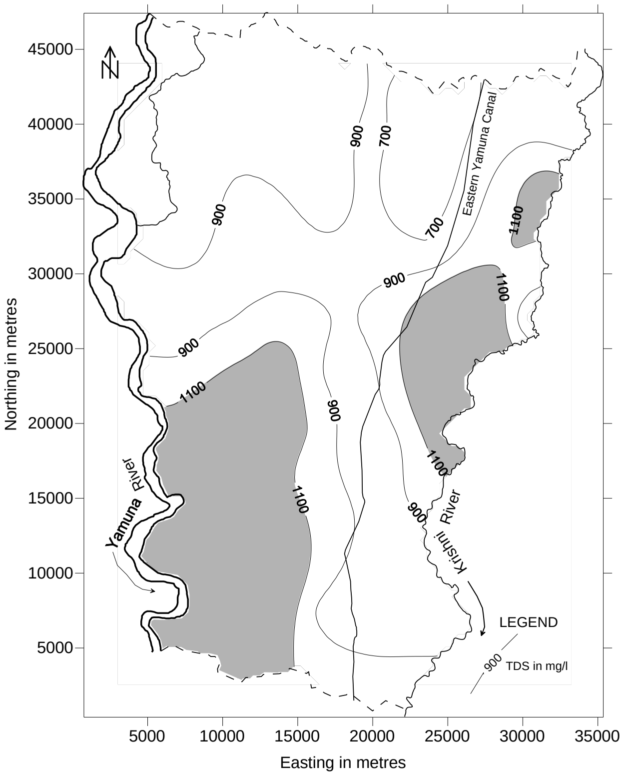


Fig.6.2 TDS distribution map in the study area

In laboratories, hardness is measured in terms of total hardness as $CaCO_3$. This does not mean that CO_3^{---} ion is necessarily present. Carbonate ions are generated only under high pH conditions (pH > 8.3) as a result of the dissociation of the HCO_3^- ion. The term total hardness as $CaCO_3$ in practice includes carbonates and bicarbonates Ca^{++} and Mg^{++}.

The hardness ranges between 76-488 mg/l, with 233 mg/l as average hardness. During June 2006 field session, hardness ranges between 120-548 mg/l with an average value of 255 mg/l. Samples no. 35 show the value above the desirable limit. However, all the samples analysed are with in the permissible limit of drinking water standard (BIS, 1991).

6.4 Salient Features of Major ion Chemistry

Water samples for chemical analysis were collected in November, 2005 and June, 2006 from 40 location, representing post and pre-monsoon periods, respectively

(Appendix VIIA, VIIB). The salient features of the groundwater chemistry are presented below.

1. The area has got high total dissolved solids (TDS) values, which range in between 491 to 1575 mg/l with an average value of 922 mg/l during November 2005.
2. Most of the samples have TDS values higher than the desirable limit of 500 mg/l. The TDS concentration during June 2006 ranges between 497 and 1922 mg/l averaging 1028 mg/l.
3. The EC values range in between 200 and 800 µmhos/cm and 200 and 1500 µmhos/cm during November 2005 and June 2006, respectively.
4. Major anions show a wide range of variations. SO_4^- content vary from 42 to 337 mg/l in November 2005 and 49 to 480 mg/l during June 2006. The Cl^- has concentration ranges of 11 to 284 and 1 to 346 mg/l and HCO_3^- ranges between 195 to 780 mg/l and 234 to 715 mg/l during November 2005 and June 2006, respectively.
5. The NO_3^- and fluoride analysis were carried out for June 2006 sample and there concentration ranges between 13 to 150 mg/l and 0.3 to 2.3 mg/l, respectively.
6. In few samples the concentration of NO_3^- and F^- is more than highest desirable limit. A maximum value of 150 mg/l of NO_3^- is recorded in sample 2 representing Sikka village. This value exceeds the permissible limit of drinking water standard (BIS, 1991).
7. In six samples the fluoride concentration exceeds the maximum permissible limit of 1.5 mg/l.
8. Alkali ions also show very large variations. Na^+ varies from 73 to 384 mg/l in November 2005 and 42 to 366 mg/l in June 2006. The K^+ concentration ranges between 0 to 116 and 0 to 67 mg/l during November 2005 and June 2006, respectively.
9. Ca^+ and Mg^+ comparatively show restricted range of concentration. Ca^+ concentration ranges between 6 to 32 mg/l during November 2005 and 5 to 64 mg/l during June 2006. Mg^+ content varies from 9 to 110 and 21 to 121 mg/l during November 2005 and June 2006 respectively.

10. Alkalis are the dominant cationic species when compared to Ca^+ and Mg^+. This statement hold good for both season's analysis i.e. pre monsoon and post monsoon.
11. The HCO_3^- is the most dominating anionic species in the groundwaters of the study area. In half of the samples the concentration of SO_4^- together with Cl^- equals to the HCO_3^-.
12. The samples were also analysed for their suitability for irrigation purposes using SAR versus EC diagram (Richards, 1954). The samples, with few exceptions, fall in good to excellent class.

6.5 Hydrochemical characteristic of Groundwater

A number of x-y plots were prepared for deciphering various chemical alteration trends of groundwaters and identifying the processes involved in the acquisition of distinct chemical characteristics.

Alkalis are distinctly far more abundant than Ca^{++} and Mg^{++} in both the sets of samples (Fig.6.3). The HCO_3^- versus $Cl^-+SO_4^-$ plot (Fig.6.4) tends to classify the groundwater in the study area in two groups, i.e. (i) $HCO_3^- > Cl^-+SO_4^-$ and (ii) $Cl^-+SO_4^- <$ HCO_3^-. Both the plots further indicate that chemical differences between pre and post monsoon sets of samples are relatively trivial.

The natural tendency between cations and anions to form ionic complexes has been tested Na^++K^+ and Cl^- (Fig.6.5) and $Ca^{++}+Mg^{++}$ and HCO_3^- (Fig.6.6). Without depicting any noteworthy change in concentration levels recorded in pre- and post monsoon samples, the majority of the samples plot below 1:1 line on alkali versus Cl^- plot implying surplus Na^+ ion over and above those used up in Na-Cl bonding..

Relative abundance of Na^+ ions is also implied in molar Cl^-/Na^+ ratios averaging around 0.25. Na behaves like a conservative elements as it is not used up in biological processes and also as an non-conservative elements as it gets fixed in clay mineral formation by ion exchanges (Subramanian and Sexena, 1983).

The $Ca^{++}+Mg^{++}$ and HCO_3^- plot (Fig.6.6) depict a moderately good correlation for about 40% of all pre and post monsoon samples. Nevertheless, there is considerable scatter in the plot due to relative preponderance of HCO_3^-, and this when viewed in the light of relative abundance of alkali over Ca^{++} and Mg^{++} (Fig.6.3) and evidence for surplus Na^+ ions (Fig.6.5) implies that in a considerable number of samples $Na\text{-}HCO_3$

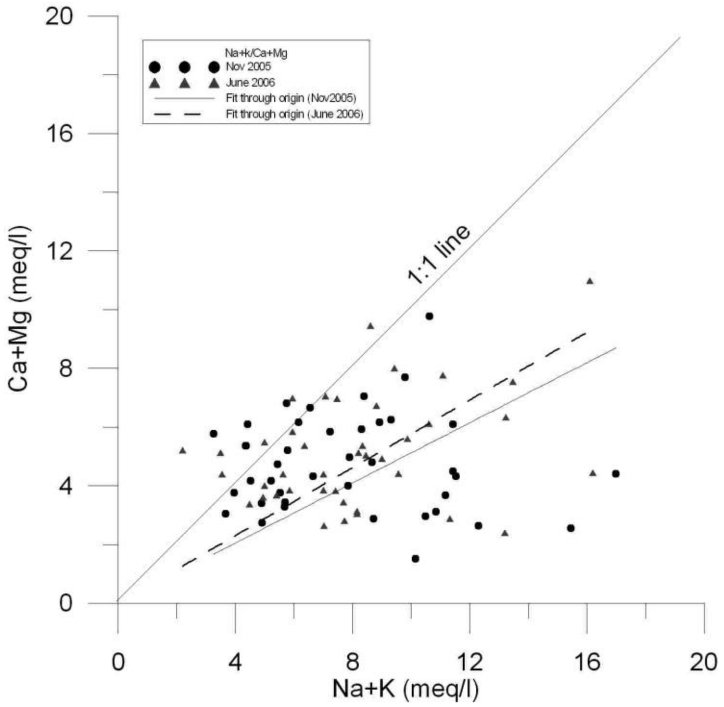


Fig.6.3 Relative abundance of Alkali's over Ca+Mg.

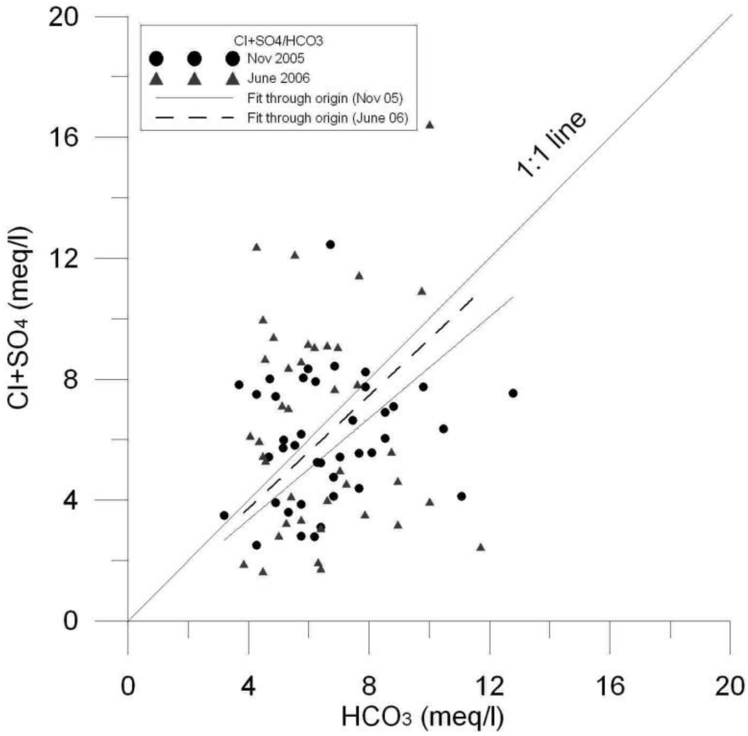


Fig.6.4 Relative abundances of HCO_3 and $Cl+SO_4$.

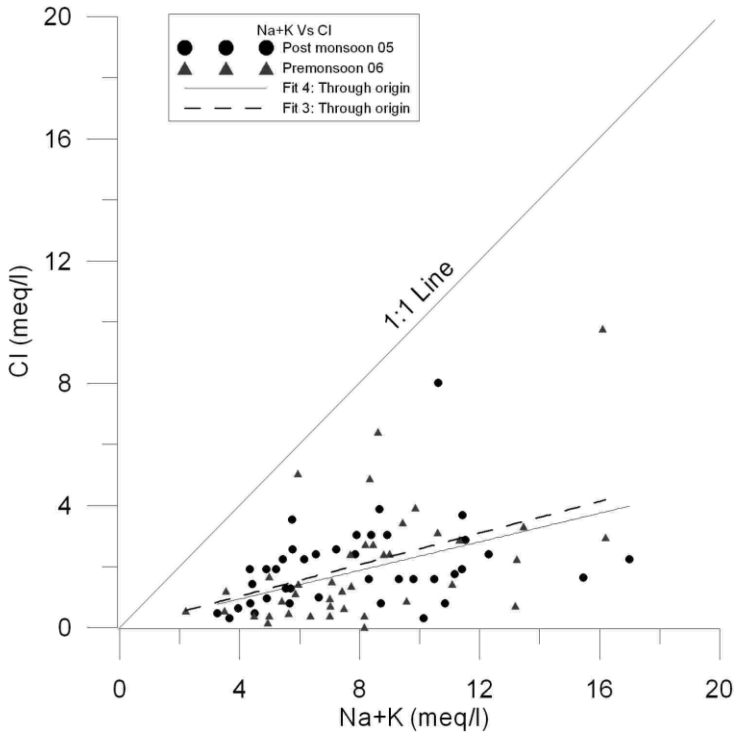


Fig.6.5 Showing bonding affinity between Alkalis and Cl.

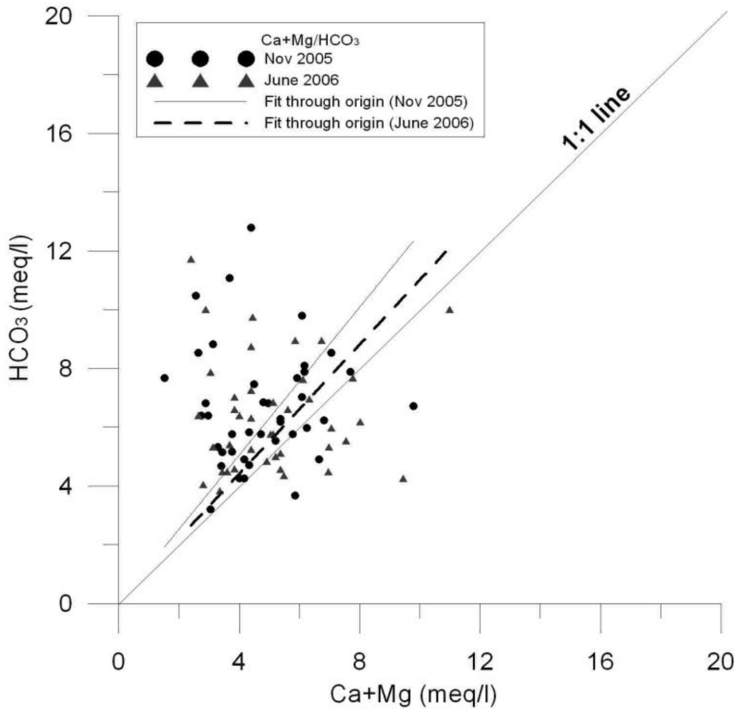


Fig.6.6 Bonding affinity between Ca+Mg and HCO_3.

may be the most dominant ionic complex. This unique chemistry acquired is because of ion-exchange reactions. The reactions that oxidize organic matter generate CO_2 as a product. This CO_2 is redistributed among H_2CO_3, HCO_3^- and CO_3^-. In aquifers where Ca^{2+}, and Mg^{2+} are exchanged in to clay minerals for Na^+, the possibility exist for carbonate dissolution and even higher HCO_3^- concentration. With CO_2 generated by redox reaction (in the upper humic zone of aeration), ion exchange and carbonate dissolution, the water will evolve to a Na-HCO_3 type (Domenico, 1997).

The ions exchange reactions are favoured by clay layers. The Na-SO_4-HCO_3 type facies is more evolved species of ion exchange reaction. The presence of calc-concretion (kankar) could favour the weathering processes.

One of the characteristic features of the groundwater from the study area is its relative enrichment in SO^{--}_4. Processes such as oxidation of sulphides and dissolution of gypsum (Valdiya, 1980 and Chakrapani, 2005) are not inferred to play a significant role in acquisition of sulphate ion by the groundwater of the area when the geological setup of the area is taken into consideration. That dissolution of gypsum (either naturally occurring as gypsite in some parts of Indo-gangetic plains or that used as a fertilizer) has almost no role to play in determining the concentration in groundwaters of the study area is also borne out by Ca-SO_4 plot (Fig.6.7),which depicts overwhelming abundance of SO_4 compared to that of Ca .

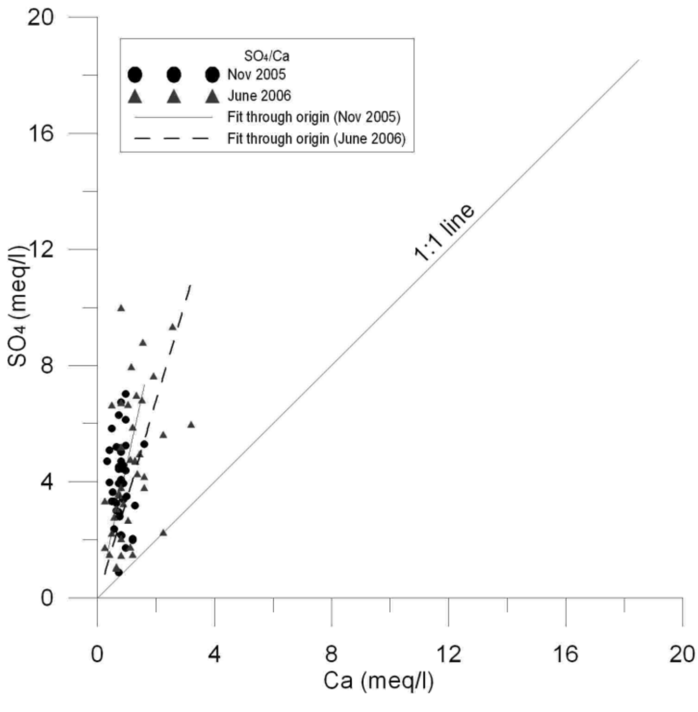


Fig.6.7 Bonding affinity between Ca and SO_4.

6.6 Classification of Groundwaters

6.6.1 Piper's Trilinear diagram

The plots of chemical analysis on a trilinear diagram for both post monsoon 2005 and pre monsoon 2006 time periods is given here (Fig 6.8a and 6.8b).

In post- monsoon the most of samples belong to biocarbonate type and few samples are No Dominant Type in the anion facies. Among cations majority of the samples fall in sodium or potassium facies as well as few samples in No Dominant type.

In pre monsoon 2006, the majority of samples show Bicarbonate Type as well as No Dominant type and few samples fall in Sulphate type. Among the cationic facies 85% of water samples fall into the class of Alkali Type and only few samples plot in the "No Dominant Type.

Comparison of chemical data on Piper's trilinear diagram shows that the few samples falling in "Biocarbonate type" (Fig 6.8a) have temporally shifted to No Dominant Type" (Fig 6.8b). Broadly, the groundwater in the study area belongs to Na-K-biocarbonate and alkali-SO_4 type on the diamond-shaped field.

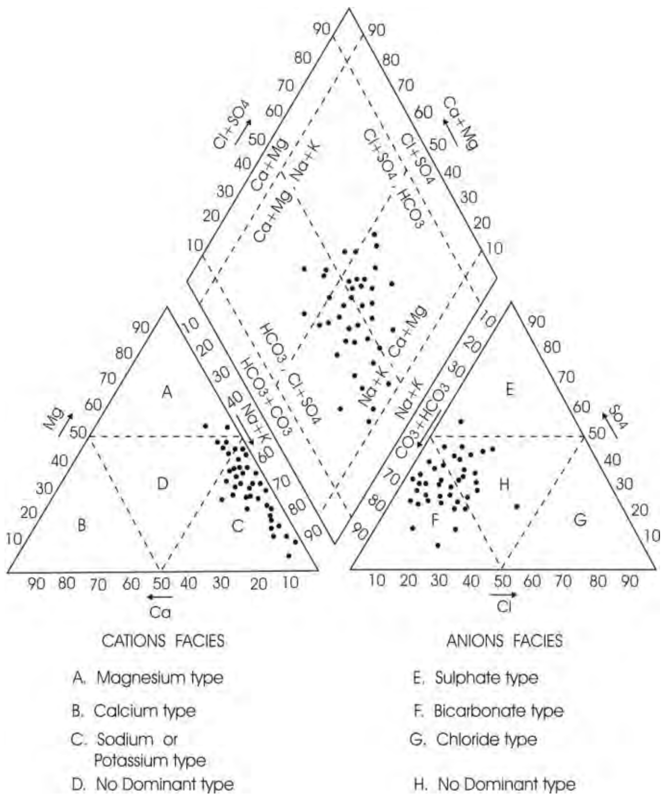


Fig- 6.8a Chemical facies of groundwater samples collected in Post-monsoon 2005, as reflected in Piper's diagram.

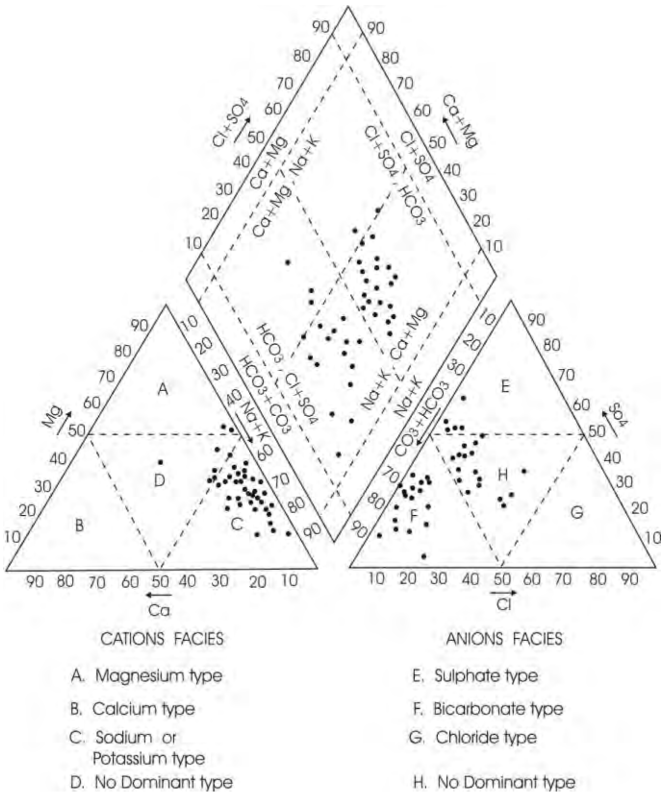


Fig- 6.8b Chemical facies of groundwater samples collected in Pre-monsoon 2006, as reflected in Piper's diagram.

6.6.2 L-L diagram

The classification of the groundwaters of the study area has been attempted on L-L diagram of both season separately (Fig 6.9a and 6.9b) given by Langelier and Ludwig (1942). Based on relative abundances of anions, groundwater of the study area may be classified into four major types. Again, based on concentration levels of cations they may be further divided into groups. In the order of decreasing abundance, the four major types of groundwater in the area are:

(I) HCO_3-SO_4 type
- (1) Na-HCO_3-SO_4
- (2) Mg-Ca-HCO_3-SO_4

(II) Cl-SO_4 type
- (1) Na-Cl-SO_4
- (2) Mg-Ca-SO_4-Cl

(III) HCO_3 type
- (1) Na-HCO_3
- (2) Mg-Ca-HCO_3

(IV) SO_4 type
- (1) Na-SO_4
- (2) Mg-Ca-SO_4

About 50% of the samples analysed belong to type I and 35% to type II. Type III samples constitute 10% of the total and type IV, the least abundant constitute only 5% of the sample analysed.

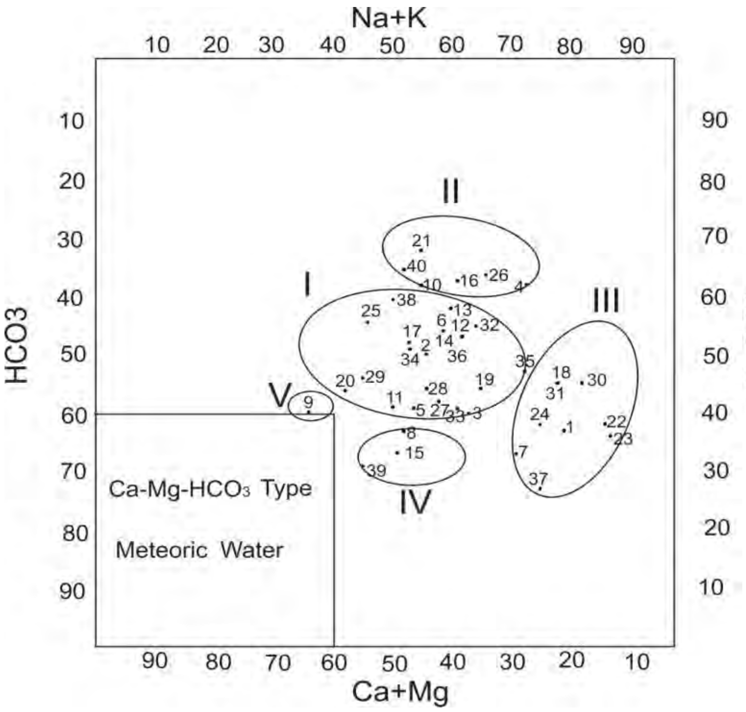


Fig.6.9a Langelier and Ludwig diagram of Post-monsoon samples (Nov 2005).

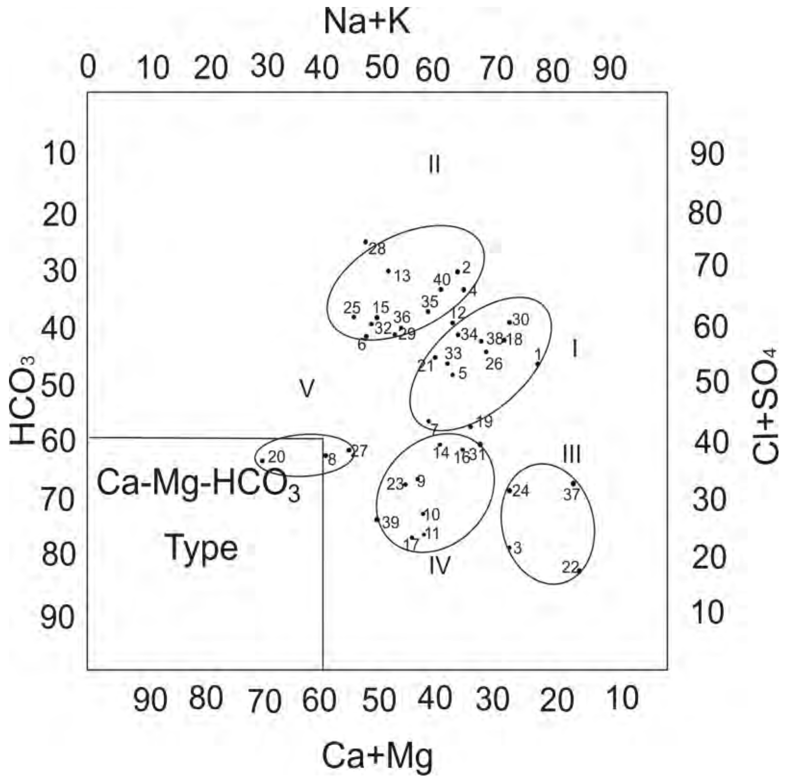


Fig.6.9b Langelier and Ludwig diagram of Pre-monsoon samples (June 2006).

6.7 Discussion

The chemical classification attempted earlier based on relative abundances of anions is further corroborated by L-L diagram of post monsoon samples. Groups I, II and III in this plot conforms to various sub types of HCO_3-SO_4 and Cl-SO_4 type waters. The samples, relatively enriched in HCO_3 and characterized by Ca+Mg>Na+K, may naturally be considered less altered and closer to the composition of meteoric water. The monsoonal effect on groundwater geochemistry as revealed by comparing Fig.6.9a with that of pre-monsoon samples (Fig.6.9b), however, is not homogeneous. For example, sample 9 shows relative enrichment of Ca+Mg in the post-monsoon period, whereas reverse is true for samples 8. Samples 20, 22, 24, 26 and 40, on the other hand show only trivial or no changes. Thus, the change depicted in the chemistry of groundwater during pre and post-monsoon period are not explicable in terms of processes, such as, evaporation, dilution, water rock interaction and variations in residence time. This is also borne out by the fact that no clear cut alteration trend is depicted in L-L plot of post and pre monsoon samples (Fig.6.9a and 6.9b). What broadly emerges out is that a set of samples with composition close to that of meteoric water has basically gained Na and SO_4 to results in the various types of groundwater observed in the area. Processes, such as mixing of two or more types of groundwater or surface water and groundwater, may also have played a significant role. This phenomenon is depicted to some extent when the water table map is compared with the map showing distribution of TDS values (Fig.6.2). TDS values of >1100 mg/l are observed between river Krishni and Eastern Yamuna Canal, in the eastern part and on the left bank of Yamuna river in the south western part of the study area. As samples from Krishni river show very high TDS values associated with high SO_4 concentration (Appendix VIII A), it is logical to infer that the western high TDS zone has been generated as the result of receiving contributions from surface of industrial waste, particularly effluent from sugar factories, paper mills (Plate-9) and steel factories. The western high TDS zone evidently has been generated due to east to west migration of groundwater as highlighted in water table contour maps of the study area. Except for sample Y4, the other samples collected from Yamuna river have moderate TDS values of <500 mg/l, consistent with the fact that no industries are located in this sector. The effluent nature of Yamuna river at sampling site Y4 (Saipat) is evident on the water table contour map. Sample Y4 is, therefore, the surface manifestation of high TDS aquifer located on the eastern bank of the river Yamuna. The dynamics of the river aquifer interaction, thus, has played a role in influencing the chemical parameters of groundwater.

The question that now needs to be answered is as to where from SO_4 and Na are contributed to the system. As far as SO_4 is concerned, sulphur finds abundant use is sugar factories for cleaning sugar solutions. The froth is rejected which on exposure oxidizes to form SO_4, which may find way to shallow aquifers. In addition, SO_4 may also be contributed from community waste and also effluents from industries, such as, paper and acid manufacturing units which are located in the eastern part of the area. This is consistent with the fact that samples from Krishni river are highly polluted with TDS of about 3000 mg/l. Basically, it drains industrial effluents. As far as Na is concerned, this too is definitely part of the industrial wastes as samples from Krishni river have >200 mg/l of Na, compared to a value of <100 mg/l (except for sample Y4) in Yamuna river. Very high concentration of K (about 150 mg/l) in Krishni river is really enigmatic and this is also indicated in groundwater samples 4 and 21 located in the same vicinity. In all likelihood, K too has origin in community and industrial wastes. Calcium also has high values in Krishni river and may be related to bleaching powder used in paper industries and as household disinfectants.

6.8 Trace elements distribution

Trace elements in groundwater are defined as chemical element dissolved in water in minute quantities, almost always, in concentration less than one milligram of trace element in one liter of water (USGS, 1993). Although present in small proportion but their desirable intake is necessary for proper functioning of human body. The excess or deficiency both, may pose health hazard.

The trace metals like Fe, Mn, Cr, Cu, As, Ag, Cd, Hg etc. have a tendency to form hydrolyzed species and to form complexed species by combining with inorganic anions such as HCO_3, CO_3, Cl, F, and NO_3. The concentrations of which are influenced by redox conditions, as a result of either the change in oxidation state of the trace metal or of non-metallic elements with which it form complexes (Freeze and Cherry, 1979).

The distribution and occurrence of trace elements in groundwater depends upon degree of weathering and mobility of these elements during weathering (Handa, 1986). The trace elements, when discharged into system, can migrate or precipitate according to their geochemical mobility and deposit in different components of systems (Edet et al. ,2003). The occurrence and mobility of trace metals in groundwater environments is strongly influenced by adsorption process which occurs because of the presence of clay minerals, organic matters and the other crystalline and amorphous substances that make up the porous media. Geochemical processes can control and, perhaps, limit contaminant concentrations in the various phases, thereby, directly impacting exposure levels. The equilibrium/disequilibrium exists between a dissolved metal in groundwater and adsorption site may also enhance metal mobility (Deutsch, 1997).

6.8.1 Trace elements in Groundwater of Yamuna-Krishni interstream

Twenty three groundwater samples were analyzed for trace element in June 2006. The results are listed in appendix IX A. Analyses of 3 groundwater sample showing high values were repeated in June 2007(Appendix IX B).

A set of 12 trace elements i.e. Al, Cr, Mn, Fe, Ni, Co, Cu, Zn, As, Se, Cd and Pb which are of varied importance for human health show that trace element like Pb, Al, Fe and Mn show higher concentration than their recommended limits in a groundwater(BIS, 1991). Concentration of such water may pose health hazard to the inhabitants of the area.

6.9 Water in Relation to its Various Uses

6.9.1 Drinking Water Quality Criteria

The concentration of various major and trace elements in the groundwater samples of the study area are compared with the drinking water standards of W.H.O, (1993) and Indian Standard drinking water specification (BIS, 1991) as summarised in Table 6.2.

Fourteen samples have NO_3^- more than highest desirable limit. Sample No. 2 with concentration of 150 mg/l, exceeds the maximum permissible limit. The high concentration of nitrate in drinking water is toxic and cause blue baby disease/metaemoglobinaemia in children and gastric carcinomas (Comly, 1945, Gilly et al., 1984). In six samples (1, 5, 16, 22, 29 and 32) the fluoride concentration exceeds the maximum permissible limit in June 2006 which is hazardous for human consumption (BIS, 1991).

The concentrations of Fe and Pb are higher than permissible limits. Sample collected from the site Kandela shows the concentration of Fe and Pb are 14.38 and 0.99 mg/l, respectively. The high intake of Iron and Lead may pose health hazard.

Table 6.2. Range of concentration of various major and Trace elements in Shallow groundwater Samples and their comparison with W.H.O. (1993) and B.I.S. (1991) Drinking Water Standards.

	(BIS 1991)		W.H.O. (1993)		Conc. In the study area (mg/l)	
Constituents	**Highest desirable level**	**Max. permissible level**	**Highest desirable level**	**Max. desirable level**	**Nov 2005**	**June 2006**
pH	6.5-8.5	6.5-9.5	7-8.5	6.5-9.2	6.7-7.7	6.8-7.6
Total Hardness	300	600	100	500	76-488	120-548
TDS	500	2000			491-1575	497-1922
Calcium	75	200	75	200	6-32	5-64
Magnesium	30	100			9-110	21-121
Sodium					73-384	42-366
Chloride	250	1000	200	600	11-284	1-346
Sulphate	200	400			42-337	49-480
Fluoride	0.6-1.2	1.5			-	0.3-2.3
Nitrate	45	100			-	13-150
Copper	0.05	1.5	0.05	15	-	0.007-0.12
Iron	0.3	1	0.1	1	-	0.376-14.384
Lead	0.1			0.1	-	0.073-0.998
Manganese	0.1	0.5	0.05	0.5	-	0.021-1.439
Cadmium	0.01	0.01		0.01	-	0-0.001
Nickel	0.1	0.3			-	0.015-0.135
Cobalt					-	0.0003-0.0222
Chromium	0.05	0.05			-	0.015-0.135
Zinc	0.1	15	5	15	-	0.072-9.125
Selenium	0.01	0.1			-	0.001-0.052

6.9.2 Irrigation Water Quality

The total dissolved content measured in terms of specific electrical conductance gives the salinity hazard of irrigation water. The Electrical conductivity is a measure of salinity hazard to crop as it reflects the TDS in the groundwater. Parameters such as sodium absorption ratio (SAR) and residual sodium carbonate (RSC) were estimated to assess the suitability of groundwater for irrigation. The salt present in the water, besides affecting the growth of plants directly also affects soil structure permeability and aeration, which indirectly affect plant growth.

6.9.2.1 Sodium Absorption Ratio (SAR)

The interpretation of water quality suitable for the irrigation purposes are given by the Richard (1954) in the form of EC versus SAR values. Electrical Conductivity (E.C.) has been treated as index of salinity hazards and sodium adsorption (SAR) as index of Sodium hazards. The SAR is defined as

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}} \qquad \text{All values in meq/l}$$

The data has been plotted in Figures 6.10a and 6.10b and Quality Classification of Irrigation water are given in table 6.3. The SAR values range from 1.87-13.60 in the samples collected during November 2005. High SAR (i.e.>10) is observed in 6 samples. The Figure 6.10a reveals that most of the water samples fall in C_1S_1, C_2S_1, and C_3S_1. Three samples fall in C_2S_2 and one sample C_3S_2 respectively, except these four samples, all the samples fall in good to excellent class.

During June 2006 field session the SAR values ranges from 1.23-12.1.The high SAR i.e. >10 is reported in three samples only. Out of these three samples, two samples are taken from hand pumps and are not used for irrigation anyway. Groundwaters from deeper sources have relatively low SAR values and pose only low intensity salinization hazard. The Figure 6.10b reveals that most of the water samples fall in C_2S_1, and C_3S_1.

Table 6.3 Quality Classification of Irrigation water (after USSL 1954).

Water	Salinity Hazard E.C. Micromhos/cm at 25°C	Alkali SAR	RSC in Meq/l
Excellent	250	Up to 10	<<1.25
Good	250-750	10-18	< 1.25
Fair	750-2250	18-26	1.25-2.5
Poor	2250	26	> 2.50

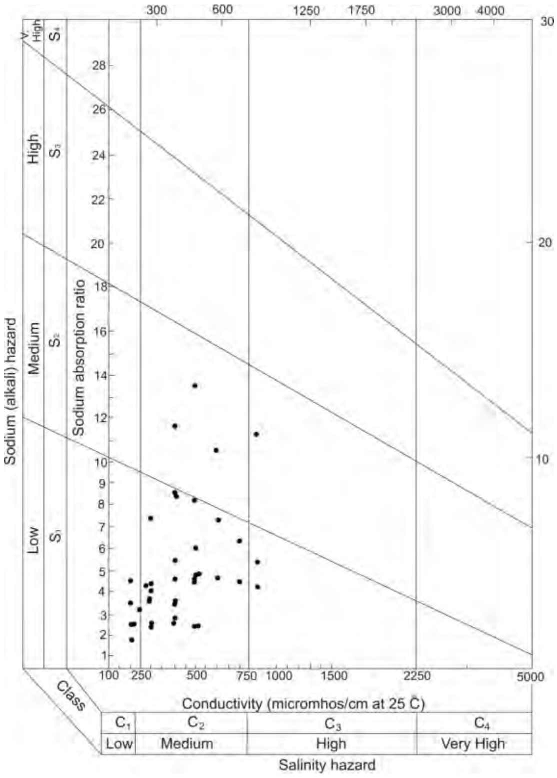


Fig.6.10a Salinity and Alkalinity hazards of Irrigation water in US Salinity diagram (November 2005).

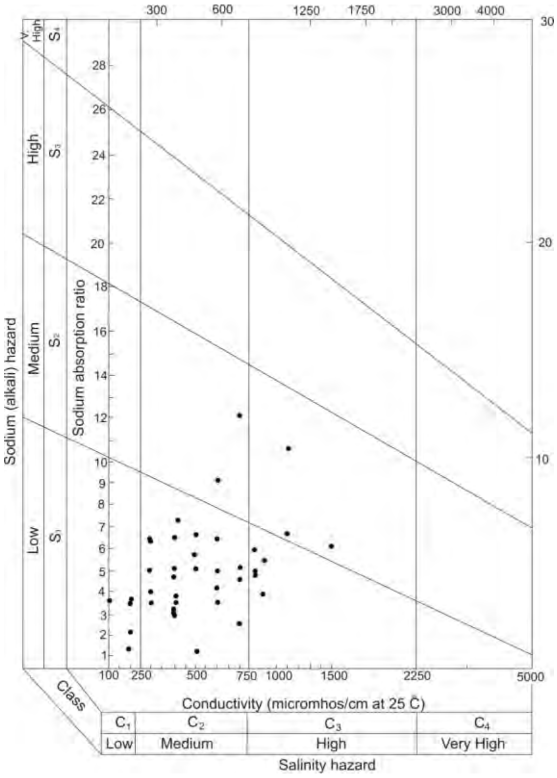


Fig.6.10b Salinity and Alkalinity hazards of Irrigation water in US Salinity diagram (June 2006)

6.9.2.2 Residual Sodium Carbonate

Eaton (1957) suggested that the excess sum of carbonate and bicarbonate in groundwater over the sum of calcium and magnesium also influences the suitability of groundwater for irrigation.

$$\text{RSC} = (CO_3^{--} + HCO_3^{--}) - (Ca^{++} + Mg^{++})$$

where the concentrations are reported in meq/l. Water with RSC below 1.25 is good, 1.25-2.5 is marginal and above 2.5 is not suitable for irrigation purposes. The classification of irrigation water according to the RSC value is presented in Table 6.4.

Table 6.4 Quality of groundwater based on residual sodium carbonate

RSC (meq/l)	Remark on quality	Post monsoon 2005	Pre monsoon 2006
		Representing samples	Representing samples
<1.25	Good	16	23
1.25-2.5	Doubtful	13	8
>2.5	Unsuitable	11	9

If RSC > 2.5, irrigation water may cause formation of salt peter (KNO_3), locally known as *Reh*.

6.10 Surface water Quality and Interaction with Groundwater

Seven surface water samples from rivers Yamuna and Krishni were analysed to assess their relationship with the groundwater regime. The samples from Krishni river show very high concentrations HCO_3^-, SO_4^-, Na^+ and K^+. The TDS values, consequently, are higher as well (Appendix-VIIIA & VIIIB).

The four Yamuna river samples with the exception of sample Y_4 show good correlation between Cl^-/Na^+ and $HCO_3^-/Ca^{2+}+Mg^{2+}$ and have moderate TDS values of 400 and 500 mg/l. Strikingly high TDS value of >1000 mg/l is recorded for sample Y_4 at the down reaches.

The groundwater samples from the vicinity of Krishni River shows higher concentration of HCO_3^-, SO_4^-, Na^+, K^+, Ca^+, Mg^+. The higher concentration is attributed to the seepage from drains, discharging the industrial effluent to Krishni River. Pollutants enter in to the shallow aquifer through downward percolation, effluent draining downward to the water table and further lateral movement below water table. The impressions of saline waste water disposal of paper mill situated at Sikka village can be seen in the groundwater sample taken from the same location. Here discharge from paper mill flows through the unlined drain long distance before joining Krishni River.

A set of twelve trace elements i.e. Cr, Mn, Fe, Al, Pb, Ni, Co, Cu, Zn, As, Se and Cd was analyzed in surface water sample of Yamuna-Krishni sub basin. The concentration of Ni, Co, Cu, Zn, As, Se, and Cd are within the permissible limit (Appendix IX C). The surface water samples have Cr, Mn, Pb and Fe concentrations more than permissible limit which was collected from river Krishni at location Bhanera and from Kandela drain i.e. 0.1142 to 0.1607, 0.423 to 0.4658 and 2.351 to 2.732 mg/l, respectively.

6.11 Analysis of Effluent of Sugar Mill

Field survey reveals that a number of sugar mills and paper factories are discharging their effluent in to the river Krishni in the upper reaches of the study area. A sugar factory is a seasonal industry. The schedule of operation varies from year to year depending on the occurrence of monsoon and availability of sugarcane. Hence the source of groundwater pollution flows only for the period of operation of the sugar factory. Two sample were collected from the Shamli Sugar mill. Out of these two, one is effluent water and the other is partially treated sample i.e. lagoon water (in the terminology used in sugar industry). The major elements analysis is given in Appendix-X-A and trace elements analysis in Appendix-X B.

Effluent water shows higher concentration of HCO_3, SO_4, NO_3, Na, K, and Ca. In partially treated (lagoon water) the concentrations of anion is much higher. Even CO_3 is present with concentration of 445 mg/l. The presence of CO_3 is an interesting feature and is related to high pH value of 9 causing dissociation of bicarbonate.

7 – PROJECT FINDINGS

Hydrogeology

- The aquifer system (upto 122 m bgl) has been taken up for detailed study in the present work. This aquifer is sub divided at places into two to three sub groups by occurrence of sub regional clay beds. By and large, the aquifer down to 122 m appears to merge with each other and behave as a single bodied aquifer. The aquifer is composed of fine to coarse sand. The sand percent map reveal that granular zone attain a maximum value of >80% in the central and southern part of the area.
- The result of grain size analysis of sand samples collected from a depth of 25-45 m bgl, shows that the effective grain size of sample ranges from 0.064 mm to 0.19 mm indicating that grain size is very fine to fine. The result of uniformity coefficient reveals that in general, the sample shows a value of uniformity coefficient <2, hence their porosity is high.
- Depth to water table varies between 5.76 to 21.96 m bgl and 5.18 to 21.02 m bgl in June 2006 and November 2006, respectively. The water level fluctuations therefore are substantial during this period.
- During 2007, the water level varies between 4.62 to 21.14 m bgl and 4.9 to 21.53 m bgl, in pre and post-monsoon periods, respectively. The water level rise during 2007 is insignificant and 70% of the well shows negative fluctuation.
- Historical water levels of 14 permanent monitoring wells were analysed for long term water level trend. Out of these wells 6 wells represent command area and 8 wells represent non-command area. The entire hydrographs show declining trend. The average rate of decline is 0.96 m/year and 0.81 m/year, respectively.
- Fourteen bimonthly water levels monitoring points were selected and to analyse the groundwater fluctuation trends in response to utilization pattern. Most of the observation wells show gradual decline in water level from the month of Feb-07 to June-07. The significant rise at the locations Kairana and Todda may be attributed to some local recharge factors.
- The water table contour maps have revealed that the movement of groundwater is, in general, from NNE to SSW. Localized groundwater flows are also encountered which

is possibly because of varied stress applied to the groundwater regime. In general the gradient varies from 2.2 m/km in the NE region to 0.4 m/km at SW region. The high rate of groundwater abstraction from shallow farmer's tubewells is mainly responsible for the water table decline in the area and resulting in to the formation of two troughs. The formation of a trough in the lower half of the study area has, seemingly, influenced the general groundwater flow pattern.

- The Eastern Yamuna canal replenishes groundwater through seepage and also act as a groundwater divide almost throughout the area. The groundwater flow direction at the left bank of canal is towards the Krishni river with an average hydraulic gradient of 1.25 m/km. While from its right bank the groundwater flows from NE-SW direction. A groundwater mound has developed near Khandrauli village which is shedding water from its eastern flank to the river Krishni and from its western flank towards Kairana township.
- The contour behaviour shows that the river Yamuna is contributing the aquifer system and hence influent through out the area. The groundwater flow direction is towards the river Krishni hence it is effluent in nature.
- An Isopermeability map has been prepared using Logan's approximation (1964) approach. The permeability 30-40 m/day covers bulk of the area. The Upland area between river Yamuna and Katha drain has the permeability value <30 m/day.
- The hydraulic conductivity of aquifer materials was also determined by constant head Permeameter. The values obtained by Permeameter ranges from 1.01 m/day to 7.7 m/day. The permeability values obtained by Permeameter are lower than the pumping test values. The possible reason for low values is that the sand samples represent shallow depth and the size of sand tested varies from very fine to fine. Moreover, the natural setup is also altered because of compaction of the sand grains in confined environment.
- Specific yield of 0.15-0.23 is used in and adjoining part of the study area by several workers. However, for the present study specific yield of 0.16 is taken.
- A long duration and 8 short duration pumping test result shows that the aquifer parameters like Transmissivity and Hydraulic conductivity varies between 1265-4003 m^2/day and 9.8-26.6 m/day, respectively.

Estimation of Dynamic Groundwater Resource

- The results of the groundwater budget for two successive years i.e. June 2006 to May 2007 and June 2007 to May 2008, shows that the total recharge to the sub-basin is 427.79 MCM, 393.65 MCM and total discharge from the sub-basin is 478.48 MCM, 493.13 MCM thus, leaving a deficit balance of 50.69 MCM, 99.48 MCM and the stage of groundwater development are worked out 111% and 125% respectively, which put the sub-basin into over-exploited category.
- The unplanned and massive groundwater exploitation is creating multifarious problems, in the study area particularly in non-command area of the sub-basin. The water level is very deep and has acquired a declining trend. As rainfall serves a major recharge component, irregularity or delay in the monsoon, may lead to the scarcity of groundwater in the area.
- The uncertainties lie with the estimation of various components of groundwater budget, owing to the limitations in the assessment methodology, as well as uncertainties in the data. Thus, further efforts may be done to minimize the computational errors.

Groundwater Flow Modelling

- Visual 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 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. Transient state calibration also shows good agreement between observed and calibrated heads.
- 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 response of the model by determining the root mean square error of the simulated heads compared to the measured heads.

- Three scenarios have been considered to predict aquifer responses under different conditions of groundwater abstraction and additional recharge through distributary and drain in deficit areas. All the three prediction scenarios were chosen so as the situation is acceptable with in the study area.
- According to prediction scenario 1 i.e. with assumed 20% increased groundwater abstraction rate the maximum 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. In second scenario the rainfall is reduced by 20% and groundwater abstraction was kept same as scenario 1. This shows that the maximum drawdown 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. In this scenario, 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.

Groundwater Vulnerability Assessment

- The vulnerability index range from 140 to 180 and is classified into four classes i.e 140-150, 150-160, 160-170 and 170-180 corresponding to low, medium, high and very high vulnerability zones, respectively. The groundwater vulnerability potential map shows that bulk of the area is covered by high to very high vulnerable zone followed by medium and low vulnerable zones. Ironically, all major townships like Shamli, Kairana and Kandhala are located in high to very high vulnerability zones. The vulnerability map thus generated helps in identifying areas which are more likely to be susceptible to groundwater contamination relative to one another.

Hydrogeochemistry

- An attempt has also been made to evaluate and determine the possible factors controlling variation in groundwater chemistry and to infer possible changes that occur in two time periods that is post and premonsoon groundwater quality. The groundwater shows strikingly high TDS concentration which seems to acquire increasing trend with time. The unique chemical characteristic of the groundwater is the outcome of several natural and anthropogenic processes. A chemical classification of groundwater was attempted on the L-L diagram and identified four major group characterized by distinct chemical compositions. The four major types of groundwater in the area are; HCO_3-SO_4 type, Cl-SO_4 type, HCO_3 type, and SO_4 type. Ion exchange and simple dissolution reactions help in carving out the present shape to groundwater chemistry. The reaction involved in the humic zone and dissolution of kankar, accumulation of salts through evaporation are also affecting the hydrochemical regime. The anthropogenic factors affecting the groundwater are application of fertilizers and manures and pollution from industrial effluents. The groundwater regime is affected significantly and the meteoric signatures have been completely obliterated. The high concentration of SO_4^-, HCO_3^- and Na^+ is of particular concern. The concentrations of NO_3^-, F^-, Fe and Pb in few groundwater samples are above the permissible limit and may pose health hazards on human consumptions. Broadly speaking, the groundwater is suitable for irrigation and drinking purposes with few exceptions.

9. Conclusions / Recommendations

(i) Conclusions

This being a research project, a pilot area was taken for study, apply the existing techniques in the best possible way by minimizing the assumptions and approximations and developing the procedures and techniques using new aspects that were suitable to match the specific condition. The detailed study carried out in the area sets an example for the similar areas as well as reduces the uncertainties in the conclusions and recommendations. Specific details are furnished below.

1. The area has experienced growth in population and hence in the water demand that has put increased stress on the groundwater system.
2. All the available information on the hydraulic parameters and also determined from the experiments in the project have been analysed and integrated in the model. However, the grain size analyses confirm the presence of Alluvial aquifers and flow system is such that the river Yamuna is influent throughout the area and for the entire period of study. This is due to increase in groundwater pumping and reduction of the base flow.
3. The two consecutive years groundwater balance has shown negative water balance and that is alarming as well as produces the water level decline.
4. A unique contribution to this project has been the aquifer modeling by calibrating the model in the steady conditions as well as for 8 years under transient conditions that is usually rare and this has made the aquifer model producing the predicted result with utmost certainty. In addition, sensitivity analyses has further given knowledge of the areas and parameters for a careful monitoring in the future. The zonal water balance that is possible only through aquifer modeling could reveal the specific situation in the area and helped in suggesting the remedial measures.
5. The groundwater quality after hydrochemical analyses and interpretations found to be acceptable for the time being but showing deteriorating trends with some important constituents higher than the permissible limits.

The study has elaborated the groundwater situation in the area with details of the system conditions with a greater certainty and is useful for further development and judicious planning to avoid the groundwater crisis that was not otherwise possible.

(ii) Recommendations

In the past time, the demand-availability ratio was positive and managing the resource was not a big deal but now a days when supply is running short and demand is escalating high, management of groundwater resource is now becomes key issue. Several components of the groundwater balance are time varying and further scientific investigations particularly region wise converge of the accuracy and precision are needed. It is very clear from the estimates that the development of groundwater in the region is intense and a slight change in one of the components e.g. an increase in draft or a decrease in recharge hence further will seriously deplete the groundwater storage. It is clear that the situation has reached to an alarming stage which is likely to deteriorate further in the coming years. It is therefore clear that strict controls on groundwater abstraction need to be introduced in order to manage the groundwater resources of the Yamuna-Krishni sub-basin. Following recommendations and consequences are suggested based on the findings.

Controlled Abstraction: In order to reduce total abstraction even the present rate of pumping has to be carefully controlled. For example groundwater withdrawal could be reduced in non-command areas where two groundwater troughs have been generated. It is suggested that groundwater withdrawal along river Yamuna flood plains can be slightly increased.

Augmentation of water resources: Suitable measures for augmentation of groundwater resources may be adopted e.g. artificial recharge may ease the situation in the study area before the situation becomes unmanageable. However, emphasis must be put on demand management as rainwater harvesting will reduce the runoff and further reduce the flow to the rivers.

Development from deeper aquifer: The groundwater abstraction can be focused on deeper aquifers. The study carried out by CGWB in alluvial parts of Central Ganga Plain have revealed the existence of a huge reserve of groundwater in the deeper aquifer, which have not been fully utilized. The thickness of the alluvium in the area exceeds 500 m and only a small fraction of this is under active circulation due to prevailing shallow groundwater development. Therefore, it is suggested that II^{nd} and III^{rd} aquifer should be taped.

Development of flood plain: Flood plains in the vicinity of rivers are good repositories of groundwater. A planned management of groundwater in the flood plain aquifers offers an excellent scope of its development to meet the additional requirement of water. The main efforts, in this regard, are needed to make the groundwater available at the place of demand.

Restoring traditional groundwater structures: In the past, every village in western Uttar Pradesh boasted of having ponds and community tanks which have been a very good source of groundwater recharge, at least locally. Now, it was observed during the field surveys that the ponds and tanks have disappeared due to encroachment by local people. This has retarded the groundwater recharge of shallow aquifer. Thus revival of such structures is recommended.

Improvement in Canal System: The present canal irrigation system in the study area is untimely and restricted to the vicinity of main canal. The irrigation channels in the down reaches do not receive water from the feeder canals and thus requires proper management policy to ensure the availability of water at the tail ends of canal vis-à-vis irrigation channels.

Conjunctive use of surface and groundwater: Conjunctive use of surface water and groundwater resources is the optimal method of obtaining maximum possible water development the same has been tested and proved in the aquifer modelling

Protection of groundwater from pollution: It is suggested that the urban landfill, garbage dumps and effluent channels should either have concrete floor or sheets of impervious film be used to prevent leaching of pollutants in the water.

Stopping subsidized power supply**:** The pumping mainly depends on the electric supply. The electric supply in the study area is at a very subsidized rate and due to this lot of water is wasted. Moreover, frequent power theft instances also encourage farmers for indiscriminate pumping. A water and energy nexus may be evolved in the further study.

People's awareness: The public support is needed to implement groundwater management. Institutional frameworks that enable effective participation of local users and communities in the management processes are essential. It is also suggested that in the local languages of region, seminars, posters presentations be arranged for educating the public of urban and rural areas for judicious use of groundwater.

The awareness of farmers towards the groundwater recharge can prove an important milestone in managing the groundwater resources.

Groundwater Legislation: A strict groundwater legislation using the scientitific studies such as the present one should be brought in to regulate harnessing of groundwater resources.

10. How do the conclusions / recommendations compare with current thinking.

The present work is one of its kinds, as the groundwater budget is performed at micro level, including all possible influential components of groundwater budget. Also, the river aquifer interaction and other boundary flows were calculated using groundwater flow modelling. Moreover the fact that the demand-supply ratio is escalating, it further necessitates that the resource evaluation should be done more precisely. The precise account of groundwater budget serves as the backbone of any groundwater management programme. Thus, after detailed hydrogeological examination the study emphasizes upon groundwater budget.

The present work can be extended as the sub-basin needs to be monitored for groundwater conditions for some years. The dynamic resource of the sub-basin is being exploited at an alarming rate. The groundwater is being harnessed continuously to cope up with the rising demands. Moreover, the recharge to the system is decreasing day by day as groundwater discharge exceeds the recharge, due to deficit rainfall. The applicability of recommendations and their socio-economical impacts need to be analysed in the times to come.

Any multidisciplinary scientific study for the evaluation of natural phenomenon carries errors at some stages of assessment, thus improvements are always inevitable. The lacunae may arise because of improper understanding of the system. It was nearly impossible to assign observation well at known altitude location, the error arises as this may locally change the flow pattern of the groundwater regime. Improvements are further possible in groundwater budget, at the statistical level, like number of groundwater draft structures and irrigation water applied may carry certain errors. The vertical leakage from the first aquifer under consideration needs to be accounted for.

In addition, emphasis has in particular been laid on aquifer vulnerability and hydrogeochemical aspects, such as, chemical types of groundwater, temporal and spatial variation in chemical characteristics, chemical alteration trends of groundwater, factors affecting the chemical quality. Again, the idea is to provide some clues to planners and administrators to mitigate the problem of groundwater pollution.

11. Field tests conducted.

Following tests were conducted during field work

(i) Coordinates of the borewells were taken using GPS.

(ii) Repeat measurements to monitor the changes in water level, for post-monsoon 2005, pre-and post-monsoon 2006 and 2007 respectively in all the monitoring wells

(iii) Bimonthly water level monitoring was also carried out from February 2007to November 2008 at 14 selected monitoring wells.

. **(iv)** pH, Temperature and EC were measured at well site during sampling.

(v) The concentrations of NO_3 and F were also determined at well site with the help of portable kits.

12. Software generated, if any: No

Visual MODFLOW 4.1 P, were used for Numerical Modelling of Yamuna-Krishni sub-basin.

13. Possibilities of any patents/copyrights. If so, then action taken in this regard: No

14. Suggestions for further work

There are following suggestions for further work.

***Artificial recharge sites*:** Study for identification of site for Artificial Recharge.

***Water level*:** Installation of Peizometre at micro level for monitoring the groundwater level.

Further scientific investigations: Several components of the groundwater balance are time-dependent and further scientific investigations (particularly region-wise) are necessary in order to provide the required additional accuracy and precision.

Groundwater quality: It is possible that further pumping may lead to deterioration of groundwater quality leading to its unsuitability as a drinking water source by the rural population; further groundwater quality investigations are required.

Paper published from project

1. Izrar Ahmed and Rashid Umar (2009) Groundwater flow modelling of Yamuna – Krishni interstream, a part of central Ganga Plain, Uttar Pradesh. J. Earth Syst. Sci. 118. No.5, pp. 507-523
2. Rashid Umar, Izrar Ahmed and Fakhre Alam (2009) Mapping Groundwater vulnerable zones using modified DRASTIC approach of an alluvial aquifer in parts of Central Ganga Plain, Western Uttar Pradesh. J. Geol. Soc. India, vol. 73, pp.193-201.
3. Rashid Umar, Izrar Ahmed, Fakhre Alam and Mohammad Muqtada Khan (2009): Hydrochemical Characteristics and seasonal variations in Groundwater Quality of an alluvial aquifer in parts of Central Ganga Plain, Western Uttar Pradesh, India. Environ. Geol. vol. 58. No. 6, pp. 1295-1300
4. Rashid Umar & Izrar Ahmed (2009) Sustainability of a shallow aquifer in Yamuna-Krishni interstream region, Western Uttar Pradesh: a quantitative assessment. *Trends and Sustainability of Groundwater in Highly Stressed Aquifer, Proc. of Symposium JS.2 IAHS publication 329 at the Joint IAHS & IAH Convention, Hyderabad, India. pp.103-112*

Ph.D Thesis:

Guided: One (Awarded)

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APPENDIX I A

Statistical analysis of Rainfall data at Kairana Raingauge Station

S.No.	Year	Rainfall (X)	Average (Y)	Departure (X/Y)-1	Cumulative Departure	(X-Y)	$(X-Y)^2$
1	1990	1220.30	664.09	0.84	0.84	556.21	309369.56
2	1991	539.40	664.09	-0.19	0.65	-124.69	15547.60
3	1992	607.80	664.09	-0.08	0.57	-56.29	3168.56
4	1993	521.50	664.09	-0.21	0.35	-142.59	20331.91
5	1994	891.80	664.09	0.34	0.70	227.71	51851.84
6	1995	997.10	664.09	0.50	1.20	333.01	110895.66
7	1996	569.40	664.09	-0.14	1.05	-94.69	8966.20
8	1997	821.80	664.09	0.24	1.29	157.71	24872.44
9	1998	608.40	664.09	-0.08	1.21	-55.69	3101.38
10	1999	443.00	664.09	-0.33	0.88	-221.09	48880.79
11	2000	815.20	664.09	0.23	1.10	151.11	22834.23
12	2001	595.90	664.09	-0.10	1.00	-68.19	4649.88
13	2002	592.30	664.09	-0.11	0.89	-71.79	5153.80
14	2003	669.60	664.09	0.01	0.90	5.51	30.36
15	2004	591.50	664.09	-0.11	0.79	-72.59	5269.31
16	2005	606.20	664.09	-0.09	0.70	-57.89	3351.25
17	2006	447.50	664.09	-0.33	0.38	-216.59	46911.23
18	2007	415.00	664.09	-0.38	0.00	-249.09	62045.83

APPENDIX I B

Statistical analysis of Rainfall data at Shamli Raingauge Station

S.No.	Year	Rainfall (X)	Average (Y)	Departure (X/Y)-1	Cumulative Departure	(X-Y)	$(X-Y)^2$
1	1990	1067	697.2	0.53	0.53	369.8	136752.04
2	1991	455	697.2	-0.35	0.18	-242.2	58660.84
3	1992	758	697.2	0.09	0.27	60.8	3696.64
4	1993	206	697.2	-0.70	-0.43	-491.2	241277.44
5	1994	925.5	697.2	0.33	-0.11	228.3	52120.89
6	1995	1099.2	697.2	0.58	0.47	402	161604
7	1996	980	697.2	0.41	0.87	282.8	79975.84
8	1997	985	697.2	0.41	1.29	287.8	82828.84
9	1998	1390	697.2	0.99	2.28	692.8	479971.84
10	1999	422	697.2	-0.39	1.89	-275.2	75735.04
11	2000	442	697.2	-0.37	1.52	-255.2	65127.04
12	2001	545	697.2	-0.22	1.30	-152.2	23164.84
13	2002	578	697.2	-0.17	1.13	-119.2	14208.64
14	2003	655	697.2	-0.06	1.07	-42.2	1780.84
15	2004	580	697.2	-0.17	0.90	-117.2	13735.84
16	2005	635	697.2	-0.09	0.81	-62.2	3868.84
17	2006	432.25	697.2	-0.38	0.43	-264.95	70198.503
18	2007	394.1	697.2	-0.43	0.00	-303.1	91869.61

APPENDIX II
Latitudes and Longitudes and their corresponding x and y of monitoring wells

S.No.	Location	Latitudes	Longitudes	x	y
1	Banat	29°27′ 59″	77°21′	25705	22636
2	Sikka	29°30′ 24″	77°21′53″	26597	27450
3	Kaidi	29°30′ 25″	77°24′21″	30428	26996
4	Sonta Rasulpur	29°31′ 56″	77°24′24″	31058	30293
5	Thana Bhawan	29°35′ 35″	77°25′19″	31584	35608
6	Jalalabad	29°37′ 25″	77°26′14″	33281	39639
7	Chandelmal	29°39′ 11″	77°27′13″	35054	43432
8	Dulawa	29°38′ 53″	77°24′21″	30595	42510
9	Khanpur	29°36′ 41″	77°24′08″	30082	38562
10	Goharni	29°28′ 46″	77°18′50″	22328	24445
11	Jhandheri	29°32′ 21″	77°19′58″	24138	31449
12	Garhi Pukhta	29°32′ 46″	77°18′37″	21038	31663
13	Dulla Kheri	29°35′ 25″	77°19′12″	22273	36141
14	Bunta	29°36′ 44″	77°20′21″	23839	38730
15	Garhi Abdullah Khan	29°38′ 29″	77°19′14″	21950	41946
16	Bhanera Uda	29°37′16.5″	77°22′06″	27113	39579
17	Harhar Fatehpur	29°32′56 ″	77°23′38.9″	29479	32109
18	Un	29°34′ 55.8″	77°15′00.5″	16427	35483
19	Pindora	29°36′ 17.6″	77°17′07.2″	19412	37471
20	Mundait	29°38′ 29″	77°16′38″	18656	42182
21	kheri khushnam	29°39′15.8″	77°15′02″	15730	43176
22	Garhi Hasanpur	29°40′14.1″	77°13′08.2″	12535	44703
23	Chausana	29°39′41″	77°10′24″	9046	44039
24	Bhari	29°40′03″	77°09′17.3″	5774	44319
25	Ulahni	29°35′54.4″	77°10′26.5″	8711	37107
26	Todda	29°37′26.4″	77°11′44.3″	10599	39414
27	Titoli	29°28′07″	77°16′18″	18085	23240
28	Badheo	29°29′10″	77°17′22″	20048	25416
29	Taprana	29°29′17″	77°15′20″	16786	25413
30	Jinjhana	29°30′ 43.1″	77°13′19.9″	13681	28708
31	Rangana	29°33′38.4″	77°13′13.5″	13086	33364
32	Bipur jalalpur	29°31′52″	77°11′05″	9377	29739
33	Mansura	29°31′16.2″	77°08′38.6″	5930	28500
34	Yusufpur choutra	29°31′52.3″	77°06′54.2″	3047	29972
35	Barla Jat	29°25′06″	77°21′08.6″	25514	17993
36	Salpa	29°22′41.5″	77°19′33.8″	23235	13333
37	Makhmulpur	29°20′18.4″	77°19′11.3″	22947	9178
38	Bhabhisa	29°18′30″	77°19′24″	22964	6184
39	Bhanera	29°16′26.3″	77°19′02.6″	22419	2518
40	Nala	29°16′58.1″	77°16′38.7″	18491	3266
41	Malakpur	29°21′09.4″	77°15′50.4″	17643	10743
42	Pauti kalan	29°29′11.7″	77°12′36.1″	11490	25654
43	Akbarpur Sunethi	29°29′05.1″	77°09′25.6″	7011	25047
44	Khurgyan	29°27′19.4″	77°09′22.7″	7068	20783

45	Khera	$29^{0}24^{\prime}51.9^{\prime\prime}$	$77^{0}09^{\prime}41.6^{\prime\prime}$	7138	17550
46	Mawi	$29^{0}22^{\prime}39.7^{\prime\prime}$	$77^{0}09^{\prime}17.7^{\prime\prime}$	7249	13492
47	Saipat	$29^{0}20^{\prime}28.8^{\prime\prime}$	$77^{0}09^{\prime}58^{\prime\prime}$	8179	9899
48	Jharkhedi	$29^{0}22^{\prime}22.1^{\prime\prime}$	$77^{0}11^{\prime}50.1^{\prime\prime}$	11188	13157
49	Kairana	$29^{0}23^{\prime}50.3^{\prime\prime}$	$77^{0}12^{\prime}49^{\prime\prime}$	12475	16137
50	Kandela	$29^{0}25^{\prime}44.8^{\prime\prime}$	$77^{0}14^{\prime}40.8^{\prime\prime}$	15150	19570
51	Bhoora	$29^{0}27^{\prime}00.6^{\prime\prime}$	$77^{0}12^{\prime}34.5^{\prime\prime}$	12011	21639
52	Kaserwa Khurd	$29^{0}27^{\prime}36.5^{\prime\prime}$	$77^{0}15^{\prime}23.8^{\prime\prime}$	16630	22170
53	Khandrauli	$29^{0}23^{\prime}12^{\prime\prime}$	$77^{0}16^{\prime}49^{\prime\prime}$	19017	14645
54	Lilaun	$29^{0}25^{\prime}39^{\prime\prime}$	$77^{0}17^{\prime}28.5^{\prime\prime}$	20154	18440
55	Erti	$29^{0}24^{\prime}25^{\prime\prime}$	$77^{0}15^{\prime}43^{\prime\prime}$	17007	16592
56	Gangeru	$29^{0}18^{\prime}42^{\prime\prime}$	$77^{0}13^{\prime}9.5^{\prime\prime}$	12888	6665
57	Unchagaon	$29^{0}21^{\prime}28^{\prime\prime}$	$77^{0}13^{\prime}48^{\prime\prime}$	13769	11252
58	Shamli	$29^{0}27^{\prime}10.9^{\prime\prime}$	$77^{0}18^{\prime}37.9^{\prime\prime}$	21731	21615
59	Kandhla	$29^{0}19^{\prime}15^{\prime\prime}$	$77^{0}16^{\prime}52^{\prime\prime}$	16830	7425
60	Garhi Rakha	$29^{0}16^{\prime}10^{\prime\prime}$	$77^{0}11^{\prime}45^{\prime\prime}$	10500	4650

APPENDIX-III
Lithological Logs of Boreholes drilled by the State Tubewell Department, Yamuna-Krishni Sub-basin, Muzaffarnagar District

S.No.	Lithology	Depth (m)	Thickness (m)
LOCATION: TAPRANA			
TUBE WELL NO. 23 KG			
1.	Surface clay	0-12	12
2.	Fine medium sand	12-24	12
3.	Clay	24-30	6
4.	Coarse sand	30-33.9	3.9
5.	Clay and Kankar	33.9-48	14
6.	Fine medium sand	48-58.8	10.8
7.	Clay	58.8-63	4.2
8.	Fine sand and sandstone	63-72	9
9.	Fine medium Sand	72-87	15
10.	Clay	87-96	9
11.	Fine sand	96-99	3
12.	Clay and Kankar	99-102	3
13.	Fine medium sand	102-112.5	10.5
14.	Clay and Kankar	112.5-117	4.5
LOCATION: PAUTI KALAN			
TUBE WELL NO. 48 KG			
1.	Surface Clay	0-3	3
2.	Medium Sand	3-12	9
3.	Clay	12-15	3
4.	Fine medium sand	15-21	6
5.	Clay	21-27	6
6.	Medium sand with pebbles	27-51	24
7.	Clay	51-57	6
8.	Very fine sand and Sandstone	57-60	3
9.	Clay	60-63	3
10.	Medium sand with sandstone	63-81	18
11.	Clay and Kankar	81-85.2	4.2
LOCATION: SAIPAT			
TUBE WELL NO. 97KG			
1.	Surface Sand	0-3	3
2.	Clay	3-15	12
3.	Medium Sand	15-24	9
4.	Clay and Kankar	24-36	12
5.	Medium sand with Sandstone	36-81	45
6.	Clay	81-85.2	4.2
LOCATION: MAWI			
TUBE WELL NO. 64 KG			
1.	Surface clay	0-3	3
2.	Medium Sand	3-12	9
3.	Clay and Kankar	12-18	6
4.	Medium sand	18-30	12
5.	Clay and Kankar	30-33	3
6.	Medium Sand	33-72.6	39.6

S.No.	Lithology	Depth (m)	Thickness (m)
7.	Clay and Kankar	81-85.2	9.6
LOCATION: TITARWARA			
TUBE WELL NO. 93 KG			
1.	Surface Sand	0-12	12
2.	Clay and Kankar	12-18	6
3.	Medium sand	18-39	21
4.	Medium sand with sandstone	39-69	30
5.	Medium sand	69-81	12
6.	Clay and Kankar	81-85.2	4.2
LOCATION: JALALPUR			
TUBE WELL NO. 37 A NL			
1.	Clay and Kankar	0-6.6	6.6
2.	Fine sand	6.6-15.9	9.3
3.	Hard Clay disintegers	15.9-22.5	6.6
4.	Fine sand and Clay	22.5-23.5	1
5.	Clay and Kankar disintegers	23.5-46.5	23
6.	Fine sand and Kankar	46.5-55.5	9
7.	Fine and medium sand	55.5-64.5	9
8.	Medium sand and sandstone	64.5-76.8	12.3
9.	Soft clay disintegers	76.8-81.0	4.2
10.	Fine sand	81-87	6
11.	Clay disintegrates	87-90	3
LOCATION: SALPA			
TUBE WELL NO. 79			
1.	Surface Clay	0-3	3
2.	Clay and Kankar	3-18	15
3.	Fine sand	18-24	6
4.	Clay and Kankar	24-30	6
5.	Medium sand and Kankar	30-39	9
6.	Medium sand and pebbles	39-45	6
7.	Clay and Kankar	45-48	3
8.	Fine sand with stone	48-54	6
9.	Sand clay with Kankar	54-60	6
10.	Medium sand with pebbles	60-69	9
11.	Medium sand	69-87	18
12.	Clay and Kankar	87-88.2	1.2
LOCATION: SHAMLI			
TUBE WELL NO. 36			
1.	Surface clay	0-6.1	6.1
2.	Fine to medium sand	6.1-24.4	18.3
3.	Fine sand with Indurated sand	24.5-30.5	6.1
4.	Coarse sand	30.5-36.6	6.1
5.	Medium sand	36.6-48.8	12.2
6.	Medium sand with indurated sand	48.8-54.9	6.1
7.	Medium sand with Kankar	54.9-67.10	12.2
8.	Medium sand	67.10-79.3	12.2
9.	Medium sand with kankar	79.3-85.4	6.1
10.	Clay	85.4-91.5	6.1
11.	Fine sand	91.5-115.9	24.4
12.	Sandy clay	115.9-122	6.1

S.No.	Lithology	Depth (m)	Thickness (m)
LOCATION: MANDAWAR			
TUBE WELL NO. 57			
1.	Surface clay	0 - 3.05	3.05
2.	Sand brownish medium	3.05-6.10	3.05
3.	Medium sand	6.10-9.14	3.04
4.	Medium sand with pebbles	9.14-12.19	3.05
5.	Medium sand	12.19-27.43	15.24
6.	Clay sand with Kankar	27.43-30.48	3.05
7.	Hard clay	30.48-36.58	6.10
8.	Medium sand	36.58-45.72	9.14
9.	Medium sand with Indurated sand	45.72-48.77	3.05
10.	Hard clay and Kankar	48.77-54.86	6.09
11.	Clay	54.86-57.91	3.05
12.	Medium sand	57.91-82.30	24.39
13.	Clay	82.30-85.34	3.04
14.	Fine sand	85.34-88.39	3.05
15.	Clay	88.39-98.76	10.37
LOCATION: MUHAMMADPUR RAIN			
TUBE WELL NO. 08			
1.	Hard Clay	0 - 3.6	3.6
2.	Medium sand with pebbles	3.6 - 18.29	14.6
3.	Fine to medium sand with Kankar	18.29-23.47	5.2
4.	Clay	23.47-27.43	3.96
5.	Medium sand with pebbles	27.43-30.48	3.05
6.	Coarse sand with pebbles	30.48-36.58	6.1
7.	Fine sand	36.58-49.07	12.5
8.	Hard clay and Kankar	49.07-56.38	7.31
9.	Fine sand with Kankar	56.38-73.76	17.38
10.	Fine sand	73.76-78.64	4.88
11.	Hard clay	78.64-80.47	1.83
LOCATION: KAIRANA			
TUBE WELL NO. 39			
1.	Surface Clay	0-2.1	2.1
2.	Medium sand	2.1-9	6.9
3.	Fine to med. Sand with Kankar	9-18	9
4.	Clay	18-21	3
5.	Medium sand	21-30	9
6.	Clay	30-33	3
7.	Fine sand	33-36	3
8.	Clay	36-39	3
9.	Fine to medium sand	39-48	9
10.	Clay	48-51	3
11.	Medium sand	51-60	9
12.	Clay and Kankar	60-63	3
13.	Fine to medium sand	63-73.2	10.2
14.	Clay and Kankar	73.2-79.5	6.3
15.	Fine to medium sand	79.5-84.6	5.1
16.	Clay and Kankar	84.6-87.6	3
17.	Fine to medium sand	87.6-100.5	12.9
18.	Clay and Kankar	100.5-106.2	5.7

S.No.	Lithology	Depth (m)	Thickness (m)
LOCATION: CHAUSANA			
TUBEWELL NO: 46(KG)			
1.	Clay	0-3.6	3.6
2.	Medium Sand	3.6-21	17.4
3.	Clay	21-24	3
4.	Fine Sand and Kankar	24-27	3
5.	Sticky Clay	27-33	6
6.	Fine to Medium Sand	33-45	12
7.	Clay and kankar	45-54	9
8.	Medium Sand	54-63	9
9.	Clay	63-66	3
10.	Fine Sand	66-69	3
11.	Clay and Kankar	69-72	3
12.	Medium to Coarse Sand	72-94.5	22.5
13.	Clay and Kankar	94.5-97.5	3
LOCATION: KHERIKHUSHNAM			
TUBE WELL NO: 52(KG)			
1.	Sandy Clay	0-3	3
2.	Medium to Fine Sand	3-24	21
3.	Kankar	24-27	30
4.	Clay	27-36	9
5.	Fine Sand	36-39	3
6.	Clay	39-48	9
7.	Medium Sand	48-69	21
8.	Clay	69-73.5	4.5
9.	Medium Sand	73.5-87	13.5
10.	Clay	87-91.5	4.5
LOCATION: BALLAMAZRA			
TUBE WELL NO: 49 (KG)			
1.	Sand	0-9	9
2.	Clay	9-15	6
3.	Fine to Medium Sand	15-21	6
4.	Clay and Kankar	21-30	9
5.	Sand	30-49.5	19.5
6.	Clay	49.5-57	7.5
7.	Medium Sand	57-60	3
8.	Clay	60-64.8	4.8
9.	Medium Sand	64.8-94.5	29.7
10.	Clay and Kankar	94.5-97.2	2.7
LOCATION: KAIDI			
TUBE WELL NO: 37B (NL)			
1.	Clay	0-8.1	8.1
2.	Clay and Kankar	8.1-17.4	9.3
3.	Fine Sand	17.4-24.9	7.5
4.	Clay and kankar	24.9-37.5	12.
5.	Sand	37.5-40.2	2.7

S.No.	Lithology	Depth (m)	Thickness (m)
6.	Clay	40.2-45.9	5.7
7.	Fine Sand	45.9-52.5	6.6
8.	Clay	52.5-54	1.5
9.	Fine to Medium Sand	54-87	33
LOCATION: GARHI			
TUBE WELL NO: 58 (NL)			
1.	Clay	0-6	6
2.	Clay and Kankar	6-18	12
3.	Fine Sand	18-21	3
4.	Sandy Clay	21-33	12
5.	Clay and Kankar	33-42	9
6.	Medium Sand	42-78	36
7.	Clay and Kankar	78-88.2	10.2
LOCATION: SHIKARPUR			
TUBE WELL NO: 70 (NL)			
1.	Clay	0-9	9
2.	Clay and Kankar	9-12	3
3.	Fine Sand	12-21	9
4.	Clay	21-24	3
5.	Clay and Kankar	24-39	15
6.	Fine Sand and Sand Stone	39-45	6
7.	Clay and Kankar	45-55.5	10.5
8.	Fine to Medium Sand	55.5-87	31.5
9.	Clay	87-93	6
LOCATION: KANDHLA			
TUBE WELL NO: 18 (NL)			
1.	Clay	0-5.7	5.7
2.	Fine to Medium Sand	5.7-24	18.3
3.	Clay and Kankar	24-38.4	14.4
4.	Fine Sand	38.4-46.5	8.1
5.	Clay	46.5-48	1.5
6.	Medium to Coarse Sand	48-75	27
7.	Hard Clay and Kankar	75-92.7	17.7
8.	Coarse to Medium Sand	92.7-104.1	11.4
9.	Sandy Clay	104.1-105	0.9
LOCATION: TODA			
TUBE WELL NO.51 (KG)			
1.	Surface sand	0.00-3.05	3.05
2.	Sand brownish, med grained	3.05-6.10	3.05
3.	Clay and Kankar	6.10-33.53	27.43
4.	Fine brownish sand	33.63-42.67	9.14
5.	Sand medium grained	42.67-53.34	10.67
6.	Clay	53.34-54.86	1.52
7.	Fine to medium grained Sand	54.86-60.96	6.10
8.	Clay	60.96-73.15	12.19
9.	Sand medium grained	73.15-96.32	23.17
10.	Clay and Kankar	96.52-101.52	5.28

S.No.	Lithology	Depth (m)	Thickness (m)
LOCATION: UN			
TUBE WELL NO.22 (KG)			
1.	Surface clay	0.00-3.05	3.05
2.	Sand, fine brownish	3.05-6.10	3.05
3.	Clay	6.10-9.14	3.04
4.	Sand fine	9.14-15.24	6.10
5.	Sand fine to medium	15.24-21.34	6.10
6.	Sand fine	21.34-27.43	6.09
7.	Clay & Kankar	27.43-30.48	3.05
8.	Sand medium	30.48-36.58	6.10
9.	Sand coarse	36.58-42.67	6.09
10.	Sand medium with pebbles	42.67-45.72	3.05
11.	Clay	45.72-47.24	1.52
12.	Sand indurated	47.24-51.82	4.58
13.	Sand fine to medium	51.82-54.86	3.04
14.	Clay & Kankar	54.86-57.91	3.05
15.	Sand medium with Kankar	57.91-60.96	3.05
16.	Sand medium with pebbles	60.96-63.40	2.44
17.	Clay and Kankar	63.40-73.76	10.36
18.	Sand fine to medium	73.76-79.25	5.49
19.	Clay	79.25-82.30	3.66
20.	Sand fine to medium	82.30-87.78	5.48
21.	Clay	87.78-91.44	3.66
22.	Sand medium	91.44-94.49	3.05
23.	Sand medium	94.49-96.93	2.44
24.	Clay	96.93-100.58	3.65
LOCATION: MALAINDI			
WELL NO.30 (KG)			
1.	Clay	0.00-6.10	6.10
2.	Lahel & Kankar	6.10-9.14	3.04
3.	Sand fine	9.14-10.36	1.22
4.	Clay	10.36-12.19	1.83
5.	Lahel	12.19-15.24	3.05
6.	Sand fine	15.24-23.77	8.53
7.	Clay	23.77-26.82	3.05
8.	Clay hard with kankar	26.82-31.09	4.27
9.	Sand fine	31.09-37.19	6.10
10.	Sand medium	37.19-44.81	7.62
11.	Sand fine	44.81-49.68	4.87
12.	Clay hard	49.68-53.64	3.96
13.	Sand fine	53.64-56.08	3.44
14.	Sand fine to medium	56.08-59.13	3.05
15.	Sand medium with pebbles	59.13-61.57	2.44
16.	Clay hard	61.57-64.62	3.05
17.	Clay hard with Kankar	64.62-68.88	4.26
18.	Sand fine yellowish	68.88-74.98	6.10
19.	Sand fine with indurated sand	74.98-77.42	2.44
LOCATION: SAUHANJINI			
TUBE WELL NO. 59			
1.	Surface clay	0.00-3.05	3.05
2.	Sand fine	3.05-6.10	3.05

S.No.	Lithology	Depth (m)	Thickness (m)
3.	Clay & Kankar	6.10-24.38	18.28
4.	Sand medium	24.38-30.48	6.10
5.	Clay & Kankar	30.48-36.58	6.10
6.	Sand medium to coarse with pebble	36.58-48.77	12.19
7.	Sand medium to coarse	48.77-54.86	6.09
8.	Clay	54.86-56.39	1.53
9.	Sand medium	56.39-67.06	10.67
10.	Sand medium with pebbles	67.06-70.10	3.04
11.	Clay	70.10-76.20	6.10
12.	Sand fine	76.20-79.25	3.05
13.	Clay	79.25-85.34	6.09
14.	Clay loose	85.34-89.61	3.25

LOCATION: JALALBAD
TUBE WELL NO. 2

1.	Clay	0.00-8.84	8.84
2.	Sand fine with Kankar	8.84-20.73	11.89
3.	Sand fine to medium	20.73-23.77	3.04
4.	Sand medium with Kankar	23.77-26.52	2.75
5.	Sand fine	26.52-29.57	3.05
6.	Clay	29.57-35.66	6.09
7.	Sand fine	35.66-41.45	5.79
8.	Sand medium	41.45-44.50	3.05
9.	Clay	44.50-56.39	11.89
10.	Sand fine to medium	56.39-59.44	3.05
11.	Clay	59.44-64.01	4.57
12.	Sand medium to coarse	64.01-69.80	5.79
13.	Clay and Kankar	69.80-74.07	4.27
14.	Sand fine Yellowish	74.07-79.86	5.79
15.	Sand medium with pebbles	79.86-91.44	11.58
16.	Clay	91.44-97.54	6.10

LOCATION: BARNAWI
TUBE WELL NO: 42(KG)

1.	Clay	0-3	3
2.	Medium sand with Gravel	3-12	9
3.	Clay and Kankar	12-15	3
4.	Medium Sand and Kankar	15-21	6
5.	Clay and kankar	21-24	3
6.	Hard Clay	24-30	6
7.	Clay Kankar	30-33	3
8.	Hard Clay	33-36	3
9.	Clay and Kankar	36-37.5	1.5
10.	Medium Sand	37.5-52.5	15
11.	Hard Clay	52.5-58.5	6
12.	Medium Sand and Sandstone	58.5-82.5	24
13.	Clay and kankar	82.5-88.2	5.7

S.No.	Lithology	Depth (m)	Thickness (m)
LOCATION: FATEHPUR			
TUBE WELL NO: 37(NL)			
1.	Surface Clay	0-3	3
2.	Clay and kankar	3-6	3
3.	Fine Sand	6-9	3
4.	Clay and Kankar	9-21	12
5.	Sand and kankar	21-24	3
6.	Clay and kankar	24-29.4	5.4
7.	Fine to Medium sand	29.4-36	6.6
8.	Medium Sand and Kankar	36-39	3
9.	Medium to Fine Sand	39-49.5	10.5
10.	Clay and Kankar	49.5-50.5	1.5
11.	Fine to Coarse to Medium Sand	50.5-73	22.5
12.	Clay and Kankar	73-74.5	1.5
13.	Clay	74.5-77.5	3
14.	Clay and kankar	77.5-83.5	6
LOCATION: JAGANPUR			
TUBE WELL NO. 12 K G			
1.	CLAY	0-5.4	5.4
2.	Clay and Bajri	5.4-11.10	5.7
3.	Fine sand	11.10-21.6	10.5
4.	Clay	21.6-23.7	2.1
5.	Medium Sand	23.7-36.0	12.3
6.	Fine to coarse sand & Pebble	36.0-53.7	17.7
7.	Hard clay and Kankar	53.7-61.2	7.5
8.	Medium sand	61.2-67.5	6.3
9.	Lahel	67.5-73.2	6
10.	Clay	73.2-74.7	1.5
11.	Fine sand	74.7-83.4	8.7
LOCATION: BHOORA			
TUBE WELL NO. 3 KG			
1.	Surface Clay	0-3	3
2.	Fine to medium sand	3-17.5	14.5
3.	Clay with Kankar	17.5-27	9.5
4.	Fine-coarse sand with sandstone	27-40.9	13.5
5.	Fine to med. Sand with gravel and pebbles	40.9-58.6	17.7
6.	Clay and Kankar	58.6-64.3	5.7
7.	Medium sand	64.3-68.5	4.2
8.	Clay and Kankar	68.5-73.6	5.1
9.	Fine sand with Kankar	73.6-83.5	10
10.	Clay with Kankar	83.5-86.5	3
11.	Medium sand with sandstone	86.5-91.3	4.8
12.	Caving Clay with Kankar	91.3-102.1	10.8
LOCATION: BANAT			
TUBE WELL NO. 67 NL			
1.	Surface Clay	0-4.8	4.8
2.	Fine sand with Kankar	4.8-10.5	5.7

S.No.	Lithology	Depth (m)	Thickness (m)
3.	Clay with Kankar	10.5-15.0	4.5
4.	Fine sand	15-21	6
5.	Clay with Kankar	21-33	12
6.	Medium sand	33-43.8	10.8
7.	Clay and Kankar	43.8-52.5	8.7
8.	Very fine sand	52.5-55.5	3
9.	Hard Clay	55.5-61.5	6
10.	Kankar	61.5-63	1.5
11.	Medium sand with pebbles	63-72	9
12.	Clay and Kankar	72-77.4	5.4
13.	Fine to medium sand	77.4-88.2	10.8
14.	Clay and Kankar	88.2-93	4.8
LOCATION: BHABHISA			
TUBE WELL NO. 86			
1.	Surface Clay	0.00-3.05	3.05
2.	Fine Sand	3.05-9.14	6.09
3.	Clay	9.14-12.19	3.05
4.	Fine Sand	12.19-15.24	3.05
5.	Clay and Kankar	15.24-27.43	12.19
6.	Fine Sand	27.43-30.48	3.05
7.	Medium Sand	30.48-41.15	10.67
8.	Clay	41.15-45.72	4.57
9.	Medium Sand	45.72-64.01	18.29
10.	Sand medium to coarse with pebble	64.01-70.1	6.09
11.	Medium Sand	70.1-76.2	6.1
12.	Clay and kankar	76.2-83.52	7.32
LOCATION: KHANPUR			
TUBE WELL NO.75 NL			
1.	Clay	0-3	3
2.	Clay and Kankar	3-9	6
3.	Fine to medium sand	9.21	12
4.	Clay and Kankar	21-27	6
5.	Fine to medium sand	27-46.5	19.5
6.	Clay and kankar	46.5-53.4	6.9
7.	Fine to medium to coarse sand	53.4-67.5	14.1
8.	Clay and Kankar	67.5-78	10.5
9.	Fine to medium sandstone & sand	78-84.6	6.6
10.	Clay and Kankar	84.6-88.2	3.6

APPENDIX IV A
Well Inventoried for water level monitoring (November 2005)

S.No.	Location	Latitudes	Longitudes	RL	H MP	WL	BGL	AMSL
1	Banat	$29^0 27' 59''$	$77^0 21'$	242	1.2	16.3	15.1	226.9
2	Sikka	$29^0 30' 24''$	$77^0 21' 53''$	244.82	0.9	13.1	12.2	232.62
3	Hind	$29^0 31' 52''$	$77^0 22' 55''$	245	2.2	16.9	14.7	230.3
4	Kaidi	$29^0 30' 25''$	$77^0 24' 21''$	244	0.7	13.74	13.04	230.96
5	Sonta Rasulpur	$29^0 31' 56''$	$77^0 24' 24''$	244.98	0.64	13.37	12.73	232.25
6	Thana Bhawan	$29^0 35' 35''$	$77^0 25' 19''$	248.74	0.5	8.6	8.1	240.64
7	Jalalabad	$29^0 37' 25''$	$77^0 26' 14''$	251.97	0.8	9.08	8.28	243.69
8	Chandelmal	$29^0 39' 11''$	$77^0 27' 13''$	254.22	0.2	7	6.8	247.42
9	Dulawa	$29^0 38' 53''$	$77^0 24' 21''$	252	0.2	7.16	6.96	245.04
10	Khanpur	$29^0 36' 41''$	$77^0 24' 08''$	249	0.9	9.28	8.38	240.62
11	Goharni	$29^0 28' 46''$	$77^0 18' 50''$	243	0.75	12.3	11.55	231.45
12	Bhainswal	$29^0 31' 00''$	$77^0 19' 16''$	248	0.72	10.13	9.41	238.59
13	Jhandheri	$29^0 32' 21''$	$77^0 19' 58''$	247	0.88	8.44	7.56	239.44
14	Garhi Pukhta	$29^0 32' 46''$	$77^0 18' 37''$	247	0.72	12.24	11.52	235.48
15	Dulla Kheri	$29^0 35' 25''$	$77^0 19' 12''$	249	0.9	12.2	11.3	237.7
16	Bunta	$29^0 36' 44''$	$77^0 20' 21''$	253	1	10.03	9.03	243.97
17	Garhi Abdullah Khan	$29^0 38' 29''$	$77^0 19' 14''$	253.66	0.47	12.53	12.06	241.6
18	Gandewra	$29^0 38' 28''$	$77^0 19' 14.6''$	254	-2.65	3.6	6.25	247.75
19	Bhanera Uda	$29^0 37' 16.5''$	$77^0 22' 06''$	252	0.34	6.07	5.73	246.27
20	Yarpur	$29^0 35' 30''$	$77^0 22' 31''$	250.72	-2.86	3.92	6.78	243.94
21	Harhar Fatehpur	$29^0 32' 56''$	$77^0 23' 38.9''$	249	1.05	12.8	11.75	237.25
22	Un	$29^0 34' 55.8''$	$77^0 15' 00.5''$	248	0.75	15.3	14.55	233.45
23	Pindora	$29^0 36' 17.6''$	$77^0 17' 07.2''$	246	0.1	11.93	11.83	234.17
24	Sapla	$29^0 38' 29''$	$77^0 22' 55''$	248	0	13.1	13.1	234.9
25	Mundait	$29^0 38' 29''$	$77^0 16' 38''$	249	0	11.8	11.8	237.2
26	kheri khushnam	$29^0 39' 15.8''$	$77^0 15' 02''$	248.1	0.98	13.78	12.8	235.3
27	Garhi Hasanpur	$29^0 40' 14.1''$	$77^0 13' 08.2''$	247	0.63	15.6	14.97	232.03
28	Gagor	$29^0 36' 55''$	$77^0 15' 06''$	247	0.65	12.8	12.15	234.85
29	Chausana	$29^0 39' 41''$	$77^0 10' 24''$	247.34	0.46	12.04	11.58	235.76
30	Bhari	$29^0 40' 03''$	$77^0 09' 17.3''$	244	0.59	7.57	6.98	237.02
31	Sakauti	$29^0 37' 48''$	$77^0 09' 42''$	242	0.53	6.95	6.42	235.58
32	Kertu	$29^0 34' 07.6''$	$77^0 09' 10.6''$	249	0.42	9.76	9.34	239.66
33	Ulahni	$29^0 35' 54.4''$	$77^0 10' 26.5''$	249	0.8	13.44	12.64	236.36
34	Todda	$29^0 37' 26.4''$	$77^0 11' 44.3''$	249	0.62	13.2	12.58	236.42
35	Titoli	$29^0 28' 07''$	$77^0 16' 18''$	243	0.85	16.23	15.38	227.62
36	Badheo	$29^0 29' 10''$	$77^0 17' 22''$	243	0.4	14.7	14.3	228.7
37	Malindi	$29^0 30' 28.2''$	$77^0 17' 26''$	241	0.92	12.36	11.44	229.56
38	Purmafi	$29^0 32' 42''$	$77^0 16' 14''$	245	0.55	16.35	15.8	229.2
39	Taprana	$29^0 29' 17''$	$77^0 15' 20''$	244.64	0.53	18.45	17.92	226.72
40	Jinjhana	$29^0 30' 43.1''$	$77^0 13' 19.9''$	240.79	0.67	15.43	14.76	226.03
41	Rangana	$29^0 33' 38.4''$	$77^0 13' 13.5''$	244	0.72	15.07	14.35	229.65
42	Bipur jalalpur	$29^0 31' 52''$	$77^0 11' 05''$	244	0.43	11.76	11.33	232.67
43	Mansura	$29^0 31' 16.2''$	$77^0 08' 38.6''$	237.6	0.22	6.87	6.65	230.95
44	Yusufpur choutra	$29^0 31' 52.3''$	$77^0 06' 54.2''$	238	0.1	4.42	4.32	233.68
45	Barla Jat	$29^0 25' 06''$	$77^0 21' 08.6''$	240	0.65	18.55	17.9	222.1
46	Salpa	$29^0 22' 41.5''$	$77^0 19' 33.8''$	239	0.68	14.84	14.16	224.84
47	Makhmulpur	$29^0 20' 18.4''$	$77^0 19' 11.3''$	239	0.00	14.47	14.47	224.53
48	Bhabhisa	$29^0 18' 30''$	$77^0 19' 24''$	234.65	0.76	17.45	16.69	217.96

49	Bhanera	29°16′26.3″	77°19′02.6″	230	1	13.7	12.7	217.3
50	Nala	29°16′58.1″	77°16′38.7″	237	0.61	12.51	11.9	225.1
51	Malakpur	29°21′09.4″	77°15′50.4″	238	0.68	11.05	10.37	227.63
52	Pauti kalan	29°29′11.7″	77°12′36.1″	240	0.5	22.46	21.96	218.04
53	Akbarpur Sunethi	29°29′05.1″	77°09′25.6″	237.84	0.76	10.75	9.99	227.85
54	Khurgyan	29°27′19.4″	77°09′22.7″	234.43	0.6	10.45	9.85	224.58
55	Khera	29°24′51.9″	77°09′41.6″	233	0.65	10	9.35	223.65
56	Mawi	29°22′39.7″	77°09′17.7″	230	0.1	5.26	5.16	224.84
57	Saipat	29°20′28.8″	77°09′58″	234	0.75	10.43	9.68	224.32
58	Issapur teel	29°18′13.2″	77°10′29.9″	235	0.78	11.35	10.57	224.43
59	Titarwara	29°20′34.9″	77°11′15.9″	237	0.85	14.35	13.5	223.5
60	Jharkhedi	29°22′22.1″	77°11′50.1″	240	0.75	16.95	16.2	223.8
61	kairana	29°23′50.3″	77°12′49″	236.02	0.75	16.65	15.9	220.12
62	Kandela	29°25′44.8″	77°14′40.8″	243.03	0.85	17.62	16.77	226.26
63	Bhoora	29°27′00.6″	77°12′34.5″	241.55	0.75	17.98	17.23	224.32
64	Kaserwa Khurd	29°27′36.5″	77°15′23.8″	244	0.85	18.45	17.6	226.4
65	Khandrauli	29°23′12″	77°16′49″	240.59	0.45	11.75	11.3	229.29
66	Lilaun	29°25′39″	77°17′28.5″	238.45	0.6	13.2	12.6	225.85
67	Erti	29°24′25″	77°15′43″	241	0.55	15.8	15.25	225.75
68	Gangeru	29°18′42″	77°13′9.5″	237.63	0.59	14.65	14.06	223.57
69	Unchagaon	29°21′28″	77°13′48″	238.36	0.65	17.89	17.24	221.12
70	Shamli	29°27′10.9″	77°18′37.9″	241.38	0.65	14.96	14.31	227.07
71	Kandhla	29°19′15″	77°16′52″	237.89	0.65	13.85	13.2	224.69

APPENDIX IV B
Water level monitoring data (June 2006)

S.No.	Location	X	Y	RL	H MP	WL	BGL	AMSL
1	Banat	25705	22636	242	1.2	18.2	17	225
2	Sikka	26597	27450	244.82	0.9	15.2	14.3	230.52
3	kaidi	30428	26996	244	0.25	15.2	14.95	229.05
4	Sonta Rasulpur	31058	30293	244.98	0.25	14.95	14.7	230.28
5	Thana Bhawan	31584	35608	248.74	0.35	10.5	10.15	238.59
6	Jalalabad	33281	39639	251.97	0.25	10.9	10.65	241.32
7	Chandelmal	35054	43432	254.22	0.2	8.3	8.1	246.12
8	Dulawa	30595	42510	252	0.2	8.36	8.16	243.84
9	Khanpur	30082	38562	249	0.9	10.58	9.68	239.32
10	Goharni	22328	24445	243	0.75	13.95	13.2	229.8
11	Jhandheri	24138	31449	247	0.88	9.55	8.67	238.33
12	Garhi Pukhta	21038	31663	247	0.72	13.95	13.23	233.77
13	Dulla Kheri	22273	36141	249	0.9	12.7	11.8	237.2
14	Bunta	23839	38730	253	1	11	10	243
15	Garhi Abdullah	21950	41946	253.66	0.47	14.1	13.63	240.03
16	Bhanera Uda	27113	39579	252	0.34	7.25	6.91	245.09
17	Harhar Fatehpur	29479	32109	249	1.05	14.25	13.2	235.8
18	Un	16427	35483	248	0.75	17.25	16.5	231.5
19	Pindora	19412	37471	246	0.1	12.3	12.2	233.8
20	Mundait	18656	42182	249	0	13.2	13.2	235.8
21	kheri khushnam	15730	43176	248.1	1.1	15.5	14.4	233.7
22	Garhi Hasanpur	12535	44703	247	0.63	17.13	16.5	230.5
23	Chausana	9046	44039	247.34	0.65	13.65	13	234.34
24	Bhari	5774	44319	244	0.59	8.45	7.86	236.14

25	Ulahni	8711	37107	249	0.8	15.15	14.35	234.65
26	Todda	10599	39414	249	0.62	14.3	13.68	235.32
27	Titoli	18085	23240	243	0.85	17.95	17.1	225.9
28	Badheo	20048	25416	243	0.4	16.15	15.75	227.25
29	Taprana	16786	25413	244.64	0.53	20.3	19.77	224.87
30	Jinjhana	13681	28708	240.79	0.67	17.05	16.38	224.41
31	Rangana	13086	33364	244	0.72	16.67	15.95	228.05
32	Bipur jalalpur	9377	29739	242.2	0.43	12.72	12.29	229.91
33	Mansura	5930	28500	237.6	0.22	7.8	7.58	230.02
34	Yusufpur choutra	3047	29972	238	0.1	5.86	5.76	232.24
35	Barla Jat	25514	17993	240	0.25	20.65	20.4	219.6
36	Salpa	23235	13333	239	0.68	16.36	15.68	223.32
37	Makhmulpur	22947	9178	239	0	16.1	16.1	222.9
38	Bhabhisa	22964	6184	236.65	0.76	17.6	16.84	219.81
39	Bhanera	22419	2518	232	1	13.7	12.7	219.3
40	Nala	18491	3266	237	0.61	13.68	13.07	223.93
41	Malakpur	17643	10743	238	0.68	12.65	11.97	226.03
42	Pauti kalan	11490	25654	241	0.5	22.46	21.96	219.04
43	Akbarpur Sunethi	7011	25047	237.84	0.76	12.25	11.49	226.35
44	Khurgyan	7068	20783	234.43	0.6	11.95	11.35	223.08
45	Khera	7138	17550	233	0.65	11.35	10.7	222.3
46	Mawi	7249	13492	230	0.1	6.3	6.2	223.8
47	Saipat	8179	9899	234	0.75	11.98	11.23	222.77
48	Jharkhedi	11188	13157	240	0.75	18.56	17.81	222.19
49	kairana	12475	16137	237.02	0.75	18.85	18.1	218.92
50	Kandela	15150	19570	243.03	0.5	19.56	19.06	223.97
51	Bhoora	12011	21639	241.55	0.75	20.15	19.4	222.15
52	Kaserwa Khurd	16630	22170	244	0.85	19.76	18.91	225.09
53	Khandrauli	19017	14645	238.59	0.45	12.25	11.8	226.79
54	Lilaun	20154	18440	238.45	0.6	13.8	13.2	225.25
55	Erti	17007	16592	241	0.55	15.8	15.25	225.75
56	Gangeru	12888	6665	237.63	0.59	15.75	15.16	222.47
57	Unchagaon	13769	11252	238.36	0.65	19.05	18.4	219.96
58	Shamli	21731	21615	241.38	0.65	16.28	15.63	225.75
59	Kandhla	16830	7425	237.89	0.65	13.85	13.2	224.69
60	Garhi Rakha	10500	4650	236	0.53	14.32	13.79	222.21

APPENDIX IV C
Water level monitoring data (November 2006)

S.No.	Location	x	y	RL	H MP	WL	BGL	AMSL
1	Banat	25705	22636	242	1.2	16.85	15.65	226.35
2	Sikka	26597	27450	244.82	0.9	15.65	14.75	230.07
3	kaidi	30428	26996	244	0.74	15.35	14.61	229.39
4	Sonta Rasulpur	31058	30293	244.98	0.25	14.1	13.85	231.13
5	Thana Bhawan	31584	35608	248.74	0.35	9.51	9.16	239.58
6	Jalalabad	33281	39639	251.97	0.66	9.4	8.74	243.23
7	Chandelmal	35054	43432	254.22	0.2	7.27	7.07	247.15
8	Dulawa	30595	42510	252	0.2	7.4	7.2	244.8
9	Khanpur	30082	38562	249	0.9	9.6	8.7	240.3
10	Goharni	22328	24445	243	0.75	12.7	11.95	231.05
11	Jhandheri	24138	31449	247	0.45	9.5	9.05	237.95

12	Garhi Pukhta	21038	31663	247	0.72	13.55	12.83	234.17
13	Dulla Kheri	22273	36141	249	0.9	12.3	11.4	237.6
14	Bunta	23839	38730	253	1	10.55	9.55	243.45
15	Garhi Abdullah	21950	41946	253.66	0.47	13.7	13.23	240.43
16	Bhanera Uda	27113	39579	252	0.69	7.4	6.71	245.29
17	Harhar Fatehpur	29479	32109	249	1.05	13.9	12.85	236.15
18	Un	16427	35483	248	0.75	16.65	15.9	232.1
19	Pindora	19412	37471	246	0.1	12.15	12.05	233.95
20	Mundait	18656	42182	249	0	13.65	13.65	235.35
21	kheri khushnam	15730	43176	248.1	0.85	15.35	14.5	233.6
22	Garhi Hasanpur	12535	44703	247	0.63	16.53	15.9	231.1
23	Chausana	9046	44039	247.34	0.65	12.78	12.13	235.21
24	Bhari	5774	44319	244	0.59	7.85	7.26	236.74
25	Ulahni	8711	37107	249	0.8	13.85	13.05	235.95
26	Todda	10599	39414	249	0.62	13.8	13.18	235.82
27	Titoli	18085	23240	243	0.85	17.15	16.3	226.7
28	Badheo	20048	25416	243	0.4	15.1	14.7	228.3
29	Taprana	16786	25413	244.64	0.53	19.4	18.87	225.77
30	Jinjhana	13681	28708	240.79	0.67	17.45	16.78	224.01
31	Rangana	13086	33364	244	0.72	16.9	16.18	227.82
32	Bipur jalalpur	9377	29739	242.2	0.43	12.9	12.47	229.73
33	Mansura	5930	28500	237.6	0.22	7.4	7.18	230.42
34	Yusufpur choutra	3047	29972	238	0.52	5.7	5.18	232.82
35	Barla Jat	25514	17993	240	0.55	19.66	19.11	220.89
36	Salpa	23235	13333	239	0.68	13.98	13.3	225.7
37	Makhmulpur	22947	9178	239	0.65	15.71	15.06	223.94
38	Bhabhisa	22964	6184	236.65	0.76	17.7	16.94	219.71
39	Bhanera	22419	2518	232	0.75	14.13	13.38	218.62
40	Nala	18491	3266	237	0.82	12.87	12.05	224.95
41	Malakpur	17643	10743	238	0.68	10	9.32	228.68
42	Pauti kalan	11490	25654	241	0.6	21.62	21.02	219.98
43	Akbarpur Sunethi	7011	25047	237.84	0.76	11.85	11.09	226.75
44	Khurgyan	7068	20783	234.43	0.2	10.62	10.42	224.01
45	Khera	7138	17550	233	0.65	10.3	9.65	223.35
46	Mawi	7249	13492	230	0.29	5.68	5.39	224.61
47	Saipat	8179	9899	234	0	10.02	10.02	223.98
48	Jharkhedi	11188	13157	240	1	20.64	19.64	220.36
49	kairana	12475	16137	237.02	0.75	18.14	17.39	219.63
50	Kandela	15150	19570	243.03	0.62	19.55	18.93	224.1
51	Bhoora	12011	21639	241.55	0.75	19.45	18.7	222.85
52	Kaserwa Khurd	16630	22170	244	0.85	18.87	18.02	225.98
53	Khandrauli	19017	14645	238.59	0.1	10.5	10.4	228.19
54	Lilaun	20154	18440	238.45	0.13	13.1	12.97	225.48
55	Erti	17007	16592	241	0.55	16.28	15.73	225.27
56	Gangeru	12888	6665	237.63	0.65	14.07	13.42	224.21
57	Unchagaon	13769	11252	238.36	0.65	18.98	18.33	220.03
58	Shamli	21731	21615	241.38	0.83	16.65	15.82	225.56
59	Kandhla	16830	7425	237.89	0.65	14.25	13.6	224.29
60	Garhi Rakha	10500	4650	236	0.53	13.52	12.99	223.01

APPENDIX IV D
Water level monitoring data (June 2007)

S.No.	Location	X	Y	RL	H MP	WL	BGL	AMSL
1	Banat	25705	22636	242	1.2	18.43	17.23	224.77
2	Sikka	26597	27450	244.82	0.9	16.88	15.98	228.84
3	Kaidi	30428	26996	244	0.7	12.72	12.02	231.98
4	Sonta Rasulpur	31058	30293	244.98	0.64	14.97	14.33	230.65
5	Thana Bhawan	31584	35608	248.74	0.5	10.21	9.71	239.03
6	Jalalabad	33281	39639	251.97	0.55	10.27	9.72	242.25
7	Chandelmal	35054	43432	254.22	0.2	7.91	7.71	246.51
8	Dulawa	30595	42510	252	0.25	9.68	9.43	242.57
9	Khanpur	30082	38562	249	0.9	10.65	9.75	239.25
10	Goharni	22328	24445	243	0.36	10.1	9.74	233.26
11	Jhandheri	24138	31449	247	0.45	10.4	9.95	237.05
12	Garhi Pukhta	21038	31663	247	0.72	13.98	13.26	233.74
13	Dulla Kheri	22273	36141	249	0.9	13.05	12.15	236.85
14	Bunta	23839	38730	253	1	11.32	10.32	242.68
15	Garhi Abdullah	21950	41946	253.66	0.51	14.78	14.27	239.39
16	Bhanera Uda	27113	39579	252	0.08	7.29	7.21	244.79
17	Harhar Fatehpur	29479	32109	249	1.05	14.75	13.7	235.3
18	Un	16427	35483	248	0.75	17.95	17.2	230.8
19	Pindora	19412	37471	246	0.65	13.8	13.15	232.85
20	Mundait	18656	42182	249	0	14.34	14.34	234.66
21	kheri khushnam	15730	43176	248.1	0.85	15.35	14.5	233.6
22	Garhi Hasanpur	12535	44703	247	0.4	17.64	17.24	229.76
23	Chausana	9046	44039	247.34	0.58	15.18	14.6	232.74
24	Bhari	5774	44319	244	0.25	7.85	7.6	236.4
25	Ulahni	8711	37107	249	0.8	15.79	14.99	234.01
26	Todda	10599	39414	249	0.4	14.45	14.05	234.95
27	Titoli	18085	23240	243	0.85	17.87	17.02	225.98
28	Badheo	20048	25416	243	0.4	17.15	16.75	226.25
29	Taprana	16786	25413	244.64	0.53	20.71	20.18	224.46
30	Jinjhana	13681	28708	240.79	0.67	17.6	16.93	223.86
31	Rangana	13086	33364	244	0.72	17.23	16.51	227.49
32	Bipur jalalpur	9377	29739	242.2	0.43	15.5	15.07	227.13
33	Mansura	5930	28500	237.6	0.22	7.61	7.39	230.21
34	Yusufpur choutra	3047	29972	238	0.3	4.92	4.62	233.38
35	Barla Jat	25514	17993	240	0.3	17.84	17.54	222.46
36	Salpa	23235	13333	239	0.5	13.97	13.47	225.53
37	Makhmulpur	22947	9178	239		17.64	17.64	221.36
38	Bhabhisa	22964	6184	236.65	0.75	18.47	17.72	218.93
39	Bhanera	22419	2518	232	0.75	14.85	14.1	217.9
40	Nala	18491	3266	237	0.82	15.72	14.9	222.1
41	Malakpur	17643	10743	238	0.68	12.85	12.17	225.83
42	Pauti kalan	11490	25654	241	0.76	21.9	21.14	219.86
43	Akbarpur Sunethi	7011	25047	237.84	1	13.15	12.15	225.69
44	Khurgyan	7068	20783	234.43	0.68	13.1	12.42	222.01
45	Khera	7138	17550	233	0.65	11.4	10.75	222.25
46	Mawi	7249	13492	230	0.2	6.1	5.9	224.1
47	Saipat	8179	9899	234	0	10.25	10.25	223.75
48	Jharkhedi	11188	13157	240	1	21.85	20.85	219.15
49	Kairana	12475	16137	237.02	0.8	19.68	18.88	218.14

50	Kandela	15150	19570	243.03	0.62	19.84	19.22	223.81
51	Bhoora	12011	21639	241.55	0.8	20.33	19.53	222.02
52	Kaserwa Khurd	16630	22170	244	0.85	19.15	18.3	225.7
53	Khandrauli	19017	14645	238.59	0.12	12.6	12.48	226.11
54	Lilaun	20154	18440	238.45	1	15.9	14.9	223.55
55	Erti	17007	16592	241	0.45	17	16.55	224.45
56	Gangeru	12888	6665	237.63	0.6	15.28	14.68	222.95
57	Unchagaon	13769	11252	238.36	0.65	19.75	19.1	219.26
58	Shamli	21731	21615	241.38	0.65	17.65	17	224.38
59	Kandhla	16830	7425	237.89	0.7	15.4	14.7	223.19
60	Garhi Rakha	10500	4650	236	0.5	14.85	14.35	221.65

APPENDIX IV E
Water level monitoring data (November 2007)

S.No.	Location	X	Y	RL	H MP	WL	BGL	AMSL
1	Banat	25705	22636	242	1.2	19.62	18.42	223.58
2	Sikka	26597	27450	244.82	0.9	17	16.1	228.72
3	Kaidi	30428	26996	244	0.7	15.73	15.03	228.97
4	Sonta Rasulpur	31058	30293	244.98	0.64	15.57	14.93	230.05
5	Thana Bhawan	31584	35608	248.74	0.5	10.55	10.05	238.69
6	Jalalabad	33281	39639	251.97	0.55	10.42	9.87	242.1
7	Chandelmal	35054	43432	254.22	0.2	7.95	7.75	246.47
8	Dulawa	30595	42510	252	0.9	9.94	9.04	242.96
9	Khanpur	30082	38562	249	0.9	10.82	9.92	239.08
10	Goharni	22328	24445	243	0.93	11.2	10.27	232.73
11	Jhandheri	24138	31449	247	0.45	10.74	10.29	236.71
12	Garhi Pukhta	21038	31663	247	0.72	13.57	12.85	234.15
13	Dulla Kheri	22273	36141	249	0.82	13.02	12.2	236.8
14	Bunta	23839	38730	253	0.9	11.3	10.4	242.6
15	Garhi Abdullah	21950	41946	253.66	0.51	15.12	14.61	239.05
16	Bhanera Uda	27113	39579	252	0.08	6.95	6.87	245.13
17	Harhar Fatehpur	29479	32109	249	1.05	15.11	14.06	234.94
18	Un	16427	35483	248	0.75	19.94	19.19	228.81
19	Pindora	19412	37471	246	0.65	13.7	13.05	232.95
20	Mundait	18656	42182	249	0	14.3	14.3	234.7
21	kheri khushnam	15730	43176	248.1	0.6	15.15	14.55	233.55
22	Garhi Hasanpur	12535	44703	247	0.4	17.29	16.89	230.11
23	Chausana	9046	44039	247.34	0.58	15.37	14.79	232.55
24	Bhari	5774	44319	244	0.25	8.21	7.96	236.04
25	Ulahni	8711	37107	249	0.8	16.39	15.59	233.41
26	Todda	10599	39414	249	0.4	12.33	11.93	237.07
27	Titoli	18085	23240	243	0.85	18.34	17.49	225.51
28	Badheo	20048	25416	243	0.4	17.14	16.74	226.26
29	Taprana	16786	25413	244.64	0.68	18.78	18.1	226.54
30	Jinjhana	13681	28708	240.79	0.65	18.12	17.47	223.32
31	Rangana	13086	33364	244	0.7	18.68	17.98	226.02
32	Bipur jalalpur	9377	29739	242.2	0.52	13.65	13.13	229.07
33	Mansura	5930	28500	237.6	0.22	7.41	7.19	230.41
34	Yusufpur choutra	3047	29972	238	0.3	5.2	4.9	233.1
35	Barla Jat	25514	17993	240	0.3	18.89	18.59	221.41

36	Salpa	23235	13333	239	0.5	14.48	13.98	225.02
37	Makhmulpur	22947	9178	239	0	17.34	17.34	221.66
38	Bhabhisa	22964	6184	236.65	0.75	18.7	17.95	218.7
39	Bhanera	22419	2518	232	0.75	14.12	13.37	218.63
40	Nala	18491	3266	237	0.82	16.22	15.4	221.6
41	Malakpur	17643	10743	238	0.68	12.31	11.63	226.37
42	Pauti kalan	11490	25654	241	0.76	22.29	21.53	219.47
43	Akbarpur Sunethi	7011	25047	237.84	1	13.67	12.67	225.17
44	Khurgyan	7068	20783	234.43	0.2	10.05	9.85	224.58
45	Khera	7138	17550	233	0.65	11.32	10.67	222.33
46	Mawi	7249	13492	230	0.29	6.08	5.79	224.21
47	Saipat	8179	9899	234	0	10.74	10.74	223.26
48	Jharkhedi	11188	13157	240	1.26	22.48	21.22	218.78
49	Kairana	12475	16137	237.02	0.8	19.53	18.73	218.29
50	Kandela	15150	19570	243.03	0.62	20.33	19.71	223.32
51	Bhoora	12011	21639	241.55	0.8	20.89	20.09	221.46
52	Kaserwa Khurd	16630	22170	244	0.85	19.65	18.8	225.2
53	Khandrauli	19017	14645	238.59	0.12	12.05	11.93	226.66
54	Lilaun	20154	18440	238.45	1	16.2	15.2	223.25
55	Erti	17007	16592	241	0.45	17.25	16.8	224.2
56	Gangeru	12888	6665	237.63	0.6	15.66	15.06	222.57
57	Unchagaon	13769	11252	238.36	0.65	20.21	19.56	218.8
58	Shamli	21731	21615	241.38	0.78	17.82	17.04	224.34
59	Kandhla	16830	7425	237.89	0.7	15.9	15.2	222.69
60	Garhi Rakha	10500	4650	236	0.5	15.65	15.15	220.85

APPENDIX V A
Well Hydrographs data in non command area (Source: UPSGWD)

Year	Bhoora	Kandela	Kairana	Khurgyan	Mawi	Titoli	Toda	Gangeru
Jun-99	9.55		11.58					8.81
Nov-99	8.95		11.07				8.54	8.37
Jun-00	10.3		12.33				10.19	10.08
Nov-00	10.23		12.22				9.53	10.07
Jun-01	11.8	13.98	13.58	8.11	3.64	8.89	10	12
Nov-01	10.7	12.78	12.57	8.07	3.72	7.89	9.33	11.02
Jun-02	12.45	14.52	14.55	9.78	3.82	10.7	12.15	14.63
Nov-02	11.9			9.7	3.6	10.5		14.1
Jun-03	13.2		15.25		5.14	12.3	13.07	14.64
Nov-03	12.4		15.06		3.03	11	10.5	13.9
Jun-04	14		16		4.85	10.9	12.6	13.9
Nov-04	14.55		15.73		4.36	10.56	11.31	12.5
Jun-05		18.51				14.9	14.17	
Nov-05	17.23	17.73	15.9	9.85	5.16	14.12	11.32	14.06
Jun-06	19.4	18.91	18.1	11.35	6.2	15.93	14.1	15.16
Nov-06	18.7	18.93	17.39	10.42	5.39	16.3	13.18	13.42
June-07	18.83	19.59	18.58	11.67	5.9	16.4	13.8	14.68

APPENDIX V B
Well Hydrographs data in command area (Source: UPSGWD)

Year	Kandhla	Bhabhisa	Thanabhawan	Jalalabad	Garhi Abdullah	Shamli
Jun-99	6.42	7.07	5.8	6.4		6.93
Nov-99	6.09	6.15		5.51	4.97	7.58
Jun-00	7.29	7.8	6.5	7.92	6.09	8.6
Nov-00	6.81	7.5	6.42	7.38	5.88	8.32
Jun-01	8.51	8.65	6.69	7.38	6.3	9.51
Nov-01	7.86	8.05	6.56	7.17	5.55	10.01
Jun-02		9.75	6.87	7.98		10.5
Nov-02		9.1	6.7	8.72		10.23
Jun-03		11.55	7.42	9.83	9.4	10.8
Nov-03			6.68	8.35	8.43	10.6
Jun-04			7.55	9.74	12.6	11.35
Nov-04			7.15	9.65	9.52	10.6
Jun-05			8.1	10.9		13
Nov-05	13.2	16.69	7.77	8.28	12.06	14.31
Jun-06	13.2	16.84	8.23	10.65	13.63	15.63
Nov-06	13.6	16.94	8.15	8.74	13.23	15.82
June-07	14.7	17.72	8.95	9.72	14.27	17

APPENDIX VI
Bimonthly water level monitoring data

S.No.	Location	Feb-07	Apr-07	Jun-07	Aug-07	Nov-07	Feb-08	Apr-08	Jun-08	Aug-08
1	Chandelmal	6.97	7.31	7.71	7.53	7.75	8.00	8.11	8.05	7.72
2	Goharni	8.95	9.41	9.74	9.68	10.27	10.75	11.22	11.38	10.79
3	Garhi Pukhta	11.71	12.78	13.26	12.32	12.85	13.66	13.58	13.88	13.77
4	Harhar Fatehpur	12.17	13.65	13.70	13.88	14.06	14.35	14.79	15.54	15.25
5	Chausana	12.34	14.35	14.60	15.02	14.79	15.47	15.70	15.75	15.44
6	Choutra	5.59	4.66	4.62	4.35	4.90	4.53	5.34	5.62	3.32
7	Bhanera	13.69	14.07	14.10	13.57	13.37	14.23	14.82	15.11	14.84
8	Malakpur	9.10	9.41	12.17		11.63	12.24	12.91	13.80	13.22
9	Khurgyan	8.77	9.04	12.42	9.95	9.85	9.60	9.94	10.20	9.95
10	Saipat	9.89	9.98	10.25	10.68	10.74	11.18	11.22	11.55	10.30
11	Kairana	17.05	17.80	18.88	16.34	18.73	19.50	20.10	20.83	20.45
12	Lilaun	12.92	13.29	14.90	14.71	15.20	15.52	16.10	16.53	16.10
13	Bunta	9.95	10.54	10.32	9.75	10.40	11.10	11.07	10.40	9.70
14	Todda			14.05	11.90	11.93	13.74	14.09	14.10	13.12

Appendix VII A
Results of chemical analysis in mg/l (November 2005)

Sample No.	Location	T^0C	pH	EC (µseimens)	TDS	Hardness	HCO_3	Cl	SO_4	Mg	Ca	Na	K
1	Banat	21.5	6.8	800	1575	220	780	80	254	34	32	384	11
2	Sikka	21	6.9	600	1164	384	481	57	295	82	19	218	12
3	Kaidi	21	7.0	300	665	164	325	28	134	31	15	128	4
4	Harhar Fatehpur	20.6	6.8	500	1072	216	355	102	248	44	14	203	105
5	Thana Bhawan	23	7.0	700	1059	352	520	108	144	78	13	188	8
6	Jalalabad	20	7.0	200	687	160	285	68	168	29	20	106	11
7	Dulawa	21	7.0	300	683	132	390	34	103	23	16	108	8
8	Jadheri	22	7.1	250	539	208	260	17	98	36	24	103	1
9	Dullakheri	20.2	7.0	200	683	288	351	17	162	59	18	73	3
10	Garhi Abdullah	20	7.3	400	491	152	195	11	152	21	26	83	2
11	Un	21.6	6.9	400	977	308	494	80	160	69	10	108	57
12	Mundait	22.4	7.0	800	754	172	314	45	213	31	18	128	5
13	Kheri Khusnam	21.8	6.7	500	1059	312	364	57	323	66	16	188	44
14	Chausana	21	7.1	300	775	188	315	45	226	36	16	113	24
15	kertu	21	7.5	200	630	188	351	23	104	36	16	78	22
16	Todda	21	7.1	400	874	216	287	35	337	41	19	151	3
17	Titauli	22	6.9	400	827	236	351	80	189	49	14	98	46
18	Malaindi	22	7.1	400	1169	156	538	28	302	29	14	238	19
19	JhinJhana	20.5	7.4	700	1293	304	598	68	280	68	10	253	16
20	Rangana	21	7.0	300	852	304	429	51	191	69	8	98	6
21	Yusuf Chautra	20	7.5	500	859	292	224	91	252	59	19	98	116
22	Barlajat	21	7.6	500	1313	128	639	58	226	27	6	354	2
23	Makhmulpur	21	7.7	400	932	76	468	11	195	9	16	233	0
24	Bhanera	20	7.0	300	846	144	416	28	160	28	11	198	4
25	Nala	20	6.8	500	956	340	380	126	211	71	19	108	41
26	Kandhla	20	7.5	400	824	200	260	85	244	44	8	178	4
27	Lilaun	19.5	6.8	500	993	296	468	57	189	61	18	178	22
28	Gogwan	22	7.2	300	644	208	299	68	95	36	24	118	3

29	Pauti Kalan	20	7.2	300	800	268	383	28	214	55	18	98	4
30	Akbarpur Sunethi	22.6	7.0	600	1145	132	520	85	216	23	14	278	8
31	Khurgaon	21	7.2	400	904	148	390	57	174	30	10	238	5
32	Khera	22.5	7.2	800	1042	240	418	138	219	48	18	195	7
33	Mawi	21.5	6.9	500	858	248	416	108	82	49	19	178	6
34	Saipat	21	7.3	400	790	260	338	91	156	56	13	128	8
35	Titarwara	22	7.2	600	1060	224	455	131	142	46	14	248	25
36	Kairana	20	6.9	500	1128	308	481	108	249	67	13	198	12
37	Kandela	21	7.1	500	1160	184	676	62	114	38	11	253	6
38	Bhura	20	7.1	400	865	332	299	85	241	71	16	148	4
39	Kaserwa	21	7.2	200	659	268	377	68	42	57	14	98	3
40	Shamli	21	7.1	800	1283	488	410	284	213	110	14	234	17

Temperature in ^{o}C

APPENDIX VII B

Results of chemical analysis in mg/l (June 2006)

Sample No.	Location	$T^{0}C$	pH	EC (µseimens)	TDS	Hardness	HCO_3	Cl	SO_4	NO_3	F	Mg	Ca	Na	K
1	Banat	21.0	7.0	1100	1584	172	595	105	382	30	1.6	40	23	366	11
2	Sikka	21.5	6.9	1100	1597	352	338	118	423	150	1.3	73	31	303	11
3	Kaidi	22.0	6.8	300	703	132	390	26	49	19	0.9	24	13	161	1
4	Harhar Fatehpur	21.0	6.8	800	1111	196	295	86	335	48	0.7	44	26	177	51
5	Thana Bhawan	23.0	7.0	800	1262	280	465	111	226	64	1.6	59	26	240	6
6	Jalalabad	21.0	7.1	400	756	192	266	60	205	16	0.3	50	27	114	2
7	Dulawa	22.5	7.1	300	789	184	330	31	156	48	1.1	34	18	124	0
8	Jadheri	21.0	7.2	300	729	256	351	20	134	38	0.7	56	11	81	0
9	Dullakheri	19.5	6.8	200	497	168	234	14	72	15	0.9	36	8	103	0
10	GarhiAbdullah	20.5	6.9	200	557	180	273	6	72	19	1.2	29	24	114	0
11	Un	21.0	7.1	600	1164	336	546	85	107	59	0.6	76	10	177	44
12	Mundait	22.0	6.9	500	1054	252	351	97	282	27	1.0	47	24	187	12
13	Kheri Khusnam	22.0	7.0	600	1119	348	273	23	449	43	1.2	54	51	156	27
14	Chausana	21.5	6.8	400	941	220	442	34	172	36	0.7	45	14	161	0

15	Kertu	22.0	6.9	400	1107	352	364	54	367	26	0.8	62	38	156	12
16	Todda	22.0	7.0	300	916	192	403	14	173	55	1.8	38	14	161	0
17	Titauli	21.5	7.0	200	708	220	385	17	70	23	0.3	44	16	129	0
18	Malaindi	22.5	7.2	300	923	156	325	14	319	17	0.6	32	10	187	0
19	JhinJhana	21.0	7.0	400	907	192	429	43	182	13	0.9	37	16	166	7
20	Rangana	22.0	7.4	200	633	260	305	20	109	34	0.7	36	45	51	0
21	Yusufpur Chautra	20.5	7.1	400	798	192	279	40	201	29	0.9	27	32	99	60
22	Barlajat	22.0	7.5	700	1256	120	715	26	83	48	2.3	26	5	303	0
23	Makhmulpur	21.0	7.6	300	758	200	390	14	128	26	1.3	36	21	114	2
24	Bhanera	20.5	7.0	500	976	152	480	1	169	48	1.1	28	14	187	0
25	Nala	20.0	6.9	700	973	348	325	179	160	34	0.6	82	5	114	39
26	Kandhla	19.0	7.3	500	801	172	273	85	147	35	1.4	34	13	177	0
27	Lilaun	20.0	6.8	500	712	220	320	43	98	41	1.2	44	16	42	67
28	Gogwan	22.5	7.3	900	1225	472	260	228	286	54	0.8	76	64	193	9
29	Pauti Kalan	20.5	7.3	400	953	268	312	14	323	42	1.8	56	16	145	2
30	Sunethi	23.0	6.8	400	862	140	247	48	229	58	1.5	21	22	177	1
31	Khurgaon	21.5	7.5	600	1133	220	533	31	227	28	1.3	38	26	219	2
32	Khera	23.0	7.2	900	1425	388	468	51	480	33	1.7	85	16	251	7
33	Mawi	22.0	7.0	600	1057	256	418	97	238	20	0.8	45	29	187	2
34	Saipat	22.0	7.3	700	1214	280	403	139	249	50	1.3	59	16	198	49
35	Titarwara	22.5	7.3	1500	1922	548	611	346	320	54	1.1	121	21	335	60
36	Kairana	21.0	6.9	700	1165	400	377	122	270	31	0.9	70	45	214	5
37	Kandela	21.5	7.2	600	1153	144	611	102	51	42	0.7	27	13	256	7
38	Bhura	21.0	7.0	400	1327	316	425	80	328	50	0.3	59	30	302	4
39	Kaserwa	21.5	7.2	400	965	292	546	51	84	32	1.1	58	22	135	4
40	Shamli	22.0	7.1	800	1014	268	278	173	183	53	1.5	46	32	187	7

Temperature in ^oC

APPENDIX VII C

Results of chemical analysis in mg/l (November 2006)

Sample No.	Location	T^0C	pH	EC (µseimens)	TDS	Hardness	HCO_3	Cl	SO_4	NO_3	Na	K	Ca	Mg
1	Banat	22	6.95	800	1163.93	200	650	88.04	74.89	64.23	210	10.5	22.44	43.83
2	Sikka	21	6.86	800	1695.38	604	767	136.32	343.19	52.27	225	19.5	12.82	139.28
3	Kaidi	23	7.3	200	736.83	264	468	17.04	21.39	67.33	78.75	10	25.62	48.7
4	Harhar Fatehpur	20.5	7.08	600	1053.11	288	442	14.2	158.83	104.1	101	180	20.84	32.14
9	Dulla Kheri	22	6.9	200	631.72	324	390	82.36	38.68	0	27.5	8	16.03	69.15
12	Mundait	19.5	6.95	300	916.94	304	429	133.48	114.39	21.26	127.5	11	16.03	64.28
13	Kheri Khusnam	21	6.65	600	1443.32	448	624	65.32	374.46	9.81	205	33	57.71	74.02
14	Chausana	21	6.93	300	1010.68	320	572	34.08	161.3	13.73	135	11	14.42	69.15
15	Kertu	22	7.01	300	809.54	308	442	53.96	62.54	15.5	140	13	19.23	63.31
16	Todda	21.5	7.11	200	793.26	300	481	19.88	83.94	3.98	116	8.5	17.63	62.33
19	Jinjhana	22	6.96	600	1283.32	268	767	93.72	104.52	5.31	231.5	13.5	6.41	61.36
20	Rangana	21	6.9	300	960.3	328	585	28.4	118.51	0	135	8.5	12.82	72.07
22	BarlaJat	19	6.98	600	1415.89	152	806	34.08	139.91	7.53	371.3	10	25.65	21.42
23	Makhmulpur	19.5	7.2	700	1204.16	220	715	36.92	143.2	17.72	205	12	52.9	21.42
24	Bhanera	23	6.95	400	1164.75	288	702	22.72	135.79	4.87	200	11	46.49	41.88
25	Nala	22	7.07	100	965.65	272	390	17.04	82.3	9.74	375	11.5	35.27	44.8
26	Khandhla	21	7.24	400	1040.77	224	390	85.2	266.65	27.9	191	8.5	43.28	28.24
27	Lilaun	21	6.99	200	598.85	188	312	48.28	101.22	9.3	67.5	5	22.44	33.11
31	Khurgaon	21	6.87	800	1889.68	348	871	119.28	312.84	24.36	348	115	36.87	62.33
34	Saipat	22	6.87	300	1223.34	300	781	36.92	164.6	5.75	130	10	56.11	38.96
35	Titarwara	21.5	6.85	600	1333.84	308	572	133.48	201.63	22.59	296.3	19	35.27	53.57
36	Kairana	23	6.68	400	1045.82	260	624	48.28	135.79	1.77	152.5	12	20.84	50.64
37	Kandela	22	6.72	400	1179.14	304	637	28.4	209.86	15.94	195	12	17.63	63.31
40	Shamli	21.5	6.99	500	1035.85	280	416	139.16	165.42	45.62	175	10	32.06	52.59

Temperature in ^oC

APPENDIX VII D

Results of chemical analysis in mg/l (June 2007)

Sample No.	Location	T^0C	pH	EC (µseimens)	TDS	Hardness	HCO_3	Cl	SO_4	NO_3	Na	K	Ca	Mg
1	Banat	22	7.16	1000	1437.62	188	832	59.64	167.06	9.74	306	13	11.22	38.96
2	Sikka	21	7	1100	1381.19	356	637	178.92	198.34	19.04	230	18	33.66	66.23
3	Kaidi	21.5	6.89	400	868.29	192	494	36.92	121.8	4.87	140	12	30.46	28.24
4	Harhar Fatehpur	22	7.42	700	1257.67	300	533	130.64	208.21	64.23	191	50	19.23	61.36
5	Thana Bhuwan	23	7.18	800	973.49	344	442	99.4	132.5	10.18	185	15	14.42	74.99
6	Jalalabad	21	7.12	500	855.46	216	403	96.56	149.78	2.21	130	10	28.85	35.06
7	Dulawa	22.5	7.07	300	1125.1	200	676	62.48	117.68	0.44	195	16	22.44	35.06
8	Jandheri	22	7.11	200	737.88	232	416	36.92	110.42	8.41	110	11	25.65	19.48
9	Dulla Kheri	19.5	7.15	300	792.02	252	403	22.72	183.52	11.51	95	8	17.63	50.64
10	Garhi Abdulla Khan	20	7.24	300	920.2	168	585	19.88	110.12	6.64	140	12	14.42	32.14
11	Un	23	7.01	500	1045.05	360	676	99.4	4.11	7.97	115	48	17.63	76.94
12	Mundait	22	7.2	600	829.81	204	442	36.92	172.83	3.1	110	9	16.03	39.93
13	Kheri Khushnam	23	7.57	500	837.28	112	338	17.04	251.12	5.31	186	5	19.23	15.58
14	Chausana	21	7.73	400	709.94	196	390	36.92	133.32	2.21	85	11	9.61	41.88
15	Kertu	21	7.51	400	757.92	228	364	28.4	148.96	12.4	105	21	57.71	20.45
16	Todda	23	7.11	200	719.22	284	468	31.24	28.8	7.08	95	8	30.46	50.64
17	Titauli	21.5	7.31	300	665.06	236	403	22.72	76.53	3.54	85	8	22.44	43.83
18	Malaindi	22	7.4	400	1357.04	172	702	56.8	252.1	7.97	277	13	16.03	32.14
19	Jhinjana	23	6.99	500	1580.89	212	884	139.16	130.03	4.43	350	16	14.42	42.85
20	Rangana	22	7.32	300	865.13	208	585	36.92	75.71	6.2	95	10	14.42	41.88
21	YusufpurChautra	21	7.38	300	520.46	176	338	28.4	51.84	7.08	30	16	16.03	33.11
22	Barla Jat	20.5	7.3	600	598.43	140	416	19.88	20.57	3.98	90	7	17.63	23.37
23	Makhmulpur	22	6.61	400	747.16	220	468	19.88	57.67	4.87	125	10	20.84	40.9
24	Bhanera	20	6.58	400	1203.81	140	689	68.16	79.83	8.86	310	12	4.8	31.16
25	Nala	20	6.75	600	949.61	188	663	22.72	23.03	14.17	165	9	17.63	35.06
26	Kandhla	19.5	6.72	400	810.47	220	416	133.48	4.1	23.92	165	10	11.22	46.75
27	Lilaun	20	6.94	600	421.06	148	286	22.72	4.9	5.75	55	5	14.42	27.27
28	Gogwan	22	7.12	900	721.28	308	364	116.44	44.4	6.64	75	31	22.44	61.36

29	Pauti Kalan	23	7.21	500	632.46	256	416	14.2	43.61	9.74	65	9	32.06	42.85
30	Akbarpur Sunethi	22	6.9	500	685.02	184	390	45.44	67.48	3.98	115	7	28.85	27.27
31	Khurgaon	21.5	7.41	400	1011.11	196	507	56.8	199.98	10.18	170	10	24.04	33.11
32	Khera	22	7.31	800	1480.14	244	585	76.68	418.9	17.72	297	16	24.04	44.8
33	Mawi	23	6.99	700	992.31	240	559	48.28	161.3	5.75	145	7	19.23	46.75
34	Saipat	23	7.11	600	1134.71	304	553	116.44	181.88	7.08	184	12	16.03	64.28
35	Titarwara	22	7.13	1300	1300.68	276	520	130.64	244.43	4.87	305	21	19.23	55.51
36	Kairana	21.5	6.98	600	1492.19	420	624	258.4	209.86	27.9	250	16	9.61	96.42
37	Kandela	21	7.22	700	1011.81	180	611	48.28	110.66	6.64	175	12	11.22	37.01
38	Bhoora	21	7.1	500	827.47	256	553	28.4	62.54	4.43	100	13	9.61	56.49
39	Kaserwa	21	7.12	400	1587.25	376	728	178.92	242.78	7.97	310	23	12.82	83.76
40	Shamli	22	7.11	600	1108.24	312	559	105.08	171.12	19.93	160	14	8.01	71.1

Temperature in ^{o}C

APPENDIX-VIII A
Results of chemical analysis of river water sample in mg/l (November 2005)

Sample No.	Location	pH	EC (µsiemens)	TDS	Hardness	HCO_3	Cl	SO_4	Mg	Ca	Na	K
1	Krishni (Banat)	6.70	2000	2838.51	700	1325	206	576.10	73.09	160.32	348	150
2	Krishni (Kaidi)	6.80	1700	2719.17	900	1200	213	574.45	85.28	220.44	288	138
3	Krishni (Salpa)	7.72	1500	3217.17	1500	1300	213	850.98	170.55	320.64	228	134
4	Yamuna(Bhari)	8.05	200	484.14	160	195	11.36	118.51	29.24	16.03	93	21
5	Yamuna(Chautra)	8.20	100	416.35	196	234	22.72	55.96	37.03	17.64	48	1
6	Yamuna (Khera)	6.80	1100	444.98	180	234	28.40	83.12	33.62	16.83	48	1
7	Yamuna (Saipat)	6.80	600	1092.77	156	424	47.48	345.00	28.26	16.03	198	34

APPENDIX-VIII B

Results of chemical analysis of river water sample in mg/l (June 2007)

Sample No.	Location	pH	EC (µsiemens)	TDS	Hardness	HCO_3	Cl	SO_4	NO_3	Na	K	Ca	Mg
1	Yamuna (Bhari)	7.31	300	270.09	140	156	11.36	9.05	6.64	35	6	30.46	15.58
2	Yamuna (Chautra)	7.61	200	334.72	148	195	19.88	18.1	5.31	40	9	28.85	18.58
3	Yamuna (Mawi)	7.56	600	260.34	120	130	17.04	29.67	4.87	35	7	19.23	17.53
4	Yamuna (Saipat)	7.43	500	306.9	116	143	11.36	44.44	4.43	60	6	24.04	13.63
5	Krishni(Chandelmal)	7.16	700	729.63	220	520	28.4	15.63	31.01	25	34	56.11	19.48
6	Krishni (Kaidi)	7.39	1000	1091.72	440	715	59.64	35.38	31.67	65	37	104.2	43.83
7	Krishni (Banat)	7.81	800	2107.92	340	1430	170.4	8.23	32.34	315	44	64.12	43.83
8	Krishni (Barla Jat)	7.33	900	1469.08	400	611	227.2	194.22	33.22	210	52	112.22	29.22
9	Krishni (Bhanera)	7.41	600	2027.3	440	1365	124.96	83.12	34.33	225	50	96.19	48.7

APPENDIX-VIII C

Results of chemical analysis of Nala/Drain samples in mg/l (June 2007)

Sample No.	Location	pH	EC (µmhos/cm)	TDS	Hardness	HCO_3	Cl	SO_4	NO_3	Na	K	Ca	Mg
1	Kandela drain (Kandela)	7.71	1200	1894.38	360	975	99.4	277.35	42.08	320	52	104.2	24.35
2	Shamli drain (Shamli)	7.62	1100	1467.87	340	780	127.8	105.34	43.19	245	46	96.19	24.35
3	Sikka Nalla (Sikka)	7.8	900	1731.78	300	585	213	404.91	32.78	330	49	112.22	4.87
4	Kandela Nalla (Salpa)	7.71	1000	1611.91	44	1040	142	10.69	47.62	175	58	80.16	58.44

APPENDIX-IX A
Trace elements analysis of groundwater sample in mg/l (June 2006)

Sample No.	Location	Al	Cr	Mn	Fe	Ni	Co	Cu	Zn	As	Se	Cd	Pb
T-1	Chandelmal	0.162	0.009	0.164	0.376	0.022	0.0003	0.007	0.161	0.002	0.001	0.001	0.271
T-2	KheriKhushnam	0.183	0.011	1.439	5.928	0.028	0.001	0.008	0.842	0.006	0.001	0.001	0.261
T-3	Chausana	0.248	0.013	0.277	2.205	0.026	0.0006	0.05	1.47	0.017	0.002	0.0009	0.329
T-4	Todda	0.397	0.01	0.103	0.568	0.025	0.0006	0.01	0.618	0.002	0.001	0.001	0.334
T-5	Dullakheri	0.234	0.015	0.142	1.667	0.028	0.0007	0.075	1.223	0.001	0.002	0.0003	0.319
T-6	Bhanera Udha	0.159	0.09	0.117	0.406	0.024	0.0005	0.009	0.094	0.001	0.001	-0.003	0.317
T-7	Thana Bhawan	3.038	0.017	0.43	3.236	0.027	0.0016	0.026	0.191	0.009	0.003	0.0007	0.276
T-8	HarharFatehpur	0.164	0.027	0.109	0.574	0.026	0.0005	0.118	0.217	0.002	0.01	0.0006	0.303
T-9	Garhipukhta	0.409	0.013	0.132	1.875	0.029	0.0007	0.034	1.172	0.015	0.003	0.001	0.368
T-10	Rangana	2.404	0.017	0.286	3.371	0.047	0.0222	0.069	3.017	0.003	0.001	0.001	0.349
T-11	Kertu	0.204	0.008	0.208	0.495	0.025	0.0005	0.01	1.84	0.003	0.004	0.001	0.291
T-12	Mansura	0.207	0.013	0.355	1.112	0.029	0.0006	0.023	0.072	0.033	0.006	0.0001	0.278
T-13	Jhinjhana	0.256	0.016	0.176	1.249	0.028	0.0005	0.036	0.826	0.009	0.002	0.001	0.306
T-14	Bhainswal	0.242	0.03	0.274	1.719	0.033	0.0006	0.027	0.175	0.002	0.003	0.0004	0.293
T-15	Sikka	0.72	0.093	0.308	0.739	0.027	0.0006	0.012	0.401	0.001	0.002	0.0007	0.292
T-16	Banat	0.196	0.011	0.081	0.743	0.026	0.0006	0.016	2.52	0.002	0.004	0.0009	0.295
T-17	Shamli	0.207	0.011	0.246	1.568	0.025	0.0008	0.013	0.612	0.001	0.002	0.0005	0.073
T-18	Kandela	0.245	0.029	0.148	14.384	0.039	0.0007	0.12	9.125	0.004	0.052	0.001	0.998
T-19	Khurgaon	0.314	0.011	0.421	0.927	0.015	0.0004	0.021	0.655	0.002	0.002	0.001	0.101
T-20	Mawi	0.861	0.01	0.144	1.126	0.028	0.0005	0.041	0.118	0.001	0.004	0.001	0.33
T-21	Kairana	0.199	0.013	0.138	3.302	0.019	0.0007	0.027	0.188	0.009	0.003	0.0008	0.08
T-22	Khandrauli	0.232	0.009	0.107	1.023	0.016	0.0008	0.011	2.992	0.001	0.002	0.001	0.262
T-23	Makhmulpur	0.31	0.014	0.042	1.034	0.034	0.0005	0.016	1.615	0.002	0.005	0.0009	0.336
T-24	Kandhla	0.354	0.013	0.021	1.865	0.023	0.0003	0.041	1.036	0.002	0.003	0.001	0.128
T-25	Titarwara	1.047	0.015	0.078	1.471	0.135	0.0009	0.022	0.392	0.001	0.014	0.001	0.348
T-26	Gari Rakha	0.371	0.013	0.069	0.615	0.018	0.0006	0.047	0.61	0.001	0.005	0.0002	0.209

APPENDIX-IX (B)

Repeat Analysis of Trace elements of groundwater sample in mg/l (June 2007)

Sample No.	Location	Al	Cr	Mn	Fe	Ni	Co	Cu	Zn	As	Se	Cd	Pb
T-1	KheriKhushnam	2.51	0.087	0.0668	0.506	0.042	0.002	0.126	0.468	0.001	0.0037	0.0005	0.375
T-2	Rangana	2.07	0.1139	0.236	0.681	0.0745	0.0025	0.127	2.89	0.0011	0.0073	0.000034	0.373
T-3	Kandela	2.56	0.0804	0.241	1.27	0.071	0.0027	0.1347	2.89	0.0023	0.009	0.0008	0.388

APPENDIX-IX C

Trace elements analysis of surface water sample in mg/l (June 2007)

Sample No.	Location	Al	Cr	Mn	Fe	Ni	Co	Cu	Zn	As	Se	Cd	Pb
YT-1	Yamuna (Bhari)	2.264	0.0763	0.033	0.418	0.051	0.002	0.201	0.25	0.0038	0.0064	0.0015	0.416
YT-2	Yamuna (Chautra)	2.533	0.1904	0.0343	0.438	0.054	0.0021	0.163	0.436	0.0061	0.005	0.001	0.403
YT-3	Yamuna (Mawi)	2.109	0.0696	0.0245	0.343	0.044	0.0017	0.248	0.155	0.0042	0.0035	0.0013	0.272
KT-1	Krishni(Chandelmal)	2.182	0.0876	0.0412	0.469	0.0556	0.0022	0.3107	0.275	0.0047	0.0056	0.0013	0.3748
KT-2	Krishni (Banat)	3.557	0.0992	0.246	0.703	0.064	0.0032	0.283	0.196	0.0043	0.0068	0.0012	0.353
KT-3	Krishni (Bhanera)	5.609	0.1142	0.423	2.351	0.1003	0.0069	0.8507	0.3698	0.0149	0.0078	0.0032	0.4408
KTD-4	Kandela Drain	15.746	0.1607	0.4658	2.732	0.1095	0.0099	0.464	0.885	0.0034	0.006	0.0033	0.297

APPENDIX-X A

Results of chemical analysis of effluent samples (Results in mg/l)

S.No	Type	TDS	pH	EC (µS/cm	CO_3	HCO_3	Cl	SO_4	NO_3	Na	K	Ca	Mg
1	Effluent (Sugar mill)	1237	8	400	0	460	71	265	105	134	79	99	25
2	Lagoon Water	2600	9	900	445	1220	185	360	120	134	54	48	34

APPENDIX-X B

Analysis of trace elements of effluent samples in mg/l

S.No	Type	B	Cr	Mn	Fe	Ni	Co	Cu	Zn	As	Se	Ag	Cd	Pb
1	Effluent (Sugar mill)	0.225	0.069	0.705	1.647	0.133	0.005	0.078	0.503	0.003	0.005	0.007	0.0005	0.047
2	Lagoon	0.129	0.076	0.119	1.216	0.084	0.003	0.136	0.607	0.001	0.008	0.001	0.0005	0.027

APPENDIX-XI A
Recharge applied for each stress period

Start time (Days)	Stop time (Days)	Recharge of non command area (mm/year)
0	152	164.60
152	365	100
365	517	238.04
517	730	126
730	882	218.18
882	1095	113.74
1095	1247	218.32
1247	1460	130.8
1460	1612	226.92
1612	1825	134.2
1825	1977	211.9
1977	2190	110.2
2190	2342	236.04
2342	2555	109.88
2555	2707	203.08
2707	2920	121.80

Start time (Days)	Stop time (Days)	Recharge of command area (mm/year)
0	30	45
30	60	25
60	152	125.8
152	365	53
365	517	125.4
517	730	54
730	882	141
882	1095	46
1095	1247	155
1247	1460	51
1460	1612	205.6
1612	1825	53.2
1825	1977	213.6
1977	2190	58.6
2190	2342	234
2342	2555	52
2555	2707	262.13
2707	2920	80.10

APPENDIX-XI B
Data of pumping rate applied for each stress period

Start time (Days)	Stop time (Days)	Pumping rates (m^3/day)			
0	152	-900	-1400	-1800	-2200
152	365	-950	-1450	-1850	-2250
365	517	-900	-1400	-1800	-2200
517	730	-950	-1450	-1850	-2250
730	882	-900	-1400	-1800	-2000
882	1095	-850	-1450	-1850	-2200
1095	1247	-900	-1400	-1800	-2250
1247	1460	-850	-1450	-1900	-2300
1460	1612	-900	-1400	-1900	-2350
1612	1825	-1000	-1450	-1950	-2350
1825	1977	-1000	-1400	-1900	-2400
1977	2190	-1000	-1500	-2000	-2400
2190	2342	-950	-1500	-2000	-2450
2342	2555	-1000	-1500	-2000	-2450
2555	2707	-1000	-1500	-2000	-2500
2707	2920	-1150	-1550	-2200	-2500

APPENDIX-XI C
Initial and final head of the study area

S.No.	Location	x	y	Initial head 1999	Final head 2007
1	Banat	25705	22636	239	224.77
2	Sikka	26597	27450	240	228.84
3	kaidi	30428	26996	239	231.98
4	Sonta Rasulpur	31058	30293	240	230.65
5	Thana Bhawan	31584	35608	242.94	239.03
6	Jalalabad	33281	39639	245.57	242.25
7	Chandelmal	35054	43432	247	246.51
8	Dulawa	30595	42510	248	242.57
9	Khanpur	30082	38562	248	239.25
10	Goharni	22328	24445	240	233.26
11	Jhandheri	24138	31449	244	237.05
12	Garhi Pukhta	21038	31663	241	233.74
13	Dulla Kheri	22273	36141	245	236.85
14	Bunta	23839	38730	246	242.68
15	Garhi Abdullah Khan	21950	41946	247.5	239.39
16	Bhanera Uda	27113	39579	248	244.79
17	Harhar Fatehpur	29479	32109	243	235.3
18	Un	16427	35483	233	230.8
19	Pindora	19412	37471	236	232.85
20	Mundait	18656	42182	242	234.66
21	kheri khushnam	15730	43176	241	233.6
22	Garhi Hasanpur	12535	44703	239	229.76

23	Chausana	9046	44039	236	232.74
24	Bhari	5774	44319	236	236.4
25	Ulahni	8711	37107	233	234.01
26	Todda	10599	39414	240	234.95
27	Titoli	18085	23240	236	225.98
28	Badheo	20048	25416	239.5	226.25
29	Taprana	16786	25413	228	224.46
30	Jinjhana	13681	28708	228	223.86
31	Rangana	13086	33364	231	227.49
32	Bipur jalalpur	9377	29739	229	227.13
33	Mansura	5930	28500	228	230.21
34	Yusufpur choutra	3047	29972	230	233.38
35	Barla Jat	25514	17993	238	222.46
36	Salpa	23235	13333	236	225.53
37	Makhmulpur	22947	9178	235	221.36
38	Bhabhisa	22964	6184	229.58	218.93
39	Bhanera	22419	2518	231	217.9
40	Nala	18491	3266	226	222.1
41	Malakpur	17643	10743	225	225.83
42	Pauti kalan	11490	25654	226	219.86
43	Akbarpur Sunethi	7011	25047	225	225.69
44	Khurgyan	7068	20783	228	222.01
45	Khera	7138	17550	222	222.25
46	Mawi	7249	13492	227	224.1
47	Saipat	8179	9899	222	223.75
48	Jharkhedi	11188	13157	222	219.15
49	kairana	12475	16137	225.42	218.14
50	Kandela	15150	19570	231	223.81
51	Bhoora	12011	21639	232	222.02
52	Kaserwa Khurd	16630	22170	228	225.7
53	Khandrauli	19017	14645	226	226.11
54	Lilaun	20154	18440	233.5	223.55
55	Erti	17007	16592	226	224.45
56	Gangeru	12888	6665	228.82	222.95
57	Unchagaon	13769	11252	222	219.26
58	Shamli	21731	21615	234.45	224.38
59	Kandhla	16830	7425	231.47	223.19
60	Garhi Rakha	10500	4650	222	221.65

Plate- 1a Yamuna River at Chautra

Plate- 1b Base flow of Yamuna River at Chautra

Plate- 1c Irrigular course of Yamuna River at Mawi

Plate-2 Well defined channel of Krishni River at Banat.

Plate- 3 Saline Soil at location Mansura

Plate-4a Water level monitoring in the study area

Plate-4b Water level monitoring in the study area

Plate-4c Water level monitoring in the study area

Plate-5 Collection of sand sample

Plate-6 Groundwater Discharge in the study area

Plate- 7a Collection of surface water sample from Yamuna river

Plate- 7b Collection of surface water sample from Krishni river

Plate- 8a Collection of surface water sample from Kandela Drain

Plate- 8b Collection of surface water sample from Sikka Nala

Plate- 9 Shamli Paper Mill at Sikka.