CHAPTER VII

HYDROGEOLOGY

INTRODUCTION

The geology and climatic characteristics of any region determine the nature and pattern of occurrence of groundwater in the area. The area under investigation is chiefly constituted by the Indo-Gangetic alluvial plains and the adjoining Siwalik Formation.

The detailed regional distribution, lithostratigraphy, petrographic studies, and size and shape analysis of the rocks of Siwalik Formation; and size and shape analysis of the Ghaggar River alluvial sediments have been presented in early parts of this work (Chapters II, IV, V & VI). The Indo-Gangetic alluvial plains comprising the Bhabar including the Pinjore Intermontane valley and the Tarai zones had briefly been discussed in Chapter III and are here in supplemented with hydrogeological sections (lithological correlation sections) prepared from bore holes drilled in the area by the Haryana State Minor Irrigation Tubewell Corporation Limited (H.S.M.I.T.C.); the Central Groundwater Board, Government of India; and the Public Health Department of the Haryana State.
The lithological logs of the bore holes exhibit the nature and character of the Intermontane Valley/Bhabar and the Tarai zones. Representative lithologs of the lithological units of the area under investigation have been selected with the aim of establishing a subsurface correlation, and to know the lateral and vertical extent of the water bearing units in the area. Representative lithological correlation sections along different section lines in the area have been made in an attempt to define the contacts and/or delineate the probable boundary between the Siwalik Formation, the Bhabar and the Tarai zones, as well as to ascertain the water bearing properties of the rock units and the occurrence of groundwater in the region. The water-bearing properties of the rock units and the information ascertained from the sub-surface correlation as well as the groundwater conditions in the area are herein discussed. Results of mechanical analyses of samples collected from the Siwalik Group and the Ghaggar alluvium sediments have already been discussed in Chapter VI. However, sand curves (Pande et al., 1968; Johnson, 1983) prepared from some of these samples and for the aquifer materials of the Bhabar zone are briefly discussed in this Chapter. Aquifer parameters and well characteristics in the area are also discussed in this Chapter.
ROCK UNITS AND THEIR WATER-BEARING PROPERTIES

THE SIWALIK GROUP: The medium to fine grained, subangular to subrounded, moderately to poorly consolidated sandstone containing granule-, pebble- and cobble-sized fragments form the aquifer beds in the Siwalik region of the research area. Petrographical studies (Chapter V) reveal that the Lower Siwalik sandstones are well indurated and contain calcareous, ferruginous and argillaceous cementing material. Development of overgrowths in quartz grains in most of the sandstones are conspicuous features of the Lower Siwalik Formation. These characters decrease the permeability and porosity of the rocks, resulting in decrease in their storing and transmitting capacity of water. The Lower Siwalik beds form poor aquifers. The Upper Siwalik Formation is made up of moderately to poorly indurated pebbly sandstones and conglomerate beds. The sandstone facies of this unit bear calcareous and some argillaceous cement which reduce porosity and permeability. The Boulder Conglomerate unit of the Upper Siwalik Formation consists of pebbly to boulder sized fragments and contain large void spaces and the rocks have higher permeabilities and are porous. The Upper Siwalik beds form moderate to good aquifers which are exploited for small domestic wells in the area.
Sand curves of the Siwalik Group (Figs. 78a and b) indicate that the uniformity coefficient of the Lower Siwalik detrital grains varies from 2 to 4.8 (Table 22) and are higher than those of the Upper Siwalik Formation (2 to 2.4), thus indicating higher permeability and porosity of the rocks of the Upper Siwalik unit (Marino and Luthin, 1982; Johnson, 1983).

The Siwalik Group as a result of their characteristic varied lithology and texture forms poor aquifers in general. The increased variety of sizes of the grains result in formation of barriers to the movement of groundwater as the fine grained detritus fills the interstices between coarse sandstones and pebbles. Few dugwells have been constructed in the Siwalik aquifers for water supply to isolated villages like Trilokpur, Beriwal, Pulewala, etc. by the local farmers.

Springs are common in the Lower Siwalik Formation and form the major source of water supply in the area (Plate Vila). The Lower Siwalik sequence constituted by alternation of sandstones and clays (Chapter III) is the oldest unit of the Siwalik Formation and has been subjected to series of upheavals (folding and faulting) (Pande and Saxena, 1968; Pande et al., 1968; and Bhanderi, 1970) and continued denudation. Mapping of the research area (Chapter III)
CUMULATIVE Wt. % (RETAINED)

FIG. 78a SAND CURVES FOR SAND-SIZED DETRITAL GRAINS FROM THE UPPER SIWALIK FORMATION

FIG. 78b SAND CURVES FOR SAND-SIZED DETRITAL GRAINS FROM THE LOWER SIWALIK FORMATION
### Table 22

RESULTS OF MECHANICAL ANALYSES OF SAND-SIZED DETRITAL GRAINS OF THE SIWALIK GROUP AND GHAGGAR RIVER ALLUVIAL SEDIMENTS

<table>
<thead>
<tr>
<th>Sample No. and Formation</th>
<th>Weight of sample taken(gms)</th>
<th>CUMULATIVE WEIGHT PERCENTAGE RETAINED OVER SIEVE SIZE (in mm)</th>
<th>Average Particle size</th>
<th>Effective size</th>
<th>Uniformity Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2.0  1.6  0.50  0.125  0.062</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>D-90  D-40  D-50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>LOWER SIWALIK</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MLV-4</td>
<td>100</td>
<td>2.2  10.2  23.5</td>
<td>94.1  98.4</td>
<td>0.0225 0.27</td>
<td>0.135 2.0</td>
</tr>
<tr>
<td>MLV-5</td>
<td>100</td>
<td>1.2  13.5  60.5</td>
<td>90.2  97.5</td>
<td>0.6  0.68</td>
<td>0.14 4.8</td>
</tr>
<tr>
<td>MLV-7</td>
<td>100</td>
<td>1.0  9.0  23.0</td>
<td>89.9  97.4</td>
<td>0.34 0.38</td>
<td>0.12 3.1</td>
</tr>
<tr>
<td>MLV-22</td>
<td>100</td>
<td>2.1  4.7  60.3</td>
<td>82.9  93.6</td>
<td>0.31 0.36</td>
<td>0.091 3.9</td>
</tr>
<tr>
<td><strong>UPPER SIWALIK</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KUV-7</td>
<td>100</td>
<td>3.0  10.2  21.2</td>
<td>87.8  97.1</td>
<td>0.21 0.24</td>
<td>0.11 2.2</td>
</tr>
<tr>
<td>KUV-10</td>
<td>100</td>
<td>3.6  8.4  20.7</td>
<td>96.0  98.6</td>
<td>0.22 0.250</td>
<td>0.125 2.6</td>
</tr>
<tr>
<td>KUV-17</td>
<td>100</td>
<td>2.9  10.6  21.3</td>
<td>91.9  99.0</td>
<td>0.36 0.4</td>
<td>0.165 2.4</td>
</tr>
<tr>
<td><strong>GHAGGAR ALLUVIAL BED</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RAGV-1</td>
<td>100</td>
<td>- 5.0  23.5  57.2</td>
<td>86.5  95.3</td>
<td>0.33 0.4</td>
<td>0.11 3.6</td>
</tr>
<tr>
<td>RAGV-2</td>
<td>100</td>
<td>- 5.1  16.3  55.6</td>
<td>81.4  94.4</td>
<td>0.27 0.32</td>
<td>0.082 3.9</td>
</tr>
<tr>
<td>RAGV-4</td>
<td>100</td>
<td>- 5.6  29.0  69.2</td>
<td>87.1  95.5</td>
<td>0.35 0.41</td>
<td>0.12 3.4</td>
</tr>
<tr>
<td>RAGV-6</td>
<td>100</td>
<td>- 5.0  14.8  29.5</td>
<td>52.3  94.9</td>
<td>0.35 0.42</td>
<td>0.125 3.36</td>
</tr>
<tr>
<td>RAGV-10</td>
<td>100</td>
<td>- 6.2  23.0  65.8</td>
<td>80.8  91.9</td>
<td>0.31 0.38</td>
<td>0.080 4.7</td>
</tr>
</tbody>
</table>

### Table 23

RESULTS OF MECHANICAL ANALYSES OF SAND-SIZED DETRITAL GRAINS OF THE SIWALIK GROUP AND GHAGGAR RIVER ALLUVIAL SEDIMENTS

<table>
<thead>
<tr>
<th>Depth Zone in metres</th>
<th>Weight of sample taken (gms)</th>
<th>CUMULATIVE WEIGHT PERCENTAGE RETAINED OVER SIEVE SIZE (in mm)</th>
<th>Average Particle size</th>
<th>Effective size</th>
<th>Uniformity Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>4  2  0.841 0.5 0.297</td>
<td>0.210 0.149 0.105</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>D-50  D-40  D-90</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. 249-277</td>
<td>100</td>
<td>- 15.08  44.47 76.75</td>
<td>79.75  99.12 95.12</td>
<td>0.74 0.93</td>
<td>0.19 4.8</td>
</tr>
<tr>
<td>2. 277-309</td>
<td>100</td>
<td>26.42  63.62 87.36</td>
<td>95.36  97.23 98.45</td>
<td>1.7 3.2</td>
<td>0.7 4.6</td>
</tr>
<tr>
<td>3. 340-362</td>
<td>100</td>
<td>36.68  82.12 90.10</td>
<td>95.52  97.62 97.67</td>
<td>3.4 3.9</td>
<td>1.1 3.5</td>
</tr>
</tbody>
</table>
reveals the presence of folds and numerous major and minor faults within the Siwalik region. The springs occur in the Lower Siwalik Formation where sandstones and clay strata are interbedded and inclined or folded, or where a set of rocks traversed by joints intercept the watertable at the land surface as observed in the vicinity of Bhor, Morni, Chakli, Kharog, Manoli, etc. which are located close to the Main Boundary Fault area. They also occur on the sides of valleys which have been eroded below the level of local groundwater table in the villages such as Dharwala, Dungi, Manoli, Tekiri, etc. The discharge of the springs varies from .63 l/sec. to 15 l/sec (54.52 m³/d to 1296 m³/d). Springs are not common in the Upper Siwalik Formation as a result of the thick accumulation of recent sediments which have not been subjected to prolonged erosion.

The beds of the Upper Siwalik Formation dip southwards and add to recharge of Bhabar aquifers.

THE INTERMONTANE VALLEY: The intermontane valley forms the northwestern part of the Pinjore Block and occupies the area drained by the Sirsa Nadi. Lithologically, the Pinjore Intermontane valley consists of recent alluvial fill. The aquifer material consists of large boulders, pebbles, gravels and sands. The sands and gravel beds form good aquifers due to their porous and permeable nature.
THE BHABAR ZONE: The Bhabar zone lies at the foot hills of the Siwalik Formation and marks the northern margin of the plains. The zone is characterized by steep slopes and is lithologically constituted of rock fragments, coarse gravels and boulders, with filling of sands; and bear the characters of an alluvial cone deposits. These deposits form the water-bearing beds in the area. The aquifers vary in thickness from 15 metres at Dera village, 98.5 m at Debkauri to 107 m at Rahna and upto 167 m at Toka. Aquifer samples from H.S.M.I.T.C. drilling well site at Dhamla were processed by mechanical analysis. Sand curves of aquifer materials of the Bhabar zone (Dhamla site) (Fig. 78c, Table 23) indicate that the effective size of the grains varies from 1.19 to 1.1 mm while the uniformity coefficient of the aquifer material varies from 3.5 to 4.8 (These values are comparable with the effective size (0.163-0.198 mm) and uniformity coefficient (1.663-5.58) values determined by Pande et al. (1968) for the aquifer materials of Ismailpur well site in Bhabar/Tarai boundary area of U.P. indicating that the materials are uniformly graded. The aquifer materials of the Bhabar zone thus have high porosity, high hydraulic conductivity and high absorptive characters. These characteristics have resulted in rapid infiltration underground, and percolation into watertable of most of the water received in the zone from rainfall and by
**FIG. 78c** SAND CURVES FOR THE GHAGGER RIVER ALLUVIUM SEDIMENTS
(Curves 1, 2, 4, 6, 10 correspond to curves for respective R A G V samples)

**FIG. 78d** SAND CURVES FOR THE AQUIFER MATERIAL FROM DHAMLA SITE, Bhabar Zone
(Curves 1, 2, 3 correspond to sample nos. 1, 2, 3.)
by seepage from the emerging streams of the Upper Siwalik Formation. Superficially, this zone is devoid of water except after the rains, but has large subsurface water storage capacity.

Groundwater in the Bhabar zone occurs mainly under watertable conditions.

THE TARAI ZONE: The Tarai zone adjoins the Bhabar zone and is characterized by fine to medium grained unconsolidated alluvial sand, silt, sandy clay, clay, with sparse pebbles, gravels and boulders. The aquifers of this zone are mainly constituted by the sands and gravels which are commonly overlain by the impermeable clay and sandy clay beds. Groundwater in the zone mostly occurs under confined to semiconfined conditions.

The sandy clay, clay and silts of the Tarai zone are highly porous and absorb large quantities of water which are retained by molecular attraction. The clay beds have low permeabilities, and hence low transmission capacity. The Tarai zone forms more or less a continuous sequence with the Bhabar zone (Figs. 79(i) and 79(ii)) and as such most of the groundwater of the Bhabar zone which are in continuous motion are received by downward percolation and lateral flow in the Tarai zone. The groundwater storage of the aquifers of the Tarai zone are therefore, very large, and the zone is ideal for construction of moderate to heavy duty water wells
for domestic and irrigation purposes (Pande et al., 1968)

During the present investigations the author did not observe any site where drilling for groundwater was going on in the Tarai zone; and as such it was not possible to collect any aquifer samples for mechanical analysis from this zone. Pande et al. (1968) had, however, observed that the effective size of aquifer materials in the Tarai zone of Uttar Pradesh, India varied from 0.19 to 0.25 mm at Pipalsama well site (Nainital District) and from 0.12 to 0.203 mm at Sarvarkhera site. The uniformity coefficient of the above wells range from 1.80 to 8.20 and 3.20 to 17.1 respectively. According to Marino and Luthin (1982) homogenous formations composed of relative fine and uniform materials have uniformity coefficient of less than 3 whereas non uniform aquifer materials have uniformity coefficient higher than 6. The above values of uniformity coefficient of Tarai aquifer materials in U.P. indicate the presence of uniform to non uniform aquifer materials (Marino and Luthin, 1982).

SUB-SURFACE LITHOLOGICAL CORRELATION OF WATER-BEARING FORMATIONS AND DELINEATION OF INTERMONTANE VALLEY BHABAR AND TARAI ZONES OF THE RESEARCH AREA:

The subsurface lithological sections have been prepared along ten section lines (AA' - JJ') (Figs. 79(i) and 79(ii)). The location of the tubewells along which the
sections have been drawn are shown on Map 7. The results of the mechanical analyses of the aquifer materials and/or the sediments (detrital sand grains) which invariably constitute the aquifers, in the Intermontane valley/Bhabar Zone and parts of the Siwalik indicate that the aquifer materials are uniformly graded (Marino and Luthin, 1982) (Tables 22 and 23). The sand analyses curves for the varicus formations have characteristic S-shapes. The S-shaped curve in the Bhabar aquifer material (Fig. 78d) is however, slightly distorted as a result of mixing of sand, gravel and boulders (Walton, 1970; Marino and Luthin, 1982; Johnson, 1983). The various features of the lithological sections which include the character of the sediments, their vertical and lateral extent, succession and correlation are herein briefly discussed.

AA' Section: The lithological correlation section (Fig. 79(i)) incorporates the lithology of the bore holes at Manakpur-Dabkauri-Manak Tabra-Dera-Kotla area. The total depth of the bore holes along this section varies between 91.5 m.b.g.l. (Manak Tabra) and 296 m.b.g.l. at Kotla. The strata exhibits great lateral and vertical variations. In the Western part of the section (Manakpur area) thin lenses of clay and sandy clay beds which are of gritty nature and with no lateral extension are buried in thick layers of fine to medium grained sand beds. At places, the sand beds bear occasional pebbles
and gravels. In the Dabkauri area predominantly medium to coarse sand beds with thickness of over 98.5 m are encountered. The beds bear occasional pebbles and gravels. Boulders occur at depth of 70.1 m.b.g.l. to 79.3 m.b.g.l. The coarse sands, pebbles and gravels constitute the water bearing beds. Sticky clay beds form the base of the sands at depth of 110 m.b.g.l.

In the Manak Tabra area, sandy clay and clay beds of thickness varying from 5 m to 15 m and having significant lateral extent are interbedded with 15 to 25 m thick sands. The clay, sandy clay and sand beds exhibit great lateral extent from Manak Tabra to Kotla area. The sand beds consist of medium to coarse sands, gravels, pebbles and boulders. They constitute the water bearing beds in the area. The aquifers in the Manak Tabra - Kotla area are encountered at depths varying from near surface level to 296 m.b.g.l.

The shallow aquifers consist of boulders, pebbles and coarse sands and extend to depth of about 79 m.b.g.l. in Dera. These aquifers vary in thickness from 15 m to 35 m in places. At depths between 70 m.b.g.l. and 296 m.b.g.l. the aquifer beds are constituted by gravels, pebbles and sand of various grades. The aquifer beds show great variation in thickness. Clay, sandy clay and occasionally, clay with kanker of varying thickness are encountered at different depths.
The clay beds exhibit maximum thickness at depths of 53 m.b.g.l. to 97 m.b.g.l. at Laha and Garhi Kotaha areas. The granular and non-granular beds occur proportionately between Dera and Kotla areas in the extreme northeast, which constitutes the Bhabar Intercone Zone with their characteristic deposits (Andrusivick, 1978).

The section AA' forms an undulating plain with steep slopes which gradually grades down. Numerous streams and rivers emerging from the Siwalik hills drain the area and act as source of natural recharge. The near absence of clay and sandy clay beds and predominance of boulders, pebbles; gravels and medium to coarse sands between Manakpur and Manak Tabra, and characteristic deposits between Dera and Kotla, exhibited by the lithological correlation Section AA', are characteristic features of the Bhabar zone. Although lenses of clay and sandy clay occur in the Manakpur areas, the limited thickness, lens-shaped, tapering and semi-permeable nature of the clay beds and their gritty nature due to their association with gravel and sand are unsuitable for creating good confined pressure heads. Groundwater in the Manakpur-Dabkauri-Manak Tabra areas occurs under watertable conditions.

Thick clay and sandy clay beds interbedded with few pebbles and finer sand encountered between Garhi Kotaha and
Laha show characteristic Tarai lithology. Groundwater in the Garhi Kotaha - Laha areas occurs under confined to Semi confined conditions.

**BB Section:** The section incorporates bore hole locs at Rashidpur, Mukandpur, Shazanpur, Azampur, Ghanaui and Sadhaura. The total depth of the bore holes varies from 75.3 m.b.g.l. in Ghanaui to 174 m.b.g.l. at Rashidpur. The lithology of the area is dominantly clay and sandy clay beds which also exhibit great lateral extent. The thickness of the clay beds vary from 10 m to 55 m. Beds of fine to medium alluvial sands and silt with occasional gravels and boulders constitute the aquifer beds which are sandwiched by the thick clay beds at various depths. A thin shallow aquifer which extends from Sadhaura and pinching towards Shazanpur is encountered at a depth of 3 to 5 m.b.g.l. Generally, the aquifers vary in thickness from 3 to 8 m and are encompassed by clay and clay-kanker beds. However, coarse sand, gravel and boulder beds with thickness varying from 15 m to 20 m are encountered between depths of 43 m.b.g.l. and 60 m.b.g.l. at Ghanaui and Sadhaura, respectively. Streaks and stringers of water-bearing beds are encountered at varying depths in the Rashidpur-Mukandpur areas. The aquifer beds generally thin down towards the south, whereas the clay beds increase in thickness with depth. The groundwater occurs under confined conditions. Perched aquifer
conditions occur locally in parts of this section where relatively clay beds of limited horizontal area are located between unconfined aquifer and the ground surface.

**CC' Section:** The Chhota-Korwa - Santoki - Buddha - Khera section passes through the southern end of the research area. The section is characterized by thin beds and lenses of fine to medium and coarse sand, silt and stringers of gravel. These constitute the aquifer beds which range in thickness from 2 m to 12 m, and occur up to a depth of 144 m.b.g.l. in Chhota Korwa. Ten metres thick boulder beds with coarse sands are encountered at a depth of 95 m.b.g.l. in Chhota Korwa area. Some of the water-bearing strata extend laterally, but generally taper towards Buddha Khera. The aquifers are interbedded and overlain by beds of hard clay and clay-kanker. The clay beds vary in thickness from 3 m to 25 m in some areas. Except at shallow depths groundwater in the area generally occurs under confined to semi-confined conditions.

**DD' Section:** The lithological correlation section DD' (Fig. 79(i)) incorporates the lithology of the bore holes at Morhanwala, Nanakpur, Karanpur and Ratpur. The bore holes have total depth varying from 30.5 m.b.g.l. at Karanpur to 80 m.b.g.l. at Morhanwala. The water-bearing
sediments in the area are constituted of boulders, pebbles, gravels and medium to coarse sands. Groundwater occurs under water table condition in the Karanpur-Ratpura area. Few lenses of clay beds are encountered at shallow depths within the aquifers at Morhanwala and Nanakpur and have resulted to the existence of locally flowing conditions in the area (Morhanwala-Nanakpur area). At depths of 33 m.b.g.l. and 56 m.b.g.l. few lenses of clay beds are also encountered at the Ratpur area. The lithological correlation section DD' exhibits intermontane (Doon) characters. The doon alluvial fill conceals the underlying Siwalik Formation and lithologically consists of brown and light grey clays, sandy clays, sands and gravels which are mostly angular and associated with boulders, cobbles, and pebbles of limestone, shale, phyllite and quartzite. Similar observations have been made by Pande et al. (1968) in the U.P. area.

Section EE': The total depth of the bore holes along this section vary from 107.3 m.b.g.l. at Khangesra to 159.4 m.b.g.l. at Alipur (Fig. 79(ii)). In the Dabkauri area, medium to coarse sand with pebbly stones and boulders extend up to a depth of 111.3 m.b.g.l. with clay beds forming at the base. The predominance of the arenaceous and clastic rocks which constitute the aquifers in this
GROUNDWATER STUDIES IN PARTS OF AMBALA DISTRICT
HYDROGEOLOGICAL CROSS-SECTIONS

SECTION E-E'

SECTION F-F'

SECTION G-G'

SECTION H-H'

SECTION I-I'

LEGEND

1. PEBBLY SAND (M. S. D.)
2. SANDY SAND WITH SANDSTONE
3. SANDY CLAY
4. CLAY
5. Silt
6. SOIL WITH SANDER
7. SANDY-MAIN HOARER
8. CLAY WITH CAPER

SCALE

0
6
10 km

WATER LEVEL

DRAWING
section diminishes away from Dabkauri in the north, and thins down towards Jalauli in the South. The aquifers are unconfined in the area. Between Khangesra and Jalauli, medium to coarse sands bearing occasional pebbles, cobbles and boulders constitute the aquifer beds; and are interbedded with clay and clay-kanker beds. The thickness of the aquifer beds vary from 98.5 m at Dabkauri in the north to 10 m and 5 m at Alipur-Jalauli areas in the south. The clay beds vary in thickness from 5 m in the shallow areas to 50 m at Alipur. In the Dabkauri-Kangesra area springs emerge in the zone where the aquifer beds thin down and are in contact with thick clay beds of the Tarai zone.

The lithological correlation section EE' reveals that the Bhabar aquifers mingle and form more or less a continuous sequence with the Tarai aquifers. The section also depicts that the clay and sandy-clay beds increase in thickness towards the Tarai zone in the south. The clay beds also increase in thickness with increased depth towards the south. Springs emerge in the area that mark the contact between the Bhabar and the Tarai zones.

Section FF': The lithological correlation section FF' embraces the bore holes at Khatauli, Toka and Ratewali. The total depth of the bore holes ranges from 91 m.b.g.l.
at Khatauli to 198.0 m.b.g.l. at Ratewali. Fine to medium sands, pebbles, gravels and boulders constitute the aquifer beds which vary in thickness from 146 m to 167 m in Ratewali and Toka, respectively. Clay with Kanker are encountered at a depth of 150 m to 198 m.b.g.l. which mark the base of the Ratewali bore hole. Groundwater in the Khatauli-Toka-Ratewali area occurs under unconfined conditions. Towards Khatauli in the south, the water-bearing beds show tremendous decrease in thickness and are intercepted by 5 m to 15 m thick clay beds. In the Khatauli area, the aquifer beds are interbedded with clay beds. Springs emerge at the zone where the clay beds taper out and the groundwater surface is intersected by the water table between Khatauli and Toka.

The Bhabar and the Tarai aquifers are interconnected and mingle into each other. The area marked by the conspicuous lithological changes and the emergence of springs mark the boundary between the Bhabar and the Tarai zones.

Section GG': The bore holes in the Hangoli-Firozpur-Garhi Kotaha-Rahna section have total depths varying from 117.2 m.b.g.l. in Firozpur to 183.8 m.b.g.l. at Garhi Kotaha. The lithological correlation section traverses the central part of the research area and exhibits wide lithological variations.
Medium to coarse sands, gravels, pebbles and boulder constitute the water-bearing beds of the bore holes in Rahna. Streaks of clay and Kanker are encountered at depths of 20 m.b.g.l. and 120 m.b.g.l. in the area. The sand-gravel-boulder bed at Rahna occur uninterrupted from depth of 23 m.b.g.l. to 120 m.b.g.l. (170 m thick), but suddenly thins down to thickness of 5 to 15 m towards the south, in the Garhi Kotaha-Firozpur-Hangoli sections. Predominance of clay, sandy clay and clay with Kanker is noticed at varying depths in the Garhi Kotaha-Hangoli areas. The clay and sandy clay beds vary in thickness from 4 m to 27 m. The clay beds gradually increase in thickness with depth. In the vicinity of Garhi Kotaha, springs emerge where the thick aquifer beds thin down towards the thick clay beds.

The lithological correlation section clearly shows the interrelationship between the Bhabar and the Tarai aquifers along the spring line.

**HH' Section:** The bore holes in the Patwi-Gobindpur-Bheron-Laha correlation section (Fig. 79(ii)) have total depths ranging from 146 m.b.g.l. at Bheron to 168 m.b.g.l. in Laha. The section is characterized by the thinning down of the aquifer beds from Laha in the north towards Patwi in the southwest. The aquifer beds constituted of
fine to medium sand with occasional gravels and pebbles vary in thickness from 3 m to 5 m in Patwi and 5 m to 15 m in Laha. Local aquifer bed with thickness upto 23 m is encountered at depth of 77 m.b.g.l. in Bheron. Clay beds which are mixed in places with kanker exhibit great lateral extent, and vary in thickness from 3 m to 55 m. The thickness of the clay beds increase with depth and also towards the south. The clay beds generally overlie the water bearing beds. Groundwater along this section occurs under confined to semi-confined conditions. The lithological correlation section exhibits the characteristic Tarai lithology.

II'-Section: The lithological correlation section passes through the bore holes at Buddha Khera, Chandauli, Ghanauli, Hamidpur and Dera. The total depth of the bore holes vary from 75.3 m.b.g.l. in Ghanauli to 182.9 m.b.g.l. in Chandauli. The aquifers at Dera without any clay interference vary in the thickness from 20 m to 42 m. In the Budha Khera area in the south the aquifer beds thin down to thickness varying from 2 m to 5 m. The maximum thickness of the aquifer beds in Ghanauli is 20 m. The aquifers at Dera are constituted of medium to coarse sands, gravels and boulders. These grade down to medium sands with occasional boulders in the southern areas of Chandauli.
and Budha Khera. Away from Dera in the north and towards Budha Khera in the south sandy clay and clay beds mixed with kanker predominate. The clay beds show gradual increase in thickness towards Budha Khera. The thickness of the clays vary from 3 m to 35 m.

The lithological section II' (Fig. 79(ii)) shows the relationship between the Bhabar and the Tarai zones. The Bhabar aquifers in Dera and Hamidpur areas are constituted of coarse sands, pebbles, gravels and boulders and are unconfined. The aquifers thin down towards the south, between Hamidpur and Ghanauli where thick Tarai clays and sandy clays predominate. The Bhabar and the Tarai aquifers form a continuous sequence. In the Ghanauli and Chandsauli areas, the aquifers are constituted of medium and fine sands and occur under confined and semi-confined conditions.

Section JJ': The bore holes at Sadhaura-Kotla-Nawangaon lithological correlation section have total depths varying from 108 m.b.g.l. in Nawangaon to 296 m.b.g.l. in Kotla. In Kotla area the aquifer beds consist of fine to medium sands and vary in thickness from 3 to 63 m. Clay beds which gradually increase in thickness with depth predominate in Sadhaura area in the south. The clays vary in thickness from 10 m to 66 m.
Summarised Results of Sub Surface Lithological Correlation

Sections:

The lithological correlation sections AA'-JJ' described above exhibit the lithological characteristics and nature of the occurrence of groundwater in the research area, and also indicate the relationship between the Intermontane valley (Doon alluvial fill), the Bhabar and the Tarai zones.

The lithological section DD' indicates that the northwestern Intermontane zone and the northern Bhabar aquifers are constituted of boulders, pebbles, gravels and medium to coarse sands. There is no marked distinction between the subsurface lithology of Intermontane valley zone and the Bhabar zones except for the complex nature of the Intermontane valley sediments, the marked topographical variations (or elevation at sites) and the diversity of outcrops (Pande et al., 1968). The lithological section BB', CC' and HH' show that the Tarai zone is lithologically constituted of fine sand, silt, sandy clay and clay. The sands bear occasional pebbles and gravels and are commonly overlain by impermeable clay beds.

The lithological correlation section AA', EE', FF', GG', II' and JJ' reveal the relationship between the Bhabar and the Tarai zones. The Bhabar alluvial aquifers
constituted of boulders, pebbles, gravels and medium to coarse sands with intercalated lenses of sandy clay have large thickness which varies to a maximum of 167 m at Toka. The rivers and streams debouching out into the plains abruptly from the Siwalik hills dissect the alluvial deposits and form characteristic alluvial cone and intercone spaces, the latter existing only in the extreme north east of the research area, east of the river Markanda particularly at the base of the foothills. These beds gradually thin down towards the southern Tarai zones, where the lithology is dominantly constituted of sandy clay and clay with kanker, and fine sands bearing occasional pebbles. The sandy clay and clay beds in the Tarai zone increase in thickness southwards and also with increase in depth. The clay beds of the Bhabar zone do not show any increase in thickness with depth. The zone of interception of the thick alluvial aquifers of the Bhabar zone with the clay beds of the Tarai are marked by the emergence of springs in the respective sections. The sections also indicate that the Bhabar and the Tarai aquifers mingle and form a continuous sequence.

The zone along which the lithological differences occur with the emergence of spring line may be delineated as indicated in (Map 7) to mark the probable boundaries between the Bhabar and the Tarai zones.
The numerous streams and rivers from the Siwalik Formation on reaching the Siwalik foothills lose their water which are absorbed into the coarse alluvial sands and gravels (thick aquifer beds) of the Bhabar zone which is characterized by high infiltration rates. The thickness of these aquifers thin down sharply towards the south and away from the hills, as the Tarai clays gradually increase in thickness over the Bhabar boulders and gravels. Consequent to the thinning down of the Bhabar aquifers, and the interception of the water-table by topographic profile, accompanied by the sharp reduction in hydraulic gradient as a result of increased thickness of the Tarai clays, springs emerge along this zone, and form the southern limit of the Bhabar zone. This implies that most of the water lost underground by infiltration or seepage in the Bhabar zone (recharge zone) reappear as springs towards the Tarai zone, which thus forms the discharge zone.

In the Bhabar and Intermontane (Doon alluvial fill) zones groundwater occurs mainly under water table conditions except in few places in the latter (Intermontane Zone) where the formations are shallow and are underlain by confined beds of the Siwalik Formation and/or where few lenses of clay beds are encountered within the shallow aquifers as in Morhanwala and Nanakpur, giving rise to locally flowing conditions. Most groundwater in the Tarai zone occurs under
confined to semi-confined conditions. However, local variations are common both in the Bhabar as well as in the Tarai zones.

Landsat images on bands 5 and 7 on 1:000000 scale (Fig. 80a) and false colour composites (bands 4, 5 and 7) of the research area on 1:250,000 scale were also studied in order to identify the Bhabar and Tarai zones. Conventional photo interpretation techniques were employed in the analysis of imageries.

On the imageries the Bhabar zone shows light tone and braided stream pattern, indicating presence of coarse sediments beneath; whereas the Tarai zone exhibits comparatively darker tone and is characterized by meandering streams, which are normally developed over the fine sediments (Fig. 80a, b). The springs on the imageries appear as dark spots. The spring line has also been located on the imageries. Knickpoints are characteristic features along the spring courses in the vicinity of the spring line (Fig. 80a, b). The spring line delineates the northern Bhabar zone from the southern Tarai zone. It may be recalled that studies of subsurface lithology of the research area indicated the existence of a springline which results from conspicuous lithological variation along the boundary of the Bhabar and the Tarai zones. Field
FIG. 80a PHOTOGRAPH OF THE LANDSAT IMAGE OF THE REGION ON BAND(7) NASA-ERTSE-2039-04452
FIG. 80b SIMPLIFIED REGIONAL GEOLOGICAL MAP SHOWING THE RESEARCH AREA PREPARED FROM LANDSAT IMAGES NASA-ERTSE-2039-04452 (5,7)
observations also confirm the delineation of the Bhabar and Tarai zones from the imageries.

Pande et al. (1968), Rao (1973), Andrusevick (1978), Singh and Tewari (1978), Singh and Dogra (1980, 1983) and others have also delineated the Bhabar and Tarai zones along the springline in other parts of the Indo-Gangetic Alluvial Plains.

AQUIFER PARAMETERS

The principal hydraulic characteristics (or aquifer parameters) that permit quantitative analysis of its water bearing properties include Transmissivity, $T$ (coefficient of Transmissibility), Hydraulic conductivity, $K$ (coefficient of permeability) and storativity, $S$ (Storage - coefficient). These hydraulic characteristics of the area under investigation have been discussed below.

TRANSMISSIVITY ($T$):

Transmissivity (also referred to as coefficient of Transmissibility) is the rate at which water of a prevailing kinetic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient (Todd, 1980). In units of common use, it may be expressed as the rate of flow of water in square metres per day ($m^2/d$) through a vertical strip one metre wide of the entire
saturated thickness of the aquifer under a unit hydraulic gradient at the prevailing temperature of the water. In an aquifer of uniform thickness, the transmissivity, \( T \) has the dimension \( L^2/T \) and is the product of coefficient of permeability (hydraulic conductivity), \( K \), and the thickness of the aquifer, \( b \), expressed in \( m^2/d \) (Marino and Luthin, 1982).

According to Johnson (1983) an aquifer whose transmissivity is less than 12.42 \( m^2/d \) can supply only enough water for domestic wells and the like; whereas well with transmissivity values of 124.2 \( m^2/d \) or more have adequate well yield for industrial, municipal, or irrigation purposes. The transmissivity values of wells in the Bhabar zone of the research area vary from 2,635 \( m^2/d \) to 4,992 \( m^2/d \) whereas in the Tarai zone transmissivity values range from 733 \( m^2/d \) to 2,932.4 \( m^2/d \) (Table 26), indicating that the well yields are suitable for industrial, municipal and irrigation purposes (Johnson, 1983).

**HYDRAULIC CONDUCTIVITY, \( K \) (Coefficient of Permeability):**

This refers to the rate of flow of water in cubic metres per day that is transmitted through one square metre cross sectional area of the aquifer at the prevailing field temperature of 15.6°C (60°F). If the flow is that occurring at the prevailing temperature of the water, the term field
hydraulic conductivity is applied. Field hydraulic conductivity is related to Transmissivity by the formula \( P_m = T \) (Olmsted et al., 1973), where \( P \) is the field hydraulic conductivity, \( m \) is the saturated thickness of the aquifer in metres and \( T \) is the Transmissivity.

Hydraulic conductivities in the Bhabar and Tarai zones of the research area vary from 19.5 m/d to 171 m/d and 9.21 m/d to 49.5 m/d, respectively (Table 26).

STORATIVITY (S):

The storativity (Storage Coefficient) of an aquifer is the volume of water released from or added to storage, per unit surface area of the aquifer, per unit fall or rise in the component of head normal to that surface (Ferris et al., 1962).

Storativity in confined aquifer results from compressibility of the water and the elastic nature of the aquifer. As such storage coefficients under confined-semi-confined conditions in the Tarai zone are small, varying from 11.8x10^{-4} to 4.7x10^{-3} in the Barsu Majra-Fatehgarh areas. In water table aquifers, storativity values are controlled by the drainage characteristics of the aquifer materials. In the Bhabar zone where groundwater occurs mainly under water table conditions storativity values are higher.
and range between $1.8 \times 10^{-1}$ at Ratewali and $2.2 \times 10^{-2}$ at Fatehpur-I. This is because the volume of water involved in gravity drainage far exceed the volume that may be attributed to compressibility of water bearing materials and of water in the saturated zone. Lohman (1972) also observed that storativity values in confined aquifers are generally low, varying from $10^{-5}$ to $10^{-3}$, whereas under water table conditions they range from $0.01$ to $0.35$.

**METHODS OF DETERMINING AQUIFER PARAMETERS**

Hydraulic properties of the aquifers can be determined by various laboratory and field techniques (Bouwer, 1978; Todd, 1980). Some of these laboratory methods are useful only for small samples of water bearing materials and do not portray natural field conditions. The field techniques give more accurate results and are generally preferred. As such pumping tests were conducted in the area for determination of aquifer parameters. The details of these pumping tests are discussed below:

**PUMPING TESTS:**

During the present investigations, aquifer performance tests were carried out at two sites in collaboration with Groundwater Cell, Agricultural Department, Haryana in an attempt to determine the aquifer characteristics of wells in the research area.
The first pump test site was located in village Karanpur, about 10 km from Pinjore, on the Pinjore-Nalagarh Road. The observation well was located 133.5 m away, east of the pumped well. A 8 HP diesel engine was run at an average discharge of 11.36 l/s (981 m³/d). Effects of pumping were measured in the observation well tapping the same aquifer during the period of pumping. Pumping was run continuously for about three hours when water level in the observation well became stable. The pump was stopped and the rate of recovery was observed in the observation well till water level attained its original position.

The data obtained from the pumping test was processed by (1) Theis non equilibrium method; (2) Chow's method and (3) Theis Recovery Method. The results obtained from processing the data of the Karanpur well by the above methods are tabulated in Table 24 and plotings are shown in figures 81 to 83.

NON-STEADY METHOD OF THEIS:

The Theis solution involve a graphical procedure (as described herein) for the computation of T and S values.

The drawdown s values are plotted against $r^2/t$ values on a double logarithmic graph paper and a 'type curve' of the Theis well function is prepared on a separate double logarithmic graph paper by plotting values of $W(u)$ against $u$. (Fig. 81).
Fig. 81: PUMPING TEST DATA ANALYSIS BY THEIS METHOD, SUPERPOSITION (NON EQUILIBRIUM EQUATION) FOR KARANPUR WELL.
The observed data plot is then placed over the type curve, keeping the coordinate axes of both the data plot and the type curve parallel until the position of best match between the two curves is located. An arbitrary match point (x) on the matching curves is then selected on the overlapping portion of the two curves. The coordinates of the matching points are read on both graph sheets to yield the values of s, \( r^2/t \), u and W(u).

These values are then substituted in the Theis equation for computation of T and S as shown below in the computation of T and S for Karanpur well using Theis method:

From the graphs (Fig. 81) of s vs. \( r^2/t \) and W(u) vs u (and their matching points)

\[
W(u) = 4.8
\]

\[
u = 4.9 \times 10^{-3}
\]

\[
s = 0.145\text{m}
\]

\[
r^2/t = (295 \times 1440) \text{ m}^2/\text{d} = 424800 \text{ m}^2/\text{d}
\]

\[
Q = 180 \text{ USGPM (981.2 m}^3/\text{d)}
\]

Applying the equation:

\[
T = \frac{Q}{4\pi s} W(u) = \frac{4709.76}{1.822} = 2584.94 \text{ m}^2/\text{d}
\]

Substituting for S and applying equation

\[
S = \frac{4Tu}{r^2/t} = \frac{4 \times 2584.94 \times 4.9 \times 10^{-3}}{424800} = 0.00012
\]
CHOW'S METHOD:

Chow (1952) developed a direct method which does not involve the curve matching procedure of Theis, and is not restricted to small values of \( r \) and large values of \( t \) as in Jacob's method.

Chow's Function, \( F(u) = \frac{N(u)}{2.3} \)

enables determination of \( N(u) \) and \( u \) corresponding to the drawdown, \( s \) and time, \( t \). (Kruseman and De-Ridder, 1976).

Chow's method involves plotting of drawdown, \( s \) on the ordinate versus time, \( t \) of the observation well on a single or semilogarithmic graph paper, with the \( t \) on the abscissa or logarithmic scale (Figs. 82 and 85).

An arbitrary point \( A \) is then selected on the curve, and the slope of the tangent to the curve at \( A \) is read on the \( s \) ordinate as the drawdown difference for one
When $F(u) = 3.6$

\[
\begin{align*}
S_A &= 0.2 \text{ m} \\
\Delta S_A &= 0.056 \text{ m} \\
t &= \frac{(30/1440)}{2102} \text{ day} = 2 \times 10^{-2} \\
F(u) &= \frac{0.2}{0.056} = 3.6
\end{align*}
\]

When $F(u) = 3.6$

\[
\begin{align*}
u &= 1.3 \times 10^{-3} \\
W(u) &= 7 \\
T &= 2733.1 \text{ m}^2/d \\
S &= 0.0003
\end{align*}
\]

FIG 82 PUMPING TEST DATA BY CHOW'S METHOD (KARANPUR WELL)
log cycle of time. The value of $F(u)$ for the point $A$ is then calculated from the equation $F(u) = \frac{s_A}{\Delta s_A}$ as shown below in Chow's method for the Karanpur well:

From the graph (Fig. 82)

$s_A = 0.2$ m

$\Delta s_A = 0.056$ m

t $= 2 \times 10^{-2}$ (30/1440) day

$F(u) = \frac{0.2}{0.056} = 3.6$

From Chow (1952) standard graph in Bouwer (1978)

When $F(u) = 3.6$

$u = 1.3 \times 10^{-3}$

$W(u) = 7$

\[
T = \frac{Q}{4\pi s} W(u) = \frac{281.2 \times 7}{4 \pi \times 0.2} = 6868.4 = 2733.1 \text{ m}^2/\text{d}
\]

\[
S = \frac{47 u}{r^2/t} = \frac{4\times 2733.1 \times 1.3 \times 10^{-3}}{33.5^2/2 \times 10^{-2}} = 14.21 = 0.0003
\]

THEIS' RECOVERY METHOD

If pumping in a test well is stopped the water level in the observation well will cease to go down but will rather tend to rise to the original level.

Theis has presented an equation for determining transmissivity from the recovery data
where, $T = \text{Transmissivity}$

$Q = \text{Discharge or recharge rate in m}^3/\text{day}$

$t = \text{time since pumping started in days}$

$t' = \text{time since pumping stopped in days}$

$\Delta s' = \text{change in residual drawdown in m.}$

If the value of $t/t'$ is selected per log cycle

the equation above reduces to

$$T = \frac{2.3Q \log t/t'}{4\pi \Delta s'}$$

Theis' recovery method involves plotting the values of residual drawdown, $s'$ versus $t/t'$ on semi-logarithmic graph paper with the $t/t'$ values on the logarithmic scale; and a straight line fitted through the plotted points (as in Fig. 83). The slope of the line is equal to $2.3Q/4\pi T$ and also to the change $\Delta s'$ in $s'$ per unit log cycle.

The Theis' recovery method enables calculation of $T$ but cannot furnish the value of $S$. It is, therefore, useful as a check on the value of Transmissivity calculated from pumping test as shown below in the Theis' method for the Karanpur well:
\[ \Delta s' = 0.066 \text{ m} \]

\[ Q = 981.2 \text{ m}^3/\text{d} \]

\[ T = \frac{2.3 Q}{4.41 \Delta s'} \]

\[ = 2722.27 \text{ m}^2/\text{d} \]

FIG. 83 PUMPING TEST DATA ANALYSIS BY THEIS' RECOVERY METHOD (KARANPUR WELL)
From the graph, Fig. 83

\[ \Delta s' = 0.066 \, \text{m} \]

Applying the formula

\[ T = \frac{2.3Q}{4\pi \Delta s'} \]

\[ T = \frac{2.3 \times 981.2}{4\pi \times 0.006} \times \frac{2256.76}{0.829} = 2722.27 \, \text{m}^2/\text{day} \]

The second aquifer performance test was conducted at Fatehpur. The pumping test was carried out for 220 minutes at a constant discharge rate of (1.334 m$^3$/minute) 1921 m$^3$/d and the observations on drawdown were recorded in an observation well located at a distance of 15 m. from the test well. Maximum drawdown recorded during pumping was 0.16 m. The data was processed by the C.E. Jacob's method and Chow's method in order to determine the aquifer parameters (T and S). The results obtained from processing the data of the Fatehpur well are tabulated in Table 25 and plottings are shown in Figs. 84 and 85.

JACOB'S METHOD:

Cooper and Jacob (1946) on the basis of the Theis formula developed a method generally referred to as the Jacob's method or Jacob's solution.

In the Jacob's method, drawdown, s values are plotted against time, t on semi logarithmic graph paper.
\[ \Delta S = 0.07 \text{m} \]
\[ t_0 = 2,144.4 \text{ days} = 1.903 \times 10^3 \text{ days} \]
\[ Q = 134,144 \text{ m}^3/\text{d} \]
\[ r = 15 \text{ m} \]
\[ S = 0.08982 \]

**FIG. 84 PUMPING TEST DATA ANALYSIS BY JACOB'S METHOD (FAKHPUR SHALLOW WELL)**
with \( t \) on the logarithmic scale (Fig. 84). A straight line is drawn through the plotted points, with the line extended to intersect the abscissa at a zero drawdown. This point is read to obtain the value of \( t_0 \).

The drawdown difference, \( \Delta s \) per log-cycle of time is determined and the values of \( Q \) and \( \Delta s \) are substituted in equation, \( T = \frac{2.3Q}{4\pi \Delta s} \) (where \( \Delta s \) = drawdown difference in metres per log cycle of time) to calculate \( T \). Substituting \( T \) and \( t_0 \) in equation \( S = \frac{2.25 T t_0}{\pi^2} \) (where \( S \) = storage coefficient, \( T \) = Transmissivity; \( t_0 \) = intercept of straight line drawn at zero drawdown in days) (Kruseman and De Ridder, 1976), yields \( S \) as below in the computation of \( T \) and \( S \) for Fatehpur well by Cooper-Jacob’s solution:

From the graphs (plots) of time vs drawdown (Fig. 84)

\[
\begin{align*}
\Delta s & = 0.07 \text{m} \\
t_0 & = 2 = 2/1440 \text{ days} = 1.39 \times 10^{-3} \\
Q & = 1.334 \times 1440 \text{ m}^3/\text{d} = 1920.96 \text{ m}^3/\text{d} \\
t & = 15 \text{min}
\end{align*}
\]

Applying Jacob’s formula:

\[
T = \frac{2.3Q}{4\pi \Delta s} = \frac{2.3 \times 1920.96}{4\pi \times 0.07} = \frac{4418.208}{0.8796} = 5022.979 \text{ m}^2/\text{d}
\]

\[
= 5022.974 \text{ m}^2/\text{day}
\]
Substituting for $S$ in the formula:

$$S = \frac{2.25 \times 5022.974 \times 1.39 \times 10^{-3}}{225} = 0.06982$$

Storage coefficient = 0.06982

**CHOW'S METHOD:**

(For Fatehpur Shallow well) (Fig. 85)

From the graph, Fig. 85

$$s_A = 0.08 \text{ m}$$

$$d_{s_A} = 0.07 \text{ m}$$

$$t_A = \frac{29}{1440} \text{ per day} = 0.02014$$

$$F(u) = \frac{s_A}{d_{s_A}} = \frac{0.08}{0.07} = 1.143$$

From Chow (1952) standard graph in Bouwer (1978)

$$W(u) = 2.75$$

$$u = 0.034$$

Substituting the above values for $T$

In the formula $T = \frac{Q}{4 \pi s}$

$$T = \frac{1920.96 \times 2.75}{4 \pi \times 0.08} = \frac{5282.64}{1.0053} = 5254.79 \text{ m}^2/\text{day}$$

$$S = \frac{4T u}{r^2/t} = \frac{4 \times 5254.79 \times 0.034}{225/0.02014} = \frac{714.65144}{11171.797} = 0.064$$
FIG. 85 PUMPING TEST DATA ANALYSIS BY CHOW'S METHOD (FATEHPUR SHALLOW WELL)

\[
\begin{align*}
S_A &= 0.08 \text{ m} \\
\Delta S_A &= 0.07 \text{ m} \\
T_A &= 29 \text{/1440 per day} = 0.02034 \\
F(u) &= 0.08 \\
W(u) &= 1.143 \\
T &= 2.75 \\
S &= 0.054 \\
\Delta S_A &= 0.07 \text{ m}
\end{align*}
\]
SUMMARISED RESULTS OF PUMPING TESTS AT KARANPUR AND FATEHPUR SITES

### TABLE 24
RESULTS OF PUMPING TEST AT KARANPUR SITE

<table>
<thead>
<tr>
<th>Method used</th>
<th>Transmissivity (T) in m²/d</th>
<th>Storage coefficient</th>
<th>Fig. number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Theis' non-Equilibrium method</td>
<td>2584.94</td>
<td>0.0001</td>
<td>81</td>
</tr>
<tr>
<td>2. Chow's method</td>
<td>2733.1</td>
<td>0.0003</td>
<td>82</td>
</tr>
<tr>
<td>3. Theis' Recovery Method</td>
<td>2722.3</td>
<td>-</td>
<td>83</td>
</tr>
<tr>
<td>Adopted values</td>
<td>2680.1</td>
<td>0.0002(2.0x10⁻⁴)</td>
<td></td>
</tr>
</tbody>
</table>

### TABLE 25
RESULTS OF PUMPING TEST AT FATEHPUR SITE

<table>
<thead>
<tr>
<th>Method</th>
<th>Transmissivity</th>
<th>Storage coefficient</th>
<th>Fig. number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Jacob's method</td>
<td>5022.974</td>
<td>0.06982</td>
<td>84</td>
</tr>
<tr>
<td>2. Chow's method</td>
<td>5254.74</td>
<td>0.064</td>
<td>85</td>
</tr>
<tr>
<td>Adopted values</td>
<td>5138.8</td>
<td>0.067(6.7x10⁻²)</td>
<td></td>
</tr>
</tbody>
</table>
The values of $T$ and $S$ (Tables 24 and 25) for the Karanpur and Fatehpur wells, respectively by the above methods, viz: Theis' method, Jacob's method, Chow's method and Theis' Recovery method are close to each other, and signify the applicability of these methods for computing aquifer parameters in the research area.

Walton (1970) suggested that aquifer tests should be carried out for at least 8 hours duration, and may even extend for periods of one week or more. As indicated above, only short-duration pump tests were conducted at two well sites, which are also limited to very small portion of the research area. However, long duration pump tests had been carried out in parts of the Bhabar and Tarai zones of the research area viz; Manakpur, Fatehpur, Ratewali, Laha, Dera, Kotla, Naraingarh, Fatehgarh, Shazadpur etc. by the Haryana State Minor Irrigation and Tubewells Corporation (HSMITC) and the Central Ground Water Board, respectively. The results of these pumping tests are shown in Map 7 at the respective drilling sites and also tabulated in Table 26. These results are adopted in this work for describing the aquifer parameters of the research area.

The study of Table 26 and Map 7 indicates that Transmissivity values in the Intermontane valley/Bhabar
TABLE 26

SUMMARY OF RESULTS OF PUMP TESTS CONDUCTED BY C.G.W.B. AND H.S.M.I.T.C. IN THE BHABAR AND TARAI ZONE OF THE RESEARCH AREA

<table>
<thead>
<tr>
<th>Name of Well Site</th>
<th>S.W.L. (m)</th>
<th>Discharge (m³/d)</th>
<th>Drawdown (m)</th>
<th>Transmissivity T (m²/d)</th>
<th>Coeff. Permeability K (m/d)</th>
<th>Storage Coefficient (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+Manakpur</td>
<td>42.99</td>
<td>5996</td>
<td>6.21</td>
<td>2500</td>
<td>31</td>
<td>2.10x10⁻²</td>
</tr>
<tr>
<td>Karonpur</td>
<td>4.4</td>
<td>981</td>
<td>5.6</td>
<td>2680</td>
<td>55</td>
<td>2.0x10⁻⁴</td>
</tr>
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<td>Dhimla</td>
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+C.G.W.B.
*H.S.M.I.T.C.
**C.G.W.B. and H.S.M.I.T.C.
zones are higher than in the Tarai zone. For instance, in the intermontane valley areas of Karanpur and Dhamla, Transmissivity values vary from 2277 m$^2$/d to 2680 m$^2$/d. In the Bhabar zone Transmissivity values range from 2635 m$^2$/d at Ratewali to 4992 m$^2$/d at Fatehpur II; whereas in the Tarai zone, the values range between 733 m$^2$/d (Naraingarh) and 2932.4 m$^2$/d at Akbarpur. The Transmissivity value at Kotla in the Bhabar Intercone area is however, low and may be attributed to the location of Kotla near the Bhabar Tarai boundary.

The map also shows that Hydraulic Conductivity values and storativities are higher in the Bhabar zone and the values decrease towards the Tarai zone. The storativity and hydraulic conductivity values vary from $1.8 \times 10^{-1}$ (Ratewali) and 171 m/d (Fatehpur I) to $2.2 \times 10^{-2}$ (Fatehpur I) and 19.5 m/d (Ratewali) respectively in the Bhabar zone; whereas in the Tarai zone, the respective values range from $1.18 \times 10^{-4}$ (Basu Majra) and 9.21 m/d (Akbarpur) to $4.7 \times 10^{-3}$ (Fategarh) and 49.5 m/d (Basu Majra). The above values indicate that the aquifers of the intermontane valley and the Bhabar zone are more productive than the Tarai aquifers.

According to Marino and Luthin (1982) and Johnson (1983) storativity values for water table aquifers range from $1.0 \times 10^{-1}$ to $3.5 \times 10^{-2}$ whereas values for confined
aquifers vary from $1.0 \times 10^{-3}$ to $1.0 \times 10^{-5}$. The values of storativity of Bhabar aquifers (Map 7, Table 26) indicate that groundwater in the zone occurs under water table conditions. Storativity values at Dhamla and Karanpur areas (Intermontane valley) signify confined to semi-confined conditions. In the Tarai zone, storativity values are low ($4.7 \times 10^{-3}$ to $11.8 \times 10^{-4}$) indicating confined conditions. These results confirm the inferences drawn from subsurface correlation sections on the nature of occurrence of groundwater in the research area. As indicated earlier, local variations occur in both the Intermontane valley/Bhabar- and Tarai zones. Generally, the discharge of the wells decreases from the Bhabar zone towards the Tarai zone. The values range from 34.71 l/sec to 69.37 l/sec (3000 m$^3$/d to 5996 m$^3$/d) in the Bhabar zone, and 23.11 l/sec to 54.30 l/sec (2007 m$^3$/d to 4693 m$^3$/d) in the Tarai zone (Table 26). The discharge of the well at Karanpur in the Intermontane valley is, however, low (11.35 l/sec or 981 m$^3$/d).

According to Johnson (1983) an aquifer whose transmissivity is less than 1000 gpd per ft ($12.42 \text{ m}^2/\text{d}$) can supply only enough water for domestic wells and the like. Where the transmissivity is on the order of 10,000 gpd per ft. ($124.2 \text{ m}^2/\text{d}$) or more, well yield can be adequate for industrial, municipal or irrigation purposes. Transmissivity
values of the aquifers in the Intermontane valley/Bhabar and Tarai zones of the research area which generally vary from \(733 \text{ m}^2/\text{d}\) to \(5996 \text{ m}^2/\text{d}\) (Table 26) therefore, indicate that well yield in the region is adequate for industrial, municipal and irrigation purposes.

INVENTORY OF WELLS AND ANALYSIS OF WATER LEVEL DATA

Seventy three hydrograph stations which include 21 dugwells from the Intermontane and Bhabar zone and 51 dugwells in the Tarai zone of the research area were inventoried from June 1984 to October 1986. Pre-monsoon and post-monsoon repeat water level measurements were made each year during the months of June and October, respectively, in these wells as to establish the depth to water level and water level fluctuations in the area. The pre-monsoon and post-monsoon water level data of the area for the period June 1981 to October 1983 were obtained from the records of the Agricultural Department, Groundwater Cell, Haryana. The location of the observation wells monitored by the author are shown in Map 8. Statistical data about depth to water level for the pre- and post-monsoon periods for the Bhabar and Tarai zones, including short term and long term variations in water level are presented in Table 27.

Depth to water level maps for the pre- and post-monsoon periods have been prepared on the basis of field
data observed in year 1984 (Maps 9a and 9b). Water level contour maps have also been prepared on the basis of observations made in the year 1984 as to know the hydraulic gradient and the groundwater flow direction in the region (Maps 10a and 10b). Hydrographs showing water level fluctuations and the relationship between rainfall and groundwater levels in the research area based on 1981-1986 data are given in (Figs. 86, 87 and 88).

DEPTHS TO WATER LEVEL

The observation wells (dugwells) range in depth from 4.17 m at Mansa Devi to 42.99 m at Manakpur in the Bhabar zone and 2.21 m to 18.17 m in Sunderpur-Shazanpur villages of the Tarai zone (Table 27). About 82.4% of the observation wells have total depths varying from about 2 m to 15 metres below ground level, whereas only about 17.6% of the dugwells tap aquifers of more than 15 m.b.g.l. The diameter of the dugwells vary from 1.37 m (Devi Nagar) to 3.28 m at Milk Jublin.

The wells in the North and Northeastern parts of the research region (Intermontane and Bhabar zones) are generally deeper, varying in depth up to 42.99 m at Manakpur, but are shallower in the south and southeastern parts of the Tarai zone. This indicates that water table occurs at fairly great depths in the Intermontane valley and Bhabar
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<th>Water Level (in metres)</th>
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zones, whereas in the Tarai zone watertable occurs at
Shallower depths.

The depth to water level in these observation
wells varies from place to place and is generally
influenced by factors such as topography, closeness to
rivers or other sources of recharge, etc. The maximum
depth to water level in the Bhabar zone, was recorded at
Manakpur in June 1982 (42.99 m.b.g.l.) whereas minimum
water level was recorded at Nadah in October 1981 (2.7
m.b.g.l). In the Tarai zone depth to water level varies
from 1.62 metres below ground level (Khera Jattan,
October, 1983) to 14 m.b.g.l. (Piawala, June, 1982).

Generally depth to water levels is shallower in
Naraingarh District of Tarai zone which gradually increases
towards the north. Maximum depths to water level are
observed in wells located near the Siwalik hills (in the
Intermontane valley and Bhabar zones) whereas shallower
depths occur in wells situated near the rivers and towards
the south and southwest (Tarai zone). It will be recalled
from the subsurface lithological correlation sections that
the thick aquifer beds in the northern Intermontane and
Bhabar zones thin down towards the south and southeast as
the Tarai clays gradually increase in thickness over the
Bhabar and Intermontane boulders, gravels and medium to
coarse sands. The high water table conditions in the
southern and southeastern parts of the research area (Tarai zone) may be attributed partly to the low hydraulic conductivity of the aquifer materials and predominance of clay beds in the Tarai zone. As a result of small sub-surface outflow (reduced pore spaces) in these clay beds, compaction and capillary effects force pore water to rise rapidly out of fine clay beds through warm holes, fissures and minute cavities in the clay beds.

GROUNDWATER FLOW DIRECTION

As in surface flow, groundwater also moves in the direction of decreasing head, but its rate of movement through granular materials, such as in the research area, is only a small fraction in relation to surface water movement, and its path is much more complex.

During the present investigation, water table contour maps have been prepared for Pre- and post-monsoon periods of year 1984 (June and October) to study the direction of movement of groundwater under natural conditions in the research area.

A perusal of the groundwater contour maps (Maps 10a and 10b) reveals that the general slope of water table, follows approximately the topography of the area. The altitude of water table ranges from 290 m to 445 m above the mean sea level in the area.
WATER TABLE CONTOUR MAP OF PARTS OF AMBALA DISTRICT
AND
ADJOINING SIWALIK HILLS
JUNE 1984

SCALE
0 5 10 Km

LEGEND
STATE BOUNDARY
BLOCK BOUNDARY
WATER TABLE CONTOUR IN METRES A.M.S.L
GROUNDWATER FLOW DIRECTION
RIVERS / STREAMS
HYDROGRAPH STATION
BLOCK HEADQUARTERS
WATER TABLE CONTOUR MAP OF PARTS OF AMBALA DISTRICT AND ADJOINING SIWALIK HILLS

OCTOBER 1984

LEGEND

STATE BOUNDARY
BLOCK BOUNDARY
WATER TABLE CONTOUR
IN METRES A.M.S.L.
GROUNDWATER FLOW DIRECTION
RIVER / STREAMS
WATER LEVEL STATIONS
BLOCK HEADQUARTERS
The general direction of groundwater movement in the region as inferred from the water table contour map is from Northeast to Southwest. The flow follows the surface slope and runs approximately parallel to the river courses. However, it appears that changes in river stage affect the direction of groundwater flow locally. For instance, during the monsoon periods, when river stage is high in the study area, the direction of flow of groundwater immediately around the river tend to be slightly perpendicular and radial in the north-central part of the research area (in the vicinity of Bhurawali, Shajanpur, Garhi Kotaha) as water flows from the river into the aquifer. During the summer months of June, when the river stage is low, the direction of groundwater flow tend to become more parallel to the river edge, although flow is still from the river to the aquifer.

A reverse in the direction of movement of the groundwater in the region is observed at the extreme northwestern direction (Intermontane valley). From the region where a water-divide exists in the Pinjore region, groundwater flows from southeast to the northwestern direction parallel to the principal direction of the flow of the river Sirsa; and in accordance with the slope of the area. Groundwater flow in the area is controlled by topography, the lithology as well as river stage.
The water table contours are more convex in the northern parts and concave towards the south and southwestern parts of the research area. According to Todd (1980), convex contours indicate regions of groundwater recharge, whereas concave contours are associated with zones of groundwater discharge. Hydraulic conductivities and permeabilities are moderately high as indicated by the wide contour spacings (flat gradient). The hydraulic gradient of the water table is steeper in the north and northeastern parts of the research area (Bhabar zone/Intermontane valley) where it varies between 2.1 metres per kilometre and 3.02 m per kilometre and gradually flattens towards the south and southwestern Tarai zone to about 0.76 metres per kilometre.

GROUNDWATER LEVEL FLUCTUATIONS

Water table fluctuations are influenced by the forces affecting recharge or discharge from the groundwater reservoir. Rise in water table occurs when groundwater recharge exceeds discharge, whereas fall in water table indicate a reverse order. The rate and magnitude of water table fluctuation during any period portray the net effect of the recharge or discharge during the particular period.

Meinzer (1942) pointed out that the rate and amount of groundwater recharge is related to precipitation which is the source of supply and to such other factors that
relate intake facilities (temperature and soil conditions of the aquifer), which determine the proportion of rain water that reaches the subterranean reservoir. Precipitation, evapo-transpiration, run-off, temperature and soil conditions of the aquifer constitute the variables which more or less affect the groundwater. Fluctuations in these variables are responsible for the fluctuations of the groundwater table. Recharge is affected by such factors as infiltration from rainfall and influent seepage from surface water bodies, groundwater inflow, etc; whereas discharge is influenced by the rate of evapo-transpiration, effluent seepage into streams, groundwater outflow, pumping from wells, etc.

Water level fluctuations in the research area, are mainly controlled by local rainfall pattern, hydraulic conductivity of the soils and aquifer materials, quantity of storage of groundwater in the catchment area and tubewell pumping for agricultural and domestic purposes. Since groundwater in the region occurs in most cases under water table condition in the top phreatic aquifers, groundwater level fluctuations observed in some of the observation wells represent the fluctuations of the water table.

Figures 86 to 88 show the plots of the water level fluctuations for the entire region. A perusal of the figures indicate that maximum water level fluctuations occurs in the unconfined areas of the Bhabar and Intermontane
zones or recharge zone, where it ranges up to 5.61 metres (Shahpur, October 1983 to June 1984). The Bhabar and Intermontane wells are more sensitive to rainfall in the region. This disparity between the Bhabar/Intermontane valley wells and the more southerly Tarai wells may be accounted for by the varying hydraulic conductivities of the Bhabar/Intermontane and Tarai zones which are also related to the lithology of the zones. Lithologically, the Bhabar/Intermontane zones are constituted of boulders, cobbles, pebbles, coarse sands and intercalated clays and have higher hydraulic conductivities as compared with the Tarai sediments which are chiefly clays, sandy clays, fine sand and silt. The Bhabar wells are also located nearer to the Siwalik hill slopes than the southerly Tarai wells.

The porous Bhabar beds which feed the wells slope moderately towards the south and southeast, and the slopes receive heavier rainfall and support dense forests. Direct evaporation and transpiration through vegetation on the non-artesian aquifer zones of the Bhabar cause great variation in water table especially when water surface is relatively near the surface soil. The thick clay bed covers and the confined conditions in the Tarai zone reduce evapo-transpiration. According to Ekstrom (1948) in his study of infiltration in relation to permeabilities of Swedish soils, the low hydraulic conductivity of clay soils causes rapidly increasing ground water levels at heavy precipitation but the textural pores in
clay soils are so fine that any flow of fresh water is out of question. However, the hydraulic conductivity of clay soils is entirely dependent on presence of instertices in the clay. It may here be remarked that the different types of aquifers in the Bhabar and the Tarai zones of the research area have different degrees of sensitivity which is related to the size of the detritus, the permeability of the aquifer, and above all in the case of the Tarai confined to semi confined aquifers with the thickness of the covering layer and its ability to absorb and regain water.

Groundwater fluctuations in the Intermontane valley, the Bhabar and Tarai zones of the research area exhibit peculiar characteristics, and are greatly influenced by the rainfall pattern in the region. The hydrographs (Figs. 86 to 88) show that groundwater levels in the wells begin to rise in the month of July following abundant monsoon rain in June, and continues upto the end of August. In the months of October, subsequent to reduced amount of rainfall in the region, water levels start to recede. The fall season is between the months of November and June. Generally, water levels rise to maximum heights in October when infiltration becomes abundant following rapid saturation of the soil water zone with the rainfall; and sink to greatest depths in the summer months of June because groundwater runoff exceeds afflux, and infiltration is
FIG. 87

WATER LEVEL FLUCTUATIONS IN TARAI ZONE OF RAIPUR RANI BLOCK
(JUNE 1981 - OCT. 1986)

MONTHLY RAINFALL DATA
insignificant as water is used up by vegetation and by the process of evaporation. It can be inferred from the hydrographs that groundwater recharge in the region does not occur immediately with the commencement of the monsoon rains in late June. This is because the fraction of rainfall reaching the water table is influenced by the water balance left after its disposal as evapo-transpiration, soil moisture recharge, surface runoff, etc. Although the hydrographs indicate appreciable rainfall during the months of April-May, the precipitation is insufficient to compensate for losses from evaporation and transpiration during the summer peak period.

It is also observed that the wells which have groundwater hydraulically well connected with surface water bodies as in Hamidpur, Milk Jublin, Shahpur, Patwi, etc. show highest amplitude of water level fluctuations. This is because the groundwater body is very well connected with the surface water of the rivers or is in their vicinity. The response and rise of water levels in these wells is related to the distance of the well from the surface waterbody (river). The nearer the well to the river, the quicker its response and the higher the rise and/or fall in the water level, corresponding to the fluctuations of water level in the rivers.

Wells located between two river profiles in the region show small amplitudes (Lower fluctuations). This
MONTHLY RAINFALL DATA

(JUNE 1981 – OCT. 1986)
may be due to the fact that hydraulic connection between the groundwater and the surface river water is not all that good. As such rise in water levels in response to recharge after the rains or due to increased discharge of bounding rivers is late, hence fluctuations are correspondingly smaller in amplitude. Generally, rivers serve as control on groundwater system and can influence groundwater levels and reflect changes in those levels.

Groundwater pumping lowers groundwater levels by inducing drawdown and change in water table gradient. Hurr (1981) observed that groundwater withdrawals in relatively close proximity to rivers influence groundwater levels by initiating drawdowns and causing river-stage decline that may induce a further reduction in groundwater levels downstream. Tubewell pumping for agricultural and domestic purposes especially in the rich agricultural lands of Naraingarh and Raipurani Blocks also contribute to water level fluctuations.

HISTORICAL WATER LEVEL BEHAVIOUR:

The water level data for 34 representative hydrograph stations (12 from Intermontane valley/Bhabar zone and 22 from the Tarai zone or 3 from Pinjore Block, 16 from Raipur Rani and 15 from Naraingarh Block, have been studied from June 1981 to June, 1986 in order to ascertain the historical water level behaviour in the
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<th>Water Level Fluctuations</th>
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**Notes:**
- Depth to water level in meters.
- Zone/Valley Name and Location.
- **Intermontane Valley/Hubber Zone**
- **Reasi Rebel**
- **Barrani**
- **Talens Zone (Reasi Beli)**
- **Talens Zone (Barrani)**

**Table 20**

- Depth to Water Level of Representative Hydrograph Stations and Water Level Fluctuations in the Research Area (1981 - 1986) in Meters.
the research area. Prior to this period, groundwater levels were not monitored by the State Groundwater organizations. The module of natural recharge and exploitable groundwater resources of the research area have also been studied on the basis of these 34 hydrograph stations and are discussed in Chapter IX of this work.

The Pinjore Block lies partly in the Intermontane valley and the Bhabar zone. From June 1981 to June 1984 groundwater level in the Pinjore Block showed a rising trend in response to increased rainfall in the area. From June 1981 to June 1982 the water level rose by 0.14 m as the amount of rainfall in the area increased from 935 mm to 1062 mm (Table 28) during the respective years. Between June 1982-83 and June 1983-84, rise of 0.01 m and 0.69 m for the respective periods were recorded in the Pinjore Block. From June 1984 to June 1986 gradual decline in water levels (-3.03 m in 1984-85; and -0.06 m in 1985-86) occurred in the Pinjore Block in response to precipitation deficit (903 mm in 1984 to 686 mm in 1985) (Table 29). The historical water level data in the Pinjore Block between June 1981 to June 1986 is marked by characteristic rise and fall in response to increased or decreased rainfall in the area. From June 1981 to June 1986, the water levels in the Pinjore Block showed an average annual depression of -0.45 m.
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Source of Data: Groundwater Cell, Agriculture Department, Haryana

Average rainfall for Kalka (1981-1985) = 1007.8 mm
Average rainfall for Narasingarh (1981-1985) = 1168.6 mm
The Raipur Rani and Naraingarh Blocks form small portions of the Bhabar zone and constitute the major parts of the Tarai zone. The average yearly water level recession from June 1981 to June 1986 in the Raipur Rani and Naraingarh Blocks are -3.04 m and -3.25 m respectively. From June 1981 to June 1982 a water level depletion of -3.85 m occurred in Raipur Rani Block (Table 29). The water level in the Block rose by 1.9 m and 1.8 m between June 1982-83 and June 1983-84 respectively in response to increased rainfall (Table 29). The period, June 1984 to June 1985 witnessed a sharp fall (-16.83 m) of water levels even though the rainfall during the period was slight. Between June 1985-86 the water level rose by 1.78 m. The water levels in the Raipur Rani Block showed from June 1981 to June 1986 an average fall of -1.31 m. However, the historical water level in the Raipur Rani Block is characterized by alternating rise and fall depending upon the amount of rainfall.

In the Naraingarh Block, a depletion of -0.39 m occurred between June 1981 and June 1982. The water level rose by 4.53 m between June 1982-83, but showed a constant depletion from June 1983 to June 1986, irrespective of increase or decrease in amount of rainfall. Between June 1983-84, 1984-85 and June 1985-86, the water levels in the
Naraingarh Block receded by -9.15 m, -9.67 m and -1.59 m, respectively. The June 1983-84 water level recession may be attributed to the decrease in rainfall in Naraingarh area from 1599 mm to 799 mm during the respective years. Although there was an increase in rainfall in the area from 1984-to 1986 (799 mm to 1055 mm) a continuous depletion in water levels occurred in the Naraingarh area. Field observations show that the number of tubewells and dugwells with pumpsets have recently been increased in the Tarai zones of Raipur Rani and Naraingarh (especially in the latter) for pumping water for irrigation and domestic purposes, and these contribute tremendously to water level depletion in the areas. Groundwater resources and landuse pattern form the topic of the later Chapter (Chapter IX).

Generally, the water level behaviour is influenced by rainfall pattern in the region. Declining trend in water level occurred during the years of less rainfall in the Intermontane/Bhabar zone of Pinjore Block as well as in the Bhabar/Tarai zones of Raipur Rani and Naraingarh respectively. However, the continuous decline in water level in the Tarai zones of Raipur Rani and Naraingarh particularly in the latter, seem to have been contributed by groundwater overdrafting in the area due to heavy pumpage for agricultural and domestic purposes and also by rapid evapo-transpiration in the shallow water table zone.