HYDROGEOLOGY OF PART OF
SOUTH-EASTERN BANGLADESH

A Thesis
submitted for the Degree
of
Doctor of Philosophy

by

S. M. MAHABUB-UL-ALAM

DEPARTMENT OF GEOLOGICAL SCIENCES
UNIVERSITY COLLEGE LONDON
1990.
TO MY MOTHER

AND

TO THE MEMORY OF MY FATHER
ABSTRACT

The present study covers 10,223 km² of the Ganges, Jamuna and Meghna river's delta, at the head of the Bay of Bengal, which was deposited in a geosynclinal environment. The morphometry of the delta was controlled by three geomorphological units, recognised as geological formations. The main aquifer comprises primarily the sandy Dupitila Formation, of Pliocene age, which is composed of unconsolidated sands showing a gradation of grain size. Finer sands are at the top with the sequence coarsening downwards; the coarse sand at the bottom is usually associated with gravels and pebbles. The thickness of the aquifer ranges from 30 m to 120 m. The aquifer is almost entirely covered by a clay/silt aquiclude of thickness ranging from <3 m to >300 m.

The loss of ground water storage during the dry season is restored rapidly and regularly by the rising water table reflecting monsoon conditions. The complicated flow behaviour suggests that all the perennial rivers maintain direct hydraulic continuity with the ground water. The flow-net analysis also reveals uniform distribution of water resource potential.

Borehole pumping tests indicate a true confined condition for the smaller eastern part while leaky confined conditions prevail elsewhere. The maximum and minimum transmissivity range from >1400 m²/d to <400 m²/d while the storativty ranges from 4.1 x 10⁻³ to 3.7 x 10⁻⁴ and the maximum leakage (BL = 368 m) is recorded around Burichong. The values of well loss factor (Cₐ) and aquifer loss factor (Bₐ) suggest highly efficient well conditions as deduced from the calculation of well efficiency and the analysis of yield-drawdown curves.

The ground water towards the outcrop appears to have been an essentially NaHCO₃ type in nature but, as it moves, hydrochemical evolution modifies the ground water into a mixed NaHCO₃/Cl type. Three major and two minor ion exchange fields were identified. The expanded Durov plot was most successful in identifying the existence of two different types of water, the dominant type being the ion-exchanged water and the less dominant but equally well defined type being old brackish water accompanied by some reverse ion exchange water. The existence of reverse ion exchange water is further suggested by the changing chemistry along flow (flow line 2 and 3). The brackish waters are segregated in few locations and are not linked to one another. Other than the brackish water, the ground water is found to be suitable both as potable as well as irrigation sources. The saturation indices calculated by means of the PHREEQE hydro-chemical model for Calcite and Dolomite establishes a unique linear relationship emphasising that the older and deeper waters are mainly super-saturated and the young waters are under-saturated with respect to these minerals, with few exceptions.

The water balance computation and the present rate of withdrawal indicates a huge recharge surplus so that the aquifer may be regarded as in a youthful state of development. The perennial yield is estimated to be about 5.7 x 10⁹ m³/year and the present rate of ground water withdrawal is about 37 percent of the perennial yield, suggesting a huge ground water potential yet to be exploited.
## CONTENTS

<table>
<thead>
<tr>
<th>CONTENTS</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONTENTS</td>
<td>i</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xv</td>
</tr>
<tr>
<td>LIST OF APPENDICES</td>
<td>xix</td>
</tr>
</tbody>
</table>

## CHAPTER 1 INTRODUCTION

1.1 Purpose and Scope ........................................... 2
1.2 Acknowledgements ........................................... 3
1.3 Size and Location of the Study Area  ....................... 4
1.4 Physiography and Topography .................................. 4
1.5 Soil Type and Characteristics ................................. 7
   1.5.1 Flood Plain Soils ........................................ 8
   1.5.2 Piedmont Soils ........................................... 8
   1.5.3 Hill Soils ............................................ 9
1.6 Climatic Conditions .......................................... 10
1.7 Vegetation and Land Use ....................................... 13
1.8 River System .................................................. 14
1.9 Well Numbering System ........................................ 16
1.10 Previous Studies ............................................. 18
### CHAPTER 2 GEOMORPHOLOGY AND GEOLOGY

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 Introduction</td>
<td>21</td>
</tr>
<tr>
<td>2.2 Major Geomorphic Units</td>
<td>22</td>
</tr>
<tr>
<td>2.2.1 Lalmai Deltaic Plain</td>
<td>28</td>
</tr>
<tr>
<td>2.2.2 Chandina Deltaic Plain</td>
<td>30</td>
</tr>
<tr>
<td>2.2.3 Meghna Flood Plain</td>
<td>31</td>
</tr>
<tr>
<td>2.3 Regional Geology</td>
<td>31</td>
</tr>
<tr>
<td>2.4 Surface Geology and Stratigraphy</td>
<td>32</td>
</tr>
<tr>
<td>2.4.1 Dupitila Formation</td>
<td>33</td>
</tr>
<tr>
<td>2.4.2 Madhupur Clay Formation</td>
<td>35</td>
</tr>
<tr>
<td>2.4.3 Chandina Formation</td>
<td>35</td>
</tr>
<tr>
<td>2.4.4 Flood Plain Deposits</td>
<td>36</td>
</tr>
<tr>
<td>2.5 Geologic Cross-Sections</td>
<td>36</td>
</tr>
<tr>
<td>2.6 Major Structural Trends</td>
<td>48</td>
</tr>
</tbody>
</table>

### CHAPTER 3 HYDROGEOLOGY

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 Historical Development of Wells</td>
<td>52</td>
</tr>
<tr>
<td>3.2 Aquifer System and Classification</td>
<td>54</td>
</tr>
<tr>
<td>3.3 Main Aquifer:</td>
<td>59</td>
</tr>
<tr>
<td>3.3.1 Upper Semi-Confining Layer</td>
<td>59</td>
</tr>
<tr>
<td>3.3.2 Physical Characteristics and Extent</td>
<td>61</td>
</tr>
<tr>
<td>3.3.3 Aquifer Thickness</td>
<td>62</td>
</tr>
<tr>
<td>3.3.4 Aquifer Nature</td>
<td>65</td>
</tr>
<tr>
<td>3.4 Deep Aquifers</td>
<td>64</td>
</tr>
</tbody>
</table>
CHAPTER 4  GROUND WATER FLOW

4.1 Water Level Monitoring System............................. 69
4.2 Water Level Data Used...................................... 70
4.3 Ground Water Level Fluctuation............................ 71
4.4 Water Table Contour Maps.................................. 75
  4.4.1 Introduction............................................ 75
  4.4.2 Minimum Elevation Contour Map....................... 76
  4.4.3 Maximum Elevation Contour Map....................... 82
  4.4.4 Annual Fluctuation Map............................... 86
4.5 Replenishment Calculation.................................. 88
4.6 Comments on Ground Water Movement
  and Flow Pattern............................................. 91

CHAPTER 5  AQUIFER TEST ANALYSIS

5.1 Introduction................................................. 94
  5.1.1 General Information................................... 94
  5.1.2 Well Structure......................................... 96
  5.1.3 Hydraulic Properties................................. 98
5.2 Analytical Solution........................................ 100
  5.2.1 Validity of Measurement............................... 100
  5.2.2 Selection of Methods.................................. 102
  5.2.3 Presentation and
        Discussion of Analysis................................ 108
CHAPTER 6  WELL PERFORMANCE

6.1 Step-Drawdown Tests................................. 218
  6.1.1 General....................................... 218
  6.1.2 Standard Procedures.......................... 219
  6.1.3 Test Procedures Used........................ 220
6.2 Analysis of Step-Drawdown Tests..................... 223
  6.2.1 Method Used.................................. 224
  6.2.2 Presentation of Analyses.................... 226
  6.2.3 Comments on the Results..................... 254
6.3 Well Efficiency..................................... 257
6.4 Specific Capacity................................... 262

CHAPTER 7  HYDROCHEMISTRY

7.1 Collation of Existing Chemical Analytical Data..... 267
7.2 Field Collection of Ground Water Samples.......... 268
7.3 Chemical Analysis of Ground Water Samples......... 270
7.4 Quality of Analytical Data ........................................ 271
7.5 Graphical Interpretation .............................................. 279
   7.5.1 Distribution Maps ............................................ 279
      a) Introduction .................................................. 279
      b) TDS Distribution Map ........................................ 280
      c) Sodium/ Cation Ratios ...................................... 282
   7.5.2 Stiff Pattern Diagram ......................................... 285
   7.5.3 Trilinear Diagram ............................................. 287
   7.5.4 Chemistry Along Flow Lines .................................. 287
   7.5.5 Expanded Durov Classification ................................ 292
7.6 Application of PHREEQE Hydrochemical Model .................... 294
   7.6.1 Introduction .................................................. 294
   7.6.2 PHREEQE Model ................................................. 296

7.7 Ground Water Quality .............................................. 302
   7.7.1 Drinking Water Quality ...................................... 302
   7.7.2 Irrigation Water Quality ..................................... 306

CHAPTER 8  GROUND WATER RESOURCES

8.1 Introduction .......................................................... 312
8.2 Assessment of Resources ............................................ 312
   8.2.1 Introduction .................................................. 312
   8.2.2 Ground Water Replenishment (Inputs) .................... 312
      a) Infiltration from Precipitation .......................... 314
      b) Irrigation Return Flow ...................................... 315
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Fig.</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Location of study area in Bangladesh................. 5</td>
</tr>
<tr>
<td>1.2</td>
<td>Map showing the distribution of major physiographic sub-division (After: Pitman, 1985)....... 6</td>
</tr>
<tr>
<td>1.3</td>
<td>Isohyetal map on the basis of long-term annual rainfall (1951-1985)........................... 12</td>
</tr>
<tr>
<td>1.4</td>
<td>Distribution of major primary and secondary rivers in the study area.......................... 15</td>
</tr>
<tr>
<td>2.1</td>
<td>Location of study area in tectonic map of Bangladesh.................................................. 22</td>
</tr>
<tr>
<td>2.2</td>
<td>Estimated thickness contours of sediments in the Bengal Basin (Source: Mirkhamidov and Mannan, 1986)................................... 23</td>
</tr>
<tr>
<td>2.3</td>
<td>Geological cross-section along selected lines across the Bengal Basin (After: Pitman, 1985)....... 24</td>
</tr>
<tr>
<td>2.4</td>
<td>Generalized geology of Bangladesh and adjoining areas (Sources: Holtrop and Keizer, 1970; Alam, 1985; Jones, 1985)............................ 26</td>
</tr>
<tr>
<td>2.5</td>
<td>Depth to Basement in Bangladesh (Source: Aeromagnetic survey, O.D.A., 1980; Jones, 1985)...... 27</td>
</tr>
<tr>
<td>2.6</td>
<td>Geology of the study area (After: Bakr, 1976)........ 29</td>
</tr>
<tr>
<td>2.7</td>
<td>Distribution of the identifiable lithological well logs.................................................. 34</td>
</tr>
<tr>
<td>2.8</td>
<td>Correlation of lithological units along the line 'A-B'............................................. 39</td>
</tr>
<tr>
<td>2.9</td>
<td>Correlation of lithological units along the line 'B-C'............................................. 40</td>
</tr>
<tr>
<td>2.10</td>
<td>Correlation of lithological units along the line 'C-D'............................................. 42</td>
</tr>
<tr>
<td>2.11</td>
<td>Correlation of lithological units along the line 'E-B'............................................. 44</td>
</tr>
</tbody>
</table>
2.12 Correlation of lithological units along the line ‘F-G’................................. 46

2.13 Distribution of major structural trends (Compiled from Bakr, 1976 and McDonald and Partners, 1986).............................. 49

3.1 Geological cross-section along ‘A-B’ line showing the distribution of both the main aquifer and the deeper aquifers of Bangladesh (After: Jones, 1985)...... 55

3.2 Geological cross-section along ‘C-D’ line showing the distribution of both the main aquifer and the deeper aquifers of Bangladesh (After: Jones, 1985)...... 56

3.3 Idealized W-E cross-sectional view of the main aquifer across the Lalmai Hills showing the recharge pattern................................. 58

3.4 Thickness distribution of the surficial clay/silt (aquiclude) layers........................ 60

3.5 Thickness distribution map of the main aquifer...... 63

4.1 Ground water level fluctuation................................. 72

4.2 Water table contour map of minimum elevation (dry period) March 1985............................ 77

4.3 Major flow direction based on minimum elevation contour map................................. 79

4.4 Water table contour map of maximum elevation (wet period) August 1985..................... 83

4.5 Major flow direction based on maximum elevation contour map................................. 84

4.6 Contour map showing annual fluctuation for 1985..... 87

5.1 Map showing the location of aquifer testing wells... 95

5.2 Generalised structure of the constructed wells...... 97

5.3.A Aquifer test analysis for OW1 at Feni; (a) Type Curve and (b) Straight Line.............. 111

viii
<table>
<thead>
<tr>
<th>Fig.</th>
<th>Aquifer test analysis for OW at location;</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.3.B</td>
<td>OW2 at Feni; (a) Type Curve and (b) Straight Line</td>
<td>113</td>
</tr>
<tr>
<td>5.3.C</td>
<td>OW3 at Feni; (a) Type Curve and (b) Straight Line</td>
<td>115</td>
</tr>
<tr>
<td>5.3.D</td>
<td>Feni; (a) Type Curve and (b) Straight Line</td>
<td>117</td>
</tr>
<tr>
<td>5.4.A</td>
<td>OW1 at Nabinagar; (a) Type Curve and (b) Straight Line</td>
<td>121</td>
</tr>
<tr>
<td>5.4.B</td>
<td>OW2 at Nabinagar; (a) Type Curve and (b) Straight Line</td>
<td>123</td>
</tr>
<tr>
<td>5.4.C</td>
<td>OW3 at Nabinagar; (a) Type Curve and (b) Straight Line</td>
<td>125</td>
</tr>
<tr>
<td>5.4.D</td>
<td>Nabinagar; (a) Type Curve and (b) Straight Line</td>
<td>128</td>
</tr>
<tr>
<td>5.5.A</td>
<td>OW1 at B’Baria; (a) Type Curve and (b) Straight Line</td>
<td>132</td>
</tr>
<tr>
<td>5.5.B</td>
<td>OW2 at B’Baria; (a) Type Curve and (b) Straight Line</td>
<td>133</td>
</tr>
<tr>
<td>5.5.C</td>
<td>OW3 at B’Baria; (a) Type Curve and (b) Straight Line</td>
<td>134</td>
</tr>
<tr>
<td>5.6.A</td>
<td>OW1 at Daudkandi; (a) Type Curve and (b) Straight Line</td>
<td>138</td>
</tr>
<tr>
<td>5.6.B</td>
<td>OW2 at Daudkandi; (a) Type Curve and (b) Straight Line</td>
<td>139</td>
</tr>
<tr>
<td>5.6.C</td>
<td>OW3 at Daudkandi; (a) Type Curve and (b) Straight Line</td>
<td>140</td>
</tr>
<tr>
<td>5.7.A</td>
<td>OW1 at Burichong; (a) Type Curve and (b) Straight Line</td>
<td>144</td>
</tr>
<tr>
<td>5.7.B</td>
<td>OW2 at Burichong; (a) Type Curve and (b) Straight Line</td>
<td>145</td>
</tr>
<tr>
<td>5.7.C</td>
<td>OW3 at Burichong; (a) Type Curve and (b) Straight Line</td>
<td>146</td>
</tr>
</tbody>
</table>
Fig. 

5.8.A Aquifer test analysis for OW1 at Chandina;  
(a) Type Curve and (b) Straight Line................. 149

5.8.B Aquifer test analysis for OW2 at Chandina;  
(a) Type Curve and (b) Straight Line................. 150

5.8.C1 Aquifer test analysis for OW3 at Chandina;  
(a) Type Curve and (b) Straight Line................. 151

5.8.C2 Aquifer test analysis for OW3 at Chandina;  
(a) Type Curve and (b) Straight Line................. 152

5.9.A Aquifer test analysis for OW1 at Kotwali;  
(a) Type Curve and (b) Straight Line................. 156

5.9.B Aquifer test analysis for OW2 at Kotwali;  
(a) Type Curve and (b) Straight Line................. 157

5.9.C Aquifer test analysis for OW3 at Kotwali;  
(a) Type Curve and (b) Straight Line................. 158

5.10.A Aquifer test analysis for OW1 at Barura;  
(a) Type Curve and (b) Straight Line.................. 161

5.10.B Aquifer test analysis for OW2 at Barura;  
(a) Type Curve and (b) Straight Line.................. 162

5.10.C Aquifer test analysis for OW3 at Barura;  
(a) Type Curve and (b) Straight Line.................. 163

5.11.A Aquifer test analysis for OW1 at Hazigang;  
(a) Type Curve and (b) Straight Line.................. 167

5.11.B Aquifer test analysis for OW2 at Hazigang;  
(a) Type Curve and (b) Straight Line.................. 168

5.11.C Aquifer test analysis for OW3 at Hazigang;  
(a) Type Curve and (b) Straight Line.................. 169

5.12.A Aquifer test analysis for OW1 at Chauddagram;  
(a) Type Curve and (b) Straight Line.................. 173

5.12.B Aquifer test analysis for OW2 at Chauddagram;  
(a) Type Curve and (b) Straight Line.................. 174

5.12.C Aquifer test analysis for OW3 at Chauddagram;  
(a) Type Curve and (b) Straight Line.................. 175
5.13.A Aquifer test analysis for OW1 at Senbagh; (a) Type Curve and (b) Straight Line............... 178

5.13.B Aquifer test analysis for OW2 at Senbagh; (a) Type Curve and (b) Straight Line............... 179

5.13.C Aquifer test analysis for OW3 at Senbagh; (a) Type Curve and (b) Straight Line............... 180

5.14 Inflow due to leakage in a Confined aquifer....... 184

5.15(a) Basis of Numerical technique for radial flow model (Confined aquifer).................. 184

5.15(b) Discrete space - discrete time grid with radial distance increasing logarithmically (After: Rushton 1979)................................. 184

5.16(a) Pictorial definition of drawdown $S_f$ and $S_b$...... 187

5.16(b) Problems involving variable saturated depth.... 187

5.17.A Comparison of (a) Manual and (b) Model result from Feni OW1............................. 191

5.17.B Comparison of (a) Manual and (B) Model result from Feni OW2............................. 192

5.17.C Comparison of (a) Manual and (b) Model result from Feni OW3............................. 193

5.18.A Comparison of (a) Manual and (b) Model result from Nabinagar OW1....................... 194

5.18.B Comparison of (a) Manual and (b) Model result from Nabinagar OW2....................... 195

5.18.C Comparison of (a) Manual and (b) Model result from Nabinagar OW3....................... 196

5.19 Response of the simulation with different values of sensitive parameters......................... 197

5.20 Distribution of transmissivity in the study area.................................................. 216

6.1 Location map showing the step testing wells....... 221
<table>
<thead>
<tr>
<th>Fig.</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.2</td>
<td>228</td>
</tr>
<tr>
<td>6.3</td>
<td>229</td>
</tr>
<tr>
<td>6.4</td>
<td>231</td>
</tr>
<tr>
<td>6.5</td>
<td>233</td>
</tr>
<tr>
<td>6.6</td>
<td>234</td>
</tr>
<tr>
<td>6.7</td>
<td>236</td>
</tr>
<tr>
<td>6.8</td>
<td>237</td>
</tr>
<tr>
<td>6.9</td>
<td>238</td>
</tr>
<tr>
<td>6.10</td>
<td>240</td>
</tr>
<tr>
<td>6.11</td>
<td>242</td>
</tr>
<tr>
<td>6.12</td>
<td>243</td>
</tr>
<tr>
<td>6.13</td>
<td>245</td>
</tr>
<tr>
<td>6.14</td>
<td>247</td>
</tr>
<tr>
<td>6.15</td>
<td>249</td>
</tr>
<tr>
<td>6.16</td>
<td>251</td>
</tr>
<tr>
<td>6.17</td>
<td>252</td>
</tr>
<tr>
<td>Fig.</td>
<td>Description</td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
</tr>
<tr>
<td>6.18</td>
<td>Step-drawdown test; Eden and Hazel solution for Chandpur well</td>
</tr>
<tr>
<td>6.19</td>
<td>Yield-drawdown plot for all sites</td>
</tr>
<tr>
<td>6.20</td>
<td>Theoretical and actual plot of specific capacity vs. transmissivity for all tests</td>
</tr>
<tr>
<td>7.1</td>
<td>Map showing the quality well locations</td>
</tr>
<tr>
<td>7.2</td>
<td>Hydrochemical contour map of total dissolved solids (mg/L)</td>
</tr>
<tr>
<td>7.2(a)</td>
<td>Modified contour map of total dissolved solids (TDS) in mg/L</td>
</tr>
<tr>
<td>7.3</td>
<td>Hydrochemical ratio distribution of sodium to total cations</td>
</tr>
<tr>
<td>7.4</td>
<td>Pattern distribution of major hydrochemical constituents</td>
</tr>
<tr>
<td>7.5</td>
<td>Piper diagram showing the hydrochemical distribution of ground water samples in terms of major ion percentages. Size of symbol is proportional to TDS (mg/L)</td>
</tr>
<tr>
<td>7.6</td>
<td>Map showing the selected flow lines from the Figure 4.5</td>
</tr>
<tr>
<td>7.7</td>
<td>Variation in ground water chemistry (arrow represent sequential directions of flow)</td>
</tr>
<tr>
<td>7.8</td>
<td>Classification of ground water types using the expanded Durov diagram: I, Ion exchanged waters; II, Old brackish water with some reverse ion exchange</td>
</tr>
<tr>
<td>7.9</td>
<td>Map showing the distribution of two water types</td>
</tr>
<tr>
<td>7.10</td>
<td>Plot showing the linear relationship between Calcite and Dolomite SI value</td>
</tr>
<tr>
<td>7.11</td>
<td>Plot showing the random distribution of Calcite and Siderite SI value</td>
</tr>
</tbody>
</table>
7.12 Plot showing the range of combined sodium and salinity hazard for classification of irrigation water quality......................... 308

8.1 Hydrograph showing the base-flow and surface run-off component................................. 319

8.2 Hydrograph showing the base-flow and surface run-off component................................. 320

8.3 Hydrograph showing the base-flow and surface run-off component................................. 321

8.4 Hydrograph showing the base-flow and surface run-off component................................. 322

8.5 Map showing the subsurface peripheral inflow and outflow zones................................. 325

8.6 Hydrograph showing the base-flow and surface run-off component................................. 339

8.7 Hydrograph showing the base-flow and surface run-off component................................. 340
<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Measured rate of infiltration through various types of clay.</td>
<td>11</td>
</tr>
<tr>
<td>2.1</td>
<td>Geological succession and aquifer potential</td>
<td>37</td>
</tr>
<tr>
<td>4.1</td>
<td>Comparison of hydraulic gradient in the two seasons</td>
<td>81</td>
</tr>
<tr>
<td>4.2</td>
<td>Volumetric changes covering the entire region</td>
<td>89</td>
</tr>
<tr>
<td>5.1</td>
<td>Pumping test analysis results (analytical) of Feni Well; (a) Time-Drawdown and (b) Distance-Drawdown</td>
<td>110</td>
</tr>
<tr>
<td>5.2</td>
<td>Pumping test analysis results (analytical) of Nabinagar Well; (a) Time-Drawdown and (b) Distance-Drawdown</td>
<td>119</td>
</tr>
<tr>
<td>5.3</td>
<td>Pumping test analysis results (analytical) of B'Baria Well; (a) Time-Drawdown and (b) Distance-Drawdown</td>
<td>131</td>
</tr>
<tr>
<td>5.4</td>
<td>Pumping test analysis results (analytical) of Daudkandi Well; (a) Time-Drawdown and (b) Distance-Drawdown</td>
<td>137</td>
</tr>
<tr>
<td>5.5</td>
<td>Pumping test analysis results (analytical) of Burichong Well; (a) Time-Drawdown and (b) Distance-Drawdown</td>
<td>142</td>
</tr>
<tr>
<td>5.6</td>
<td>Pumping test analysis results (analytical) of Chandina Well; (a) Time-Drawdown and (b) Distance-Drawdown</td>
<td>148</td>
</tr>
<tr>
<td>5.7</td>
<td>Pumping test analysis results (analytical) of Kotwali Well; (a) Time-Drawdown and (b) Distance-Drawdown</td>
<td>155</td>
</tr>
<tr>
<td>5.8</td>
<td>Pumping test analysis results (analytical) of Barura Well; (a) Time-Drawdown and (b) Distance-Drawdown</td>
<td>160</td>
</tr>
</tbody>
</table>
Table

5.9 Pumping test analysis results (analytical)
of Haziganj Well; (a) Time-Drawdown and
(b) Distance-Drawdown............................166

5.10 Pumping test analysis results (analytical)
of Chauddagram Well; (a) Time-Drawdown and
(b) Distance-Drawdown............................171

5.11 Pumping test analysis results (analytical)
of Senbagh Well; (a) Time-Drawdown and
(b) Distance-Drawdown............................177

5.12 Aquifer test results of Feni Well; (a) Numerical
results and (b) Overall comparison of results
obtained by all the methods..................... 203

5.13 Aquifer test results of Nabinagar Well; (a) Numerical
results and (b) Overall comparison of results
obtained by all the methods.......................204

5.14 Aquifer test results of B’Baria Well; (a) Numerical
results and (b) Overall comparison of results
obtained by all the methods......................... 205

5.15 Aquifer test results of Daudkandi Well; (a) Numerical
results and (b) Overall comparison of results
obtained by all the methods......................... 206

5.16 Aquifer test results of Burichong Well; (a) Numerical
results and (b) Overall comparison of results
obtained by all the methods......................... 207

5.17 Aquifer test results of Chandina Well; (a) Numerical
results and (b) Overall comparison of results
obtained by all the methods......................... 208

5.18 Aquifer test results of Kotwali Well; (a) Numerical
results and (b) Overall comparison of results
obtained by all the methods......................... 209

5.19 Aquifer test results of Barura Well; (a) Numerical
results and (b) Overall comparison of results
obtained by all the methods......................... 210

5.20 Aquifer test results of Haziganj Well; (a) Numerical
results and (b) Overall comparison of results
obtained by all the methods......................... 211

xvi
Table

5.21 Aquifer test results of Chauddagram Well; (a) Numerical results and (b) Overall comparison of results obtained by all the methods.............. 212

5.22 Aquifer test results of Senbagh Well; (a) Numerical results and (b) Overall comparison of results obtained by all the methods.......................213

6.1 Comparison of step-drawdown test results............. 255

6.2 Verification of Lennox (1966) conditions for obtaining good results............................258

6.3 Quantitative assessment of well efficiency factor................................261

6.4 Specific capacity data at 100 minutes and 1000 minutes for all the pumping wells........... 265

7.1 Results of chemical analysis of ground water in the Comilla-Noakhali region (1976-1987)....... 272

7.1(a) Summary of ionic-balance and comparison of TDS........................................275

7.2 A modified form of the Phreeq model calculated result output for well: 144....................... 297

7.3 Summary of saturation indices of certain mineral matrix....................................299

7.4 Comparative tabulation of potable water quality in terms of various ions with selected international standards.................. 304

7.5 Comparative study of the irrigation water quality in terms of various types of hazards.............. 310

8.1 Sub-surface Inflow of ground water along various Zones across the boundary.............. 327

8.2 Separation of various soil moisture components using the Grindley model (1969).............. 331

8.3 Estimated crop coefficient ($K_{\text{crop}}$) for various kinds of rice in Comilla-Noakhali region......... 334

8.4 Separation of various soil moisture components using the Agnew model (1982)................ 335

xvii
<table>
<thead>
<tr>
<th>Table</th>
<th>Subsurface Outflow of ground water along various Zones across the boundary.</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.5</td>
<td>Page 343</td>
</tr>
<tr>
<td>8.6</td>
<td>First ground water budget using the $I_*$ value calculated by the Grindley (1969) and Agnew (1982) model.</td>
</tr>
<tr>
<td>8.7</td>
<td>Second ground water budget using the $I_*$ value calculated from the ground water fluctuation contour map.</td>
</tr>
</tbody>
</table>
## LIST OF APPENDICES

<table>
<thead>
<tr>
<th>Appendix</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1 Seasonal water level measurements used to draw various types of contour maps</td>
<td>370</td>
</tr>
<tr>
<td>5.1 Pump test data for all test sites</td>
<td>374</td>
</tr>
<tr>
<td>5.2.1 Rushton numerical (Radial Flow) model</td>
<td>384</td>
</tr>
<tr>
<td>5.2.2 Model data plotting program</td>
<td>388</td>
</tr>
<tr>
<td>5.2.3 Program to draw Time Drawdown Type Curve plot</td>
<td>291</td>
</tr>
<tr>
<td>5.2.4 Program to draw Time Drawdown Straight Line plot</td>
<td>392</td>
</tr>
<tr>
<td>5.3.1.A Comparison of (a) Manual (b) Model results from B'Baria OW1</td>
<td>394</td>
</tr>
<tr>
<td>5.3.1.B Comparison of (a) Manual (b) Model results from B'Baria OW2</td>
<td>395</td>
</tr>
<tr>
<td>5.3.1.C Comparison of (a) Manual (b) Model results from B'Baria OW3</td>
<td>396</td>
</tr>
<tr>
<td>5.3.2.A Comparison of (a) Manual (b) Model results from Daudkandi OW1</td>
<td>397</td>
</tr>
<tr>
<td>5.3.2.B Comparison of (a) Manual (b) Model results from Daudkandi OW2</td>
<td>398</td>
</tr>
<tr>
<td>5.3.2.C Comparison of (a) Manual (b) Model results from Daudkandi OW3</td>
<td>399</td>
</tr>
<tr>
<td>5.3.3.A Comparison of (a) Manual (b) Model results from Burichong OW1</td>
<td>400</td>
</tr>
<tr>
<td>5.3.3.B Comparison of (a) Manual (b) Model results from Burichong OW2</td>
<td>401</td>
</tr>
<tr>
<td>5.3.3.C Comparison of (a) Manual (b) Model results from Burichong OW3</td>
<td>402</td>
</tr>
<tr>
<td>5.3.4.A Comparison of (a) Manual (b) Model results from Chandina OW1</td>
<td>403</td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>5.3.4.B</td>
<td>Comparison of (a) Manual (b) Model results from Chandina OW2</td>
</tr>
<tr>
<td>5.3.4.C1</td>
<td>Comparison of (a) Manual (b) Model results from Chandina OW3</td>
</tr>
<tr>
<td>5.3.4.C2</td>
<td>Comparison of (a) Manual (b) Model results from Chandina OW3</td>
</tr>
<tr>
<td>5.3.5.A</td>
<td>Comparison of (a) Manual (b) Model results from Kotwali OW1</td>
</tr>
<tr>
<td>5.3.5.B</td>
<td>Comparison of (a) Manual (b) Model results from Kotwali OW2</td>
</tr>
<tr>
<td>5.3.5.C</td>
<td>Comparison of (a) Manual (b) Model results from Kotwali OW3</td>
</tr>
<tr>
<td>5.3.6.A</td>
<td>Comparison of (a) Manual (b) Model results from Barura OW1</td>
</tr>
<tr>
<td>5.3.6.B</td>
<td>Comparison of (a) Manual (b) Model results from Barura OW2</td>
</tr>
<tr>
<td>5.3.6.C</td>
<td>Comparison of (a) Manual (b) Model results from Barura OW3</td>
</tr>
<tr>
<td>5.3.7.A</td>
<td>Comparison of (a) Manual (b) Model results from Haziganj OW1</td>
</tr>
<tr>
<td>5.3.7.B</td>
<td>Comparison of (a) Manual (b) Model results from Haziganj OW2</td>
</tr>
<tr>
<td>5.3.7.C</td>
<td>Comparison of (a) Manual (b) Model results from Haziganj OW3</td>
</tr>
<tr>
<td>5.3.8.A</td>
<td>Comparison of (a) Manual (b) Model results from Chauddagram OW1</td>
</tr>
<tr>
<td>5.3.8.B</td>
<td>Comparison of (a) Manual (b) Model results from Chauddagram OW2</td>
</tr>
<tr>
<td>5.3.8.C</td>
<td>Comparison of (a) Manual (b) Model results from Chauddagram OW3</td>
</tr>
<tr>
<td>5.3.9.A</td>
<td>Comparison of (a) Manual (b) Model results from Senbagh OW1</td>
</tr>
</tbody>
</table>
5.3.9.B Comparison of (a) Manual (b) Model results from Senbagh OW2......................420

5.3.9.C Comparison of (a) Manual (b) Model results from Senbagh OW3......................421

6.1 Program to analyze step-drawdown tests (Eden and Hazel method)...........................422

7.1 Program to plot trilinear diagram...................... 424

7.2.1 (a) Plot showing constituents of ground water samples in terms of major ion percentages, (b) Piper-Hill (1944) sub-division for classification of ground water types........... 427

7.2.2 (a) Plot of the constituents of ground water samples in terms of major ion percentages, (b) Back’s (1961, 1966) classification diagram for anion and cation facies.................. 428

8.1 Program to draw river discharge hydrograph....... 429

8.2 Program to separate base-flow from hydrograph................................. 430
CHAPTER 1  INTRODUCTION

1.1 Purpose and Scope.
1.2 Acknowledgements.
1.3 Size and Location of the Project Area.
1.4 Physiography and Topography.
1.5 Soil Type and Characteristics.
1.6 Climatic Conditions.
1.7 Vegetation and Land Use.
1.8 River System.
1.9 Well Numbering System.
1.10 Previous Studies.
1.1 Purpose and Scope:

The south-eastern part (Comilla-Noakhali region) of Bangladesh includes some of the best agricultural land in the country which produces significant amounts of crops thereby playing a vital role in alleviating part of the serious food shortages of the nation. Although there is too much water in Bangladesh during summer time (May-October), which occasionally causes floods, being an area that enjoys tropical monsoonal climatic conditions, it also suffers serious shortages of surface water during the winter period (November-April). This is because of prolonged dry conditions when normal rainfall virtually ceases and surface-water flow dramatically reduces to its lowest level. At that time the ground water resource is the only alternative source of irrigation water to ensure normal crop production. As a result, huge amounts of ground water are withdrawn seasonally from underground storage.

Another important cause of concern is the occurrence of poor quality and saline ground water in several locations which poses a serious threat to the quality of the existing ground water resources. All these background problems have encouraged the author to carry out a detailed hydrogeological study using the latest available conventional and selected numerical techniques to extract as much information as possible. The purpose of the study is to evaluate the present state of ground water potential of these finite resources, to devise a possible solution as to how they can best be utilized for irrigation, and to maximise their potability without disturbing the ecological balance. More importantly, there is a need to understand the extent of occurrence and the pattern of distribution of the existing saline ground water problem within the study area.

The entire research work is based on, firstly, the collection of pre-existing hydrogeological data, and secondly, on subsequent field sampling done during two seasonal visits to the project area.
1.2 Acknowledgements:

The author extends his particular gratitude to his supervisor Mr. Glyn P. Jones for excellent hydrogeological tuition and expresses sincere thanks for his guidance, patient explanation of the more difficult concepts, and above all for spending valuable time correcting the manuscript.

The author also expresses his gratitude to Dr. G. T. K. Pitman, the former World Bank adviser for the Bangladesh National Water Planning Project, for his encouragement to take up a Bangladeshi project and more importantly for playing the key role in supplying the existing relevant data.

Special and heartful thanks are due to Mrs. Susan White for her wholehearted co-operation from the very beginning of the M.Sc./Diploma course in all respects, particularly her skilful computing lessons which have played a vital role during the computer analysis of most of the data.

Sincere thanks are due to Dr. J. M. McArthur for discussions of the hydrochemical data analysis. Thanks and acknowledgements are also extended to Dr. Thabit Madhi-Bashi, one of author’s colleagues for his helpful computing assistance.

The Association of Commonwealth Universities are owed extra special thanks for selecting the author as one of their Commonwealth Scholars in the first place, and their subsequent financial support.

The co-operation of all fellow research workers is greatly appreciated, particularly that of Mr. Masoud Al-Ahmadi for use of the hydrochemical Phreeqe model.

All academic and departmental staff who extended their support deserve special thanks, particularly, A. T. Osborn, for his assistance during the chemical analysis of water samples and Janet Baker and Colin Stuart for their help during the preparation of some of the drawings.
Finally, the author acknowledges with great pleasure, the support and encouragement that he has received from his wife, Mrs. Rukhsana Mahabub, when it was most needed.

1.3 Size and Location of the Study Area:

The present study includes the former Greater Comilla and Noakhali districts, excluding the off-shore islands, and occupies an area of some 10,223 sq. km. (about 3942 sq. ml.). It is of elongate shape and lies between Latitudes 22° 45' and 24° 16' N and Longitudes 90° 30' and 91° 34' E. To the east the area shares a common boundary with the Tripura States of India; to the west, south-west and north-west it is bounded by the Meghna river; to the north by the Madhabpur upazilla of Sylhet district, and finally to the south by the joint Meghna and Feni estuary that leads to the Bay of Bengal (see Fig. 1.1). The area is separated from the capital city of Dhaka by the Meghna river. The shortest distance between Dhaka and the study area (Daudkandi) is about 35 miles (60 km) and is linked to the capital by both road transport and rail.

1.4 Physiography and Topography:

The study area constitutes the south-eastern part of the alluvial Bengal deltaic plain, the largest in the world. The major sections of this part of the delta are formed of relatively older deltaic sediments which have developed a coastal plain along the western and south-western margins. The sequential distribution of various parts of the delta from the point of view of surface configuration, its relative position and as well as its genetic variability are so well developed that it has been divided into a number of physiographic units (Fig. 1.2) as follows: Madhupur tracts (1), Noakhali-Chittagong Coastal Plain (2), Old Meghna Estuarine Flood Plain (3), Middle Meghna Estuarine Flood Plain (4) and Young Meghna
Fig. 1.2: Map showing the distribution of major physiographic sub-divisions (after: Pitman, 1985).
Estuarine Flood Plain (5). Of these sub-divisions, the various flood plain units make up about 85 percent of the total land surface.

Physiographically, the area is bounded on the east by the Tertiary rocks of the Tripura Hills of India and by a part of their northern continuation into Bangladesh, the Raghunandan Hills; on the west the Meghna river forms the natural boundary; which to the north is formed by the hills and plain of Sylhet basin, and on the south jointly by the Meghna and Feni estuaries leading to the Bay of Bengal. From the eastern Hills, the area gently slopes in all other directions. The land is low-lying with elevations of the surface ranging from 25 ft (<8 m) above msl in the east to around 5 ft (<2 m) above msl in the south-west. The morphometry is greatly influenced by the mighty Mehgna river which defines the present arcuate shape of the area.

The Lalmai Hills are the only relic of previous geological activity that emerges like an island in the dissected tract of the alluvial plain. It is located 5-10 miles west of Comilla town and is approximately 12 miles long with a north-south elongation. They are also called the 'red hills' because of the highly oxidized surface soil cover and lateritic nature which is thought to be of Pliocene to Pleistocene age. The Lalmai Hills have a flat top which gently slopes in the east but forms a scarp in the west.

1.5 Soil Type and Characteristics:

The vast majority of the soils have developed on a flood plain background and have been classified previously by various authors (Pacheco, 1970; Islam, 1973) on the basis of physiographic units taking into account the dominant composition material, texture and degree of induration. A different approach has been adopted in the present study to classify soil types as adequate for our purposes. All the soils developed on different flood plains which were previously
identified as belonging to different series have been grouped together under the general name 'Flood Plain Soils' since they consist of almost similar materials. The soils developed on the 'Lalmai Hills' and the adjacent 'Piedmont plain' are also easily separable. The different series recognized previously for the Lalmai Hills area are grouped as 'Hill Soils' and the various series recognized in parts of Piedmont Plain are collectively called as 'Piedmont Soils'. Brief descriptions of these three different groups of soil are presented below.

1.5.1 Flood Plain Soils:

The various flood plain deposits (Old Meghna Estuarine Flood Plain, Middle Meghna Flood Plain, Young Meghna Estuarine Flood Plain and Noakhali-Chittagong Coastal Plain) are characteristically developed on similar types of gently undulating topography consisting of broad flood plain ridges and shallow basins. Most 'ridge soils' are silty loams with some clay; they are predominantly light grey to very pale brown in colour and are comparatively more friable than the basin soils. Basin soils, on the other hand, are mostly clayey loam in texture with some silty loam, and range in colour from olive to dark grey to pale brown. At the basin edges the colour grades to greyish-brown. Both ridge and basin soils:

a) in most places have developed two-layer characteristics. The top layer is neutral in reaction when flooded but mainly becomes acidic when dry. The lower layer is mainly neutral to moderately alkaline in reaction;

b) show varying degree of mottling of yellow and brown colour; and

c) are richer in plant nutrients in comparison with hill soils and piedmont soils; therefore the flood plain soils have higher potential for cultivation.

1.5.2 Piedmont Soils:

The Old Piedmont soils have developed as narrow belts both along the
piedmont plain associated with the eastern foot hills distributed along the common India-Bangladesh border and also along the base of the Lalmai Hills. The soil consists of unconsolidated silty clays and loams of yellowish-brown colour. In the better drained areas, the soils are almost entirely composed of red and yellow clay. The more recent piedmont soils have developed in the depressed Comilla basin located in between the Lalmai Hills and the Eastern border hills. These soils originated on outwash material. On gently sloping areas they takes the form of pale brown clay; on flat areas grey silty-clay to clay and in the centre of depression the soils are dark grey clays.

1.5.3 Hill Soils:

The soils which have emerged particularly on the top and along the slopes of Lalmai Hills are described using the term 'Hill soils'. The hills have a flat top and steep sided gullies. Dark-red clay soils have developed on the flat summit of the Lalmai Hills. Along the slopes the soil grades to a mixed red-brown and brown clay loam and yellow-brown sandy loam. In the depression of the Lalmai Hills the soil consists of alternate layers of pale brown sandy clay, clay and loam. These hill soils are strongly acidic, low in plant nutrients and suffer from drought in the dry season.

All three types of soils:

1) are subject to heavy rainfall; the flood plain usually becomes flooded both by rain water and flood water; the piedmont soil usually is flooded only by rain water; and the hill soil never becomes flooded;

2) appear to be rich in weatherable minerals.

The infiltration rates through the different types of soil materials have been measured by McDonald and Partners, 1985 (Table 1.1).
Table. 1.1: Measured rate of infiltration through various types of clays.

<table>
<thead>
<tr>
<th>Soil texture</th>
<th>Infiltration rate (m/d)</th>
<th>Moist</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry</td>
<td></td>
</tr>
<tr>
<td>1) fine sandy loam</td>
<td>0.48 - 2.40</td>
<td>0.048 - 0.249</td>
</tr>
<tr>
<td>2) silty loam</td>
<td>0.48 - 2.40</td>
<td>0.048 - 0.192</td>
</tr>
<tr>
<td>3) loam</td>
<td>0.48 - 2.40</td>
<td>0.396</td>
</tr>
<tr>
<td>4) silty clay loam</td>
<td>0.48 - 2.40 *</td>
<td>0.048 - 0.120</td>
</tr>
<tr>
<td>5) clay loam</td>
<td>0.48 - 2.40 *</td>
<td>0.084</td>
</tr>
<tr>
<td>6) silty loam</td>
<td>1.80 *</td>
<td>0.048 - 0.072</td>
</tr>
<tr>
<td>7) Basin clay</td>
<td>0.84 - 1.92 *</td>
<td>0.024 - 0.072</td>
</tr>
</tbody>
</table>

* increased rate due to soil cracking

The infiltration rate ranges from 24 to 192 mm/day. The soil storage co-efficient within the study area ranges from 5 to 6 percent but in the root zone this increases up to 25 percent.

1.6 Climatic conditions:

The entire Bengal deltaic plain enjoys a tropical monsoonal climatic condition, and the study area is no exception. It is characterized by moderate to high temperature, heavy rainfall, seasonally dry conditions and marked changes in each at different times of the climatic cycle. The year-round changes in the climatic pattern are marked by two primary and two secondary transitional seasons. The primary monsoon (or rainy) season is followed by the secondary post-monsoon transition season and again the primary winter (or dry) season is followed by the secondary pre-monsoon transition season.

The Monsoon, the longest of all the seasons, extends from May through September. During this period, the area receives more than 80 percent of its total annual rainfall. The Monsoon rain is not stormy but frequent, heavy and uneven and very often continues for a long time, usually from a couple of days to several days. The longer and heavy rainfall is frequently associated with floods.
High temperatures and high humidity levels prevail throughout this season.

The Winter begins in November and continues until the beginning of March, and is characterized by long dry sunny spells associated with cool northerly breezes. This period is almost rainless except for some very light scattered showers which seldom exceed 5 percent of the total annual rainfall. During this time of the year humidity falls to its lowest value and the temperature remains at a pleasant level.

The Pre-monsoon transition season, March-May, is unpleasantly very hot and characterized by thunder-storms and squalls, called 'Nor'westers', with heavy localized rainfall and hail. Both the temperature and humidity levels rise to their annual maximum levels.

The Pre-winter (Post-monsoon) transition season covers the period between late September and early November which is moderately warm and humid. The temperature and humidity levels gradually decline and the season is marked by unstable atmospheric condition. During this time of the year, rapid changes in climatic conditions takes place with decreasing rainfall. The changing climatic conditions during pre-monsoon and pre-winter transition seasons induce thunderstorms and cyclones in the Bay of Bengal which are very often catastrophic for the country.

Rainfall: The isohyetal map (Fig. 1.3) has been prepared using long-term mean annual rainfall (1951-1985) to show the rainfall distribution pattern over the area. It may be seen that the highest amounts of rainfall (>3200 mm) occur in the south-eastern part of the study area bordered by the Bay of Bengal. The lowest amounts of rainfall (<2200 mm) are distributed in a curved band which initially shows a north-west to south-east trend in the upper middle part and gradually swings in a south-westerly direction and finally maintains that trend into the Meghna river as
Fig. 1.3: Isohyetal map on the basis of long-term annual rainfall (1951 - 1985)
a result of which rainfall distribution again increases in north-west and northerly directions.

1.7 Vegetation and Land Use:

In the past, the hilly areas used to be covered by tropical forest but this has almost completely disappeared because of massive deforestation by the local people to meet the acute demand for fuel. The hills are thus left with permanent grasses (locally called 'uri'), thorny bushes, shrubs and various kinds of large tropical fruit trees. Exceptionally, small areas have been planted as deciduous forests controlled by the public sector. The elevated lands (both natural and man-made) which are not usually flooded have a dual usefulness; a minor part is used as homestead land, while the major part is used for cultivation. Most commonly, the flooded lands are devoid of any vegetation except the low and medium flooded areas on which temporary grass vegetation develops during the intervening dry season but is washed away by the next seasonal flooding.

Other than the homestead lands and hilly areas having high slopes, the entire land area is under cultivation to varying degrees. The crop distribution, cropping pattern, and cultivation practices are mainly governed by the topography, depth and duration of flooding, availability of dry period irrigation and partly by the salinity of the area. The historical cropping pattern was to produce single or double crops, mostly rice, both because of monsoonal flooding and serious shortages of irrigation water during dry season. But the availability of ground water irrigation is rapidly converting the cropping practices to a triple cropping pattern. This facilitates year-round production of crops and at the same time makes it possible to bring more and more lands under full-scale cultivation which previously had to remain as fallow during the dry season.
Rice is by-far the most important and extensive food crop grown in the area. Various kinds of rice are produced at different times of the year depending on their degree of tolerance to the prevailing climatic conditions. Traditionally, the rice varieties are called Aus, Aman and Boro/Irri. Aus is broadcast as seed in the fields during the months from March until May, and harvested between July and September. Transplanted Aman seedlings are introduced into the puddled ground between July and September, but broadcast Aman is sown in March and April and both varieties are harvested during the months of November and December. Boro/Irri is transplanted in December or January and harvested in April or May. Jute, the major cash crop, and Chilies are grown extensively in the western part of the Chandpur and Noakhali area. Betel-nut and Coconut are widespread in Chandpur and the northern part of Noakhali area. Sugar-cane is locally important. The adjoining homestead and man-made high lands are continuously used to produce both the rabi (winter varieties) and kharif (summer varieties) crops and vegetables.

1.8 River system:

The surface water distribution is mainly controlled by the large Meghna river and six other small but important perennial rivers (Fig. 1.4) which combine to form the Meghna river system. The Meghna itself is formed by the confluence of two small but important rivers, the Surma and the Kusiyara, beyond the north of study area and both these rivers originate in the Meghalaya and Assam Hills in the north-west part of India. All other perennial rivers-the Titas, the Buri, the Gumti, the Dakatia, the Little Feni and the Muhuri river leading to Feni river have their source in the eastern Tripura hills of India and depending on their direction of slope, they flow in north, west and southwardly directions and eventually most of them merge with the Meghna river. All these streams have numerous branches
Fig. 1.4: Distribution of major primary and secondary rivers in the study area.
in the form of tributaries and distributaries and by means of these all the rivers are connected with each other, thereby creating a criss-cross network producing different drainage patterns depending on surface topography and land forms.

Three different but distinct drainage patterns may be recognized in the study area. In the eastern part, the streams are typically *dendritic*, in the central part they are *rectangular*, and in the western part over the Meghna flood plain areas the streams are basically of a *braided type*. The development of rectangular drainage patterns in the central part is largely due to artificial activities undertaken to improve the irrigation channel network. All the branching tributaries and distributaries remain active during the monsoon but most of them become dry during the winter season. Detailed geological and geomorphological studies (Morgan & McIntyre, 1959; Bakr, 1976) have revealed that some of the rivers, particularly the Meghna, Titas, Gumti and Dakatia have shown significant changes in their courses during the last few hundred years. This indicates that the Meghna river system has been unstable for quite a long time. All these rivers carry enormous loads both in suspension as well as bed-load especially during monsoon, when these loads are carried away very quickly by strong currents during a sudden rise of flood flow. Then on their route, a considerable amount of erosion and scouring takes place; this phenomenon also encourages the channel shifting processes. During every major channel shifting event, there are left behind typical landscapes like abandoned meanders, ox-bow lakes and elevated sandy ridges, the remains of levees, now mostly filled-in. The Comilla-Noakhali region has been built up by the deposition of these huge amounts of sediment carried by all the rivers of the Meghna river system.

1.9 Well numbering system:

Most of the maps used in this study to illustrate the hydrogeological
conditions were produced in a modified form from two basic base maps. The first base map was prepared to show the distribution of the available identifiable lithological logs (see Fig. 2.7) and subsequently lithological cross-section maps (Figs. 2.8 to 2.12) were constructed using these locations. The numbering system of these lithological distribution map is done on an upazilla basis (an upazilla is a secondary administrative sub-division). In doing this, the number of available lithological logs for each upazilla was identified and then located in its correct location. Then the wells belonging to a particular upazilla were numbered in such a way that the well located at the northernmost point is identified as well 1 with the number increasing towards the south; for the well located at the southern most point the maximum number is allocated. This system of well numbering is repeated for all the upazillas.

The second and the most important master base map was prepared to show the wells or the water level measuring stations (Fig. 4.2), pump test wells (Fig. 5.1), step-drawdown test wells (Fig. 6.1) and the quality sample wells (Fig. 7.1). Firstly, all these wells were correctly plotted using a different symbol for different types of wells for their easy identification. Then the wells were numbered, also from north to south, but regardless of types of wells and the upazilla boundary. The entire study area was considered specifying the northern-most well as well 1 and progressively increasing the numbers towards the south with the southern-most well identified by the maximum number. During the analysis of a particular type of well, a new sub-base map was prepared from the master base map simply by deleting the other kinds of wells. Therefore, it is important to remember that the maximum number that is read in every sub-base map has arisen because of the cumulative aggregate of all types of wells in the master map.
1.10 Previous Studies:

This detailed hydrogeological study is the first of its kind that takes into account most aspects of evaluation technique, thoroughly and systematically.

A fair amount of hydrogeological work has been done for the northern part of study area covering Comilla district, either with Comilla being the project area or as part of a bigger project area. Two such studies that delineated the general hydrogeological conditions were one prepared by a United Nations team (1981) for Comilla district only, and a second prepared by IDA with the assistance of the British Overseas Development Administration (ODA) which included Comilla as part of a bigger area. This study looked in some detail at the ground water potential for irrigation and was completed by McDonald & Partners (1986). No such work had been done for the Noakhali district which also suffers from a serious shortage of basic essential data for better assessment of the ground water potential.

Three different reconnaissance studies to assess the general hydrogeological conditions of the entire country have been completed with the assistance of various international agencies, and these provided some useful information about conditions in the present study area. The first was done by the UN ground water survey (1982) and in 1985 the World Bank carried out another such study. The most up-to-date multi-disciplinary ground water related work was conducted by the Bangladesh National Water Planning Project (1986) under the supervision of Dr. Pitman. All the above-mentioned works necessarily grossly idealized and simplified the prevailing complex situation.

Reconnaissance soil studies for the area were carried out by FAO (1970) for most of the present study area, and the northern part was also studied by the Soil Resources Research Institute (SRDI, 1973). Some physical properties of the soil were experimentally established by SRDI (1977) and McDonald & Partner (1983) during the preparation of water balance studies. In addition, a wide
range of published and unpublished literature has been reviewed and relevant information extracted to make the present research work more meaningful.
CHAPTER 2 GEOMORPHOLOGY AND GEOLOGY

2.1 Introduction.

2.2 Major Geomorphic Units.
   2.2.1 Lalmai Deltaic Plain.
   2.2.2 Chandina Deltaic Plain.
   2.2.3 Meghna Flood Plain.

2.3 Regional Geology.

2.4 Surface Geology and Stratigraphy.
   2.4.1 Dupitila Formation.
   2.4.2 Madhupur Clay Formation.
   2.4.3 Chandina Formation.
   2.4.4 Flood Plain Deposits.

2.5 Geologic Cross-Sections.

2.6 Major Structural Trends.
2.1 Introduction:

The Bengal basin, of which Bangladesh is a part, is bordered to the north by the Himalayan foot hills and Shillong plateau, a large elevated uplifted faulted block of Pre-Cambrian basement rocks with an area of Cretaceous and Tertiary shelf sediments. To the west the boundary is formed by the outcropping Pre-Cambrian basement of the Indian shield which is popularly known as the Indian Platform. The eastern margin is bordered by hills of the NNW-SSE and N-S trending frontal folded zones of the Neogene phase of the Arakan-Yoma orogenic belt (Fig. 2.1).

Bangladesh lies at the head of the Bay of Bengal and occupies the central and eastern part of the Bengal Basin, a major geosynclinal feature which began to form in the Late Cretaceous period (approx. 70 million years ago) where down-warping is believed to have been continuous with and analogous to the Sub-Himalayan fore-deep of the Ganges basin and continues subsiding today (Alam, 1972). Sediments washed from the surrounding hills have filled this geosynclinal basin to depths exceeding 18 kilometres in the southern mainland and the offshore islands (Barisal-Patuakhali-Hatiya region). On the basis of the information obtained from deep drilling (done for oil and gas exploration) and geophysical investigations, the thickness contour map of the sedimentary cover of the Bengal Geosyncline (Fig. 2.2) has been prepared by Mirkhamidov and Mannan (1981) and in two cross-section (Fig. 2.3) the shape and size of the Geosyncline has been demonstrated and different geological formations up to a depth of many kilometres have been identified.

Subduction of the Indian continental plate by north-ward movement beneath the Tibetan plate resulted in down-warp of the Indian continental crust to depths greater than 25,000 ft (7,600 m) south of and adjacent to the Himalayan front range (the Siwalik Hills). Simultaneously, westward propagation of
Fig. 2.1: Location of study area in tectonic map of Bangladesh.
Fig. 2.2: Estimated thickness contours of sediments in the Bengal Basin (Source: Mirkhamidov & Mannan, 1986).
<table>
<thead>
<tr>
<th>Sedimentary</th>
<th>Formation/Group</th>
<th>Aquifer Potential Deep Basin</th>
<th>Aquifer Potential Deep Shelf</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>U. Miocene</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>Holocene</td>
<td>Tipam, Dupitila</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>M. Clay &amp; Alluvium</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Miocene</td>
<td>Surma</td>
<td>None</td>
</tr>
<tr>
<td>3</td>
<td>M. Miocene</td>
<td>Jainta - Barail</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>- Oligocene</td>
<td>None</td>
<td>Limited</td>
</tr>
<tr>
<td>4</td>
<td>Cretaceous</td>
<td>Rajmahal trap</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td></td>
<td>sst. Volcanic ash</td>
<td>None</td>
</tr>
<tr>
<td>5</td>
<td>Permian</td>
<td>Gondwana</td>
<td>None</td>
</tr>
<tr>
<td>6</td>
<td>Precambrian</td>
<td>Granite gneiss</td>
<td>None</td>
</tr>
</tbody>
</table>

Fig. 2.3: Geological cross-section along selected lines across the Bengal Basin (after: Pitman, 1985).
the Arakan-Yoma orogenic belt progressively narrowed the seaway east of the Indian continental plate as it moved northward (Jones, 1985).

The tectonic elements of the Bengal Basin (Figs. 2.1 and 2.4) can broadly be divided into Shelf, Slope or Hinge, and Bengal fore-deep or Basin fore-deep areas (Bakhtine, 1966; Holtrop and Kiser, 1970; Guha, 1978; and Alam, 1985). The shelf in the north and north-west is characterized by comparative stability and reduced sedimentary cover. The geosynclinal Bengal fore-deep in the south and south-east has greater tectonic mobility and a very thick sedimentary infill. Jones (1985) suggested from an interpretation of aero-magnetic data (Fig. 2.5) that the Bengal fore-deep is concave eastward reflecting the topography of the Tripura Hills and accounting for both the Surma basin down-warp and the present position of the Meghna-Brahmaputra estuary. These two units are separated by a hinge zone running in a NE-SW direction through the middle of the basin.

Most of present-day Bangladesh comprises a gently-sloping surface formed by Recent and ancient delta and alluvial plains of the Ganges, Brahmaputra and Meghna rivers with their numerous tributaries and is underlain almost exclusively by poorly-consolidated and/or unconsolidated deposits of Tertiary and Quaternary ages. This huge sub-aerial delta has been found to grade offshore to the world's largest submarine fan complex that extends over 3,000 kilometres south to 10°S latitude beneath the Indian Ocean (Curry and Moore, 1974).

2.2 Major Geomorphic Units:

The study area surface shows a general slope towards west, south-west and south-eastern directions. The land is generally flat in nature and the degree of flatness increases along with a decrease of surface irregularities in the direction of slope, except for the north-south elongated Lalmai Hills, which are relics of a previous large-scale ancient Lalmai anticline.
Fig. 2.4: Generalized geology of Bangladesh and adjoining areas (Sources: Holtrop & Kiser, 1970; Alam, 1985; Jones, 1985).
Fig. 2.5: Depth to Basement in Bangladesh (Source: Aeromagnetic Survey, O.D.A, 1980; Jones, 1985).
According to M. A. Bakr (1976) the area can be divided into three major geomorphic units (Fig. 2.6) on the basis of their lithological characteristics, drainage patterns, degree of artificial modification, relative position to one another, degree of modification by denudation processes and the degree of induration. From east to west these morphological units are: (1) Lalmai Deltaic Plain, (2) Chandina Deltaic Plain and (3) Meghna Flood Plain. Brief descriptions of these units are presented below:

2.2.1 Lalmai Deltaic Plain:

The Lalmai deltaic plain fronts the Tripura Hills and slopes gently towards the west. The land forms developed by this formation are of a terraced type and gently rolling. The drainage pattern is subsequent and dendritic. Its present disposition suggests that it has been uplifted and occurs at elevations ranging from 20 ft (>6 m) to over 100 ft (>30 m) above mean sea level (msl). Bakr (1976) believes that the Lalmai deltaic plain (also called the Lalmai terrace by Morgan and McIntyre, 1959) along with other terraces may be related to the penultimate major (fourth) stage of Himalayan upliftment. It may be recalled that the Himalayas mountain chain was brought to its present position by five major stages of uplift and the indications suggest that the Himalayan orogeny is still active. It has been concluded that large parts of this plain have been eroded and/or covered by younger sediments. The shape of the Lalmai Deltaic Plain in the study area is arcuate with convexity westward, which is also an indication that the formation was laid down in a deltaic environment. The sediments underlying the synclinal depression between the Tripura and Lalmai Hills also suggest the existence of an inlet or tidal channel reaching Comilla town in the past which has disappeared because of the artificial modifications to the plain by uplift. According to Morgan and McIntyre (1959) the Lalmai deltaic plain has not been folded but
is broken into a number of faulted blocks as a result of earth movement and some of these blocks are slightly tilted in the western edge of the study area producing a fault scarp of 3 to 10 metres (10 to 30 ft) in height. Dendritic patterns of drainage are characteristic throughout the plain.

2.2.2 Chandina Deltaic Plain:

The distinctive flat-lying surface that surrounds the Lalmai Hills and extends towards the Meghna flood plain and which has relatively lower elevation has been given various names by different authors: M. A. Bakr (1976) and H. R. Khan (1978) refer to it as the Chandina deltaic plain whereas it is called the Tippera surface by Morgan and McIntyre (1959). It is a flood plain long since abandoned by flowing rivers, where the original topography has almost disappeared and the surface features have been modified by man’s action. In particular, the drainage system has been transformed into a rectangular pattern primarily for irrigation purposes. The surface is weathered but not to such a depth as in the Lalmai plain. It is slightly more elevated than the western flood plain but much lower than the eastern Lalmai deltaic plain. Bakr (1976) suggests that the elevation ranges from 10 ft (>3 m) to 25 ft (>7 m) amsl, and the differential elevation between the Chandina deltaic plain and the younger Meghna flood plain probably ranges from 4 (>1 m) to 6 ft (<2 m) (Morgan & McIntyre, 1959). The elevation of the Chandina deltaic plain (Tippera surface) is probably due to Recent activation of the pre-existing blocks in the area. It would appear to form a relatively stable block which is slowly being eroded by the Meghna and its tributaries. The geological formation that makes up this plain is called the Chandina Formation.
2.2.3 Meghna Flood Plain:

This flood plain is the result of the present day depositional activities of the Meghna and its numerous tributaries which have criss-crossed the whole area and result in a network structure of merging and branching channel bars, meander bars, and levees and other old stage characteristics. The delta building process is still continuing, and elevations range from less than 5 ft (<2 m) to about 20 ft (>6 m) amsl. The boundary between the Chandina deltaic plain and the Meghna flood plain can only be approximately drawn since the morphological change at their junction is gradual.

2.3 Regional Geology:

The Bengal fore-deep is the result of rapid deposition and contemporaneous regional subsidence, with very little internal deformation of the sedimentary sequences created during most of Miocene and much of Pliocene times. The uplift and gentle folding of the eastern margin of the Bengal fore-deep increases in intensity eastward. This is primarily due to the westward advancement of the Arakan-Yoma orogenic belt producing north-south trending folds and thereby dividing the fore-deep zone into an eastern folded flank and a western unfolded flank. Because of the basinal configuration, the unfolded flank is again subdivided from north-west to south-east into (a) the Faridpur Trough, (b) the Barisal-Chandpur gravity high and (c) the Hatiya Trough.

The present study area occupies the north-eastern part of the Barisal-Chandpur gravity high, the western part of the unfolded flank and the northern part of the Hatiya Trough (Figs. 2.1 and 2.4). No basement rock crops out within the study area (or in any part of Bangladesh as a whole) and thus all the surface and subsurface geology consists of these Recent geosynclinal deposits.
2.4 Subsurface Geology and Stratigraphy:

The Lalmai Hills are the only outcrop area where all the rock types are exposed that make up the sub-surface geology down to a depth of several hundred metres. At the outcrop, the relationship between the older and younger rocks becomes clearer and the lithological variations are better defined. The oldest geological formation exposed here is the Dupitila Formation which blankets the entire study area and beyond in all directions as a thick sub-surface layer. It is exposed in the northern Sylhet Hills and Tripura Hills to the east of India; both the outcrops are located outside the study area. On the erosional surface of this formation, the younger Madhupur Clay Formation is unconformably deposited. It is reported by several workers (Morgan & McIntyre, 1959; Bakr, 1976; and others) that most probably, in the past, the Madhupur Clay must have been distributed over a much larger area but because of its long exposure its lateral extension has seriously been disrupted as erosional activity has removed a major part leaving behind the disconnected, individual segments of Madhupur Clay which lie covered by the younger formations. Remnants of the Madhupur Clay were encountered and identified in some of the drilled holes and are located in the geological cross-sections (Figs. 2.8 to 2.12).

The principal geological formations (Fig. 2.6) which make up this part of the delta down to an investigated depth of around 500 ft (150 m) are described below with the youngest at the top:

4) Meghna Flood Plain Deposits

3) Chandina Formation

2) Madhupur Clay Formation and

1) Dupitila Formation.

The Madhupur Clay Formations and the younger formation correspond to the geomorphic sub-divisions. The Dupitila Formation and the
Madhupur Clay Formation belong to the Madhupur Group and these formations were formed during Plio-Pleistocene times. The Chandina Formation and the Flood Plain deposits are Holocene deposits. The surface and sub-surface boundaries of these formation have not yet been established firmly. The lack of horizontal continuity as a result of a complex intermixing and rapid facies changes made it extremely difficult to attempt a straightforward subdivision.

Along with the available surficial information, 367 borehole lithological logs (Fig. 2.7) have been analyzed to prepare a modified correlation of the lithological units. However, since the maximum depth of the borehole logs seldom exceeds 125 m (400 ft) it was felt that the maximum deposit depth was much greater, at least in some places in the south. The number of well logs available for the south and south-western parts is much too low to reconstruct an accurate distribution of the sub-surface lithology. Other problems include the poor distribution of some of the data points on the map, repetitious well logs, and poor description of the sediments encountered. With all those problems in mind, a detailed description of the lithological units is presented below to facilitate correlation.

2.4.1 Dupitila Formation:

This geological formation is exposed only in the Lalmai Hills but has been encountered in every bore hole drilled in the study area. The unit is dominantly sandy and is grey to yellowish-grey in colour. A typical characteristic of this formation is its gradation in grain size, being finer at the top and coarsening with depth (Figs. 2.8 to 2.12). It consists of very fine to fine sand, silty sand and a mixture of different kinds of sand with occasional intercalations of silt and clay. Usually, the lower part is composed of medium to coarse sand associated with pebbles and gravels. Since the overlying formation is unconformably deposited on
Figure 2.7: Distribution of the Identified Lithological Well Log.
the erosional surface of the Dupitila Formation, in many places therefore the uppermost finer sandy fraction is missing. Within these sandy deposits, predominant mica and quartz grains are noticeable. This formation has been encountered throughout the region at varying depth. The thickness of the unit is variable and cannot be determined because in most of the cases the borehole was not taken down to the base of this formation.

2.4.2 Madhupur Clay Formation:

The Lalmai Deltaic Plain is underlain by the Madhupur Clay Formation which unconformably overlies the tilted Dupitila Formation of Plio-Pleistocene age. The Madhupur Clay consists of reddish-brown or yellowish-brown clay and sandy/silty clay, a host of highly oxidized red deposits. Ferruginous nodules are encountered at places within this formation which is generally unconsolidated and flat lying. The Madhupur Clay is exposed at the base of the Tripura Hills and on the slopes and ridges of the Lalmai Hills (Fig. 2.6). It was presumably laid down by the ancient streams draining the Tripura and Assam Hills to the north and north-east. On the other hand, because of their older age, they are characteristically more compact and weathered than the other younger deposits. Though this clay is massive, occasionally it becomes mottled and vesicular and an interesting feature of the unit is that it is compact when dry but becomes very soft when wet. The clay is occasionally intercalated with very fine sand and silt. The thickness of the formation is highly variable and in many places the unit is missing as it has suffered long exposure to erosion.

2.4.3 Chandina Formation:

The geological unit that forms the Chandina deltaic plain is called the Chandina Formation. It is composed of silt, silty clay, clay and very fine
sand. The sediments of these units are lithologically similar to those of the Recent flood plain deposits except that the Chandina Formation is comparatively more compact and oxidized. The sediments of the Chandina Formation, according to Morgan and McIntyre (1959), are alluvial deposits but later studies provide enough evidence for a brackish, marine and/or estuarine origin. The brackish water origin of these sediments is provided by the presence of flora content, different types of organic matter and soil formation. However, these deltaic sediments are underlain by thick sandy layers of coarse or medium-grained sand, frequently with pebbles and gravels. The formation extends from the surface to a depth of over 100 ft (Fig. 2.6).

2.4.4 Flood Plain Deposit:

These alluvial sediments were deposited by the present day Meghna river and its numerous tributaries during Post-Recent and Contemporary times. The materials laid down are silts, silty clays, clays and sands similar to those of the Chandina Formation except that the Flood Plain deposits are comparatively more loosely consolidated, and typically grey to yellowish grey in colour. The geological succession in Table 2.1 briefly outlines the ground water potentiality of the different geological formations.

2.5 Geologic Cross-Sections:

A number of geological cross-sections have been prepared in different directions covering most of the study area on the basis of the available lithological logs (Fig. 2.7). The cross-sections were prepared along the 'A-B, B-C, C-D, E-B and F-G' lines (Figs. 2.8 to 2.12). These sections have been prepared with reference to mean sea level (msl). Except for very few, most wells were drilled to a depth less than 125 m (400 ft) with a majority being drilled to a depth
<table>
<thead>
<tr>
<th>GEOLOGICAL AGE</th>
<th>GEOMORPHIC UNITS</th>
<th>GROUP</th>
<th>FORMATIONS</th>
<th>LITHOLOGICAL DESCRIPTION</th>
<th>AQUIFER POTENTIAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>HOLOCENE (LATE)</td>
<td>MEGHNA FLOOD PLAIN</td>
<td>FLOOD DEPOSITS</td>
<td>Alluvial deposits, mainly of silts, silty clay, clay and fine sands. Mainly deposited by the present day river system.</td>
<td>Water transmitting capacity as well as storage capacity is very low.</td>
<td></td>
</tr>
<tr>
<td>HOLOCENE (EARLY)</td>
<td>CHANDINA DELTAIC PLAIN</td>
<td>CHANDINA FORMATION</td>
<td>The deposit consists of silts, silty clay, clay and very fine sand in the upper part but the lower part is increasingly sandy.</td>
<td>Upper clay/silt part shows low transmissive as well as storage capacity but the lower sandy part shows higher transmittin and storage capacity.</td>
<td></td>
</tr>
<tr>
<td>PLEISTOCENE</td>
<td>LALMAI DELTAIC PLAIN</td>
<td>MADHUPUR CLAY FORMATION</td>
<td>Consists of reddish brown or yellowish clay and sandy/silty clay. Highly oxidized occasionally with fine sandy layers.</td>
<td>Very poor transmitting and storage capacity because of clay dominant sediments.</td>
<td></td>
</tr>
<tr>
<td>PLIO-PLEISTOCENE</td>
<td></td>
<td>MADHUPUR</td>
<td>DUPITILA FORMATION</td>
<td>Dominantly sandy with occasional clay/silty lenses in between. Sand layers are graded, finer at the top with coarsening down-wards. Lower coarse sands are associated with gravels and pebbles.</td>
<td>Higher ground water potential with high water transmitting and storage capacity.</td>
</tr>
</tbody>
</table>

Table 2.1: Geological succession and aquifer potential.
A computer program was available in the Department which had been written originally for the presentation of geological sections at outcrops and primarily used by research students in Sedimentology and Petrology. This program was modified to prepare and present borehole log cross-sections for the wells used to correlate the lithology and to identify the extent of the major units (Figs. 2.8 to 2.12).

a) Geological Cross-Section 'A-B': (Fig. 2.8) starts from south eastern boundary of the study area and extends towards north almost touching the India-Bangladesh border. It includes Sonagazi 4, Sonagazi 2, Feni 19 and Feni 15 wells which were drilled through the Meghna Flood Plain Deposits at the surface. At the northern end it includes Chauddagram 11 and Chauddagram 4 which were drilled through the exposed Madhupur Clay Deposits and wells Feni 7, Feni 2, Chauddagram 20, Chauddagram 19, Chauddagram 16 and Chauddagram 12 in between which were drilled through the Chandina Formation.

From this section it appears that a layer of silt and clay, occasionally with very fine sand, is present everywhere and its thickness is lowest in the centrally located Chandina Formation and gradually increases to either sides. Below this unit there is a dominantly sandy layer, 50 to 70 metres thick, which includes occasional gravels and pebbles at its base. In turn this sandy layer is bounded by another clay/silt layer at the bottom which is present in most of the wells at a depth of between 80 to 100 metres.

b) Geological Cross-Section 'B-C': (Fig. 2.9) is the northern continuation of 'A-B' cross-section line which is extended from Chauddagram to the central part
Fig. 2.8: Correlation of lithological units along the line 'A - B'.
Fig. 2.9: Correlation of lithological units along the line 'B - C'.
of the Brahmanpara upazilla. Except for Chauddagram 4 well, which is drilled on
the exposed Madhupur Clay Formation, all other wells belonging to this section
encounter the Chandina Formation at the surface. Here the Chandina Formation
seems to be more clayey and its thickness is more variable. The sub-surface
presence of Madhupur Clay has been identified in Comilla 26 and Comilla 23
wells. The well-defined lower bounding clay/silt layer that was identified in the
'A-B' cross-section at a depth of about 80 to 100 metres has not been found to a
depth of 110 metres. This indicates a gradual plunging of the clay layers towards
the deeper part and implies a much deeper occurrence of the clay/silt layer at a
depth not yet drilled. The present distribution of both the upper and lower bounding
clay allows the intermediate sandy layer to become thicker.

c) Geological Cross-Section 'C-D': is the third and the concluding segment
(Fig. 2.10) of the longer 'ABCD' cross-section line which is extended from central
Brahmaputra to the northern end of Nasirnagar upazilla marked by the Meghna
river. The Sarail 11, Sarail 5 and Sarail 1 wells encounter the flood plain deposits
as the uppermost layer but all other wells lying along the section were drilled
through the Chandina Formation. The uppermost finer layer of clay and silt with
fine sand is present throughout the entire length of the section. This layer is thickest
in the middle and its thickness gradually reduces towards either end of the section
to as low as 3 m (Brahmanpara 2). In general, the upper clay/silt layer in this
section is somewhat thinner than the other two previous sections of the 'ABCD'
cross-section line indicating the occurrence at shallow depths of the middle sandy
layer. One special feature of this sandy layer in this section is that in several places
multiple clay/silt layers are present in the form of lenses. In Kasba 14 and Kasba
12 wells the intermediate clay/silt layer is thought to be of Madhupur Clay type.
The occurrences and distribution of the lower bounding clay/silt layer has been
Fig. 2.10: Correlation of lithological units along the line 'C - D'.

encountered at a depth of about 100 metres in Kasba 12. Beyond that, in a northern direction, it has not been encountered even at a depth of 120 metres, suggesting a deeper occurrence along that direction.

d) Geological Cross-Section 'E-B': is a NE-SW section (Fig. 2.11) and is located in the lower part of the study area extending from the Chauddagram upazilla to the south-western boundary of Laksmipur upazilla which is demarcated by the Meghna estuary. In the south-west it includes wells Laksmipur 4 and Laksmipur 1 in which the uppermost layer is flood plain deposits. In the wells from Chatkhil 1 to Chauddagram 7 the surficial cover is the Chandina Formation and at the extreme north-east end the exposed Madhupur Clay Formation represents the topmost layer in Chauddagram 6 and Chauddagram 4 wells.

The topmost clay/silt layer is relatively thin in the middle portion but gradually thickens either direction. The thickness of the Flood Plain Deposits sharply increases in the flood plain Laksmipur area beyond Chatkhil 1 well which rises to as high as 328 ft (100 metres). Several inter-bedded fine sandy layers have been identified within this thick surficial clay/silt layer. A deep drilling to a depth of 350 metres (Laksmipur 4) suggests that there is a marked change in lithology with the increasing supply of finer sediment. Other than the occurrence of sandy layers at different depth horizons from 100 to 140 m, 165 to 185 m and between 195 to 205 m the entire lithology is dominated by finer materials. Therefore, it is difficult to say for certain that in this part of the study area which particular sandy layer is the extension of the main aquifer. Alternatively, because of the supply of finer material at different times the thicker aquifer may have been divided into several horizons or it may be that the main aquifer located at shallow depth in the northern part has plunged to much greater depth and has not been encountered in the boreholes in the southern part particularly at the Laksmipur 1
Fig. 2.11: Correlation of lithological units along the line ‘E - B’.
To answer these questions correctly, much more subsurface information is essential for the entire southern part of the study area. It is not clear that the clay/silt layer encountered in Laksam 15 well at a depth of 90 metres is the lower bounding clay/silt or not, since it has not been encountered in any of the wells located in the south at this depth.

e) Geological Cross-Section 'F-G': is an east-west line (Fig. 2.12) chosen at about the middle part which roughly divides the study area into two halves and covers the Comilla town (Kotwali upazilla), northern minor part of Barura, and most part of Chandina and Daudkandi upazilla. Only the Daudkandi 4 well has been drilled through the Flood Plain Deposits. In all other wells from the Daudkandi 8 well to the other end of the section the uppermost covering layer is the Chandina Formation except for Comilla 16 well which is reported to be drilled in the area where the Dupitila Formation is exposed. The formation is dominated by sandy sediments and the entire drilled depth is characterised by this material. In this well the top clay/silt layer and the bounding clay/silt layer is absent although present in the nearby wells on either side. The intermediate clay/silt layer at the Comilla 14 well could be of Madhupur Clay type.

The thickness of the upper clay is variable. It shows the highest thickness at the Chandina 3 well but at the same time the clay/silt layer in this locality also contains a considerable amount of fine sandy material which is thought to be one of the characteristics of the Chandina Formations. The thickness of this layer decreases to either side of the Chandina 3 well. After a sudden decrease in thickness at the Daudkandi 8 well in the west the thickness again increases into the flood plain. The upper clay/silt layer along this section beyond the Comilla 16 well in the east is particularly dominated by clayey materials. None of the wells on this section were drilled to find and locate the depth of the lower bounding
Fig. 2.12: Correlation of lithological units along the line 'F - G'.
clay/silt layer therefore the thickness of the sandy layer is really not known.

Comments:

From the foregoing discussion it can be concluded that the entire area except for the Lalmai Hills is covered with a clay/silt layer of varying thickness. In general the clay/silt layer is more silty in the west and more clayey in the east. This layer also sometimes contains fine sandy materials in several places. The thickness of this covering layer seems to increase in south-west and southern directions especially into the flood plain deposit area, though this pattern is interrupted in many places. In this south and south-western part, the upper clay/silt layer is very thick but its continuity is interrupted by several intermediate finer sandy layers. Another clay/silt layer has been identified more clearly in the upper and eastern part at a depth between 80 and 90 metres (Fig. 2.9 and Fig. 2.12). This bounding clay layer seems to plunge to a much greater depth in west, south-west and western directions as it has not been found at a greater depth in those parts of the area. The second clay/silt layer is described here as the lower bounding clay/silt layer since between lies a considerably thick intermediate sandy layer which extends throughout the area. This sandy layer is more distinct and sandy and contain relatively coarser grains along the eastern 'A-B' and 'B-C' section and centrally located 'F-G' section but the sandy layer seems to contain more clay/silty materials and some times is separated into layers by lenses of clay/silt materials along the 'C-D' section in the north and 'E-B' section in the south-western part. Though the finer sediments contain a certain portion of the sandy layer in the south and south-west and are more divided by inter-bedded clay/silt layer yet the thickness of the sandy layer seems to increase in this section.
2.6 Major Structural Trends:

The mountain building processes during the late Tertiary Period (Miocene and early Pliocene) have played the most important role in producing significant structural changes in and around the study area, especially along the border area (folded flank of the Bengal fore-deep) and further east in India. It is also the period when the major upheaval of the mighty Himalayas occurred. As a result, a large number of folds and faults were created, most of them having a general north-south trending orientation in which the Tertiary sediments have been compressed into folds parallel to the eastern Arakan-Yoma geanticline, which also has north-south trending structure (Fig. 2.13). Because of this upheaval, the landmass was exposed to erosional activity for a considerably longer period, hence the combined denudation processes have significantly levelled the surficial expression of these structural features. On the erosional surface of the Tertiary sediments, the Madhupur Group of sediments was deposited under transitional, brackish marine to estuarine or fluvial environments. As a result, all these Tertiary structures have been buried underneath the Quaternary sediments, except for the Lalmai Hills, the remnants of the previous larger Lalmai anticline. The area is still tectonically active supported by various occurrences of earthquakes and sudden changes of river courses. A detailed geophysical study revealed a lot of information about these structural features which seem to have little or no control at all over the sediments which covered them. It has been found that these structures are similar to those Tertiary structures exposed on the surface in the adjacent northern and eastern regions. The folds are simple and vary from closed structures with wide flat crests and gentle flanks to gentle flat crested, steep sided, box like structures and are typified by their 'en echelon' position. The width of the synclines is greater than that of the anticlines and varies from 15 to 20 kilometres, whilst fold amplitudes range from 200 to 3500 metres. The folds are asymmetrical and in most
Fig. 2.13: Distribution of major structural trends
(compiled from Bakr, 1976 & MacDonald & partners, 1986).
cases the eastern limbs is the steeper. Huge amounts of gas reserves have been discovered within some of these buried folds distributed in the northern (Titas anticline), north-eastern (Bakhrabad anticline) and south-eastern (Begumganj anticline) part of the study area. The seismic studies in particular have successfully identified a number of major deep seated transverse faults (Fig. 2.13), some of which have cut and displaced some of the folds. In some of the synclines the faults are found to behave like axial thrust faults. A majority of these fault planes shows north-south extension.

**Lalmai Anticline:**

The Lalmai anticline (Fig. 2.6) which caused the Lalmai Hills is 12 miles long and has an average elevation of about 100 feet above the sea level. It is bounded by a series of parallel faults and the whole hilly area is surrounded by the Chandina Deltaic Plain (M. A. Bakr, 1976) or Tippera surface (Morgan and McIntyre, 1959). These hills are gently sloping to the east but the western flanks are cliff-like (Fig. 2.6 and 2.13).
CHAPTER 3 HYDROGEOLOGY

3.1 Historical Development of Wells.
3.2 Aquifer System and Classification.
3.3 Main Aquifer:
   3.3.1 Upper Confining Layer.
   3.3.2 Physical Characteristics and Extent.
   3.3.3 Aquifer Thickness.
   3.3.4 Aquifer Nature.
3.4 Deep Aquifers.
3.1 Historical Development of Wells:

An organised effort to increase the development of ground water in Bangladesh was initiated in 1966 primarily for irrigation and also to enhance the availability of potable water in the rural areas. Also, there was the extension of municipal water networks in the important urban areas. The Ground Water Circle (GWC) within the Directorate of Hydrology of the Bangladesh Water Development Board (BWDB) is the present day national organization responsible for ground water development and management. More systematic and large scale studies of ground water resources began in the early 1970’s, though the earliest small scale hydrogeological data collection programme had started as early as 1961 with the measurement of water levels on a monthly basis for 147 wells distributed throughout Bangladesh. A regular nation-wide measurement of the water table on a weekly basis was started in the 1970’s by BWDB. Thereafter along side the BWDB, ground water development programmes were carried out increasingly by several other organizations like Bangladesh Agricultural Development Corporation (BADC), Bangladesh Krishi Bank (BKB), Department of Public Health Engineering (DPHE), and Bangladesh Rural Development Board (BRDB), gradually by putting down more and more deep tube wells every year. The BADC and BKB were primarily interested in irrigation, while BWDB, DPHE and BRDB were more concerned with potable water.

The initial wells were mainly of shallow tube well (STW) type and were restricted to between 80 and 180 feet in depth. The structure is 4 to 6 inches in diameter with a suction lift centrifugal pump mounted on the surface which usually provides a discharge of 15 l/s (130 m³/d) and a capacity to irrigate 8-15 acres of crop land. Many of them are no longer in use. Gradually increasing irrigation demand has made the installation of deep tube wells (DTW) more popular than the shallow tube wells (STW). Most deep tube
wells are installed to a depth between 180 (55 m) and 400 feet (122 m) though some test holes may be installed down to a depth of 1200 feet (>365 m). The deep tube wells are drilled mainly by reverse circulation methods. In almost every case the upper 80 feet (24 m) is cased with 1.16 feet (0.35 m) diameter pipe to accommodate the pump and thereafter the entire length is kept constant with 8 inch (200 mm) diameter pipe. It is fitted with a turbine pump usually set at a depth between 50 (15 m) to 80 feet (24 m) which in most cases has a discharge of 58 l/s (5000 m³/d). Except in the urban areas, all the deep tube wells are used primarily for irrigation purposes. The wells are usually pumped for some 800-1600 hours during the winter (dry) season and a single DTW irrigates about 40-60 acres of cropland. In most cases the crops are rice but every year increasing amounts of other crops and vegetables are grown, particularly during the winter period using the ground water resources.

The earliest installation of ground water wells in the Comilla-Noakhali region was documented during 1968/69 and since then the cumulative number of DTW’s is constantly increasing, mainly for irrigating croplands. Until September 1985, the present study area alone had a total number of 1961 deep tube wells (1786 deep tube wells in Comilla and 135 deep tube wells in Noakhali districts) and 95 permanent observation wells (60 in Comilla and 35 in Noakhali) which indicates quite a significant amount of progress in ground water resources study (Pitman, 1985). Because of insufficient information regarding location the majority of the wells could not be identified in the lithological maps (Fig. 2.7).

Though Bangladesh as a whole is criss-crossed by hundreds of small and several major rivers and receives rainfall at rates among the world’s highest yet the country suffers a severe shortage of water. Some 60% of 19 million acres of excellent cropland lies fallow for about 5 months during the dry season, a consequence of the monsoonal climatic condition.
3.2 Aquifer System and Classification:

To acquire detailed comprehensive knowledge about the hydrogeological conditions and the occurrence of ground water both at shallow depth as well as at the much greater depths in this deltaic geosynclinal basin, a nation-wide investigation was carried out by Jones of Louisiana University, U.S.A. in 1985. In his investigation he studied the nature and extent of the aquifer down to a depth of 6,000 feet (1800 m). To accomplish this work he accumulated and used all the available records of ground water related work which had been done by every related organization. This included the records available in the Ground Water Circle (GWC), BWDB (the agency responsible for nation-wide development and research of Ground water resources) and complementary to these some more geophysical logs like the electric logs, gamma-ray logs, caliper logs etc. for some 20 oil and gas wells from Bangladesh Oil Gas and Mineral Corporation (BOGMC). Eventually after careful evaluation, the occurrence of six well-defined potential aquifers was identified (Figs. 3.1 and 3.2) within the investigated depth. In his report they were numbered with the shallowest as aquifer 1 and the aquifer number increasing with increasing depth marking the deepest aquifer no 6. All these aquifers have a crescent-like shape with convexity downwards giving maximum depth for these aquifers in the central part (Dhaka) of the Bengal foredeep. Gradually the depth decreases in western and eastern directions, more rapidly to the east where ultimately the aquifers become exposed in both the Chittagong Hills and beyond in the Tripura Hills (India).

All six aquifers either entirely or mostly contain fresh ground water except in a few places. A small part of aquifers 2, 3, 5 and 6 are affected by salinity along the southern coastal area of Barisal and Noakhali which lies beyond the study area. Aquifer 4 in the vicinity of Lalmai 2 well (Fig. 3.2) is also affected by salinity on a limited scale.
Fig. 3.1: Geological cross-section along 'A - B' line showing the distribution of both the main aquifer and the deeper aquifers of Bangladesh (After: Jones, 1985).
Fig. 3.2: Geological cross-section along 'C - D' line showing the distribution of both the main aquifer and the deeper aquifers of Bangladesh (After: Jones, 1985).
The uppermost aquifer (aquifer 1) depending on its geological and geographical location, changes its nature from unconfined to leaky confined and then to fully confined conditions and is mostly recharged by direct infiltration of the surface precipitation. Additionally, considerable amounts of recharge come from the outcrop in the eastern hilly areas as horizontal flow (Fig. 3.3). The separation of aquifer 1 and aquifer 2 is neither uniform nor continuous, therefore in several places the division is arbitrary as a result of which the lower (aquifer 2) in several locations where the separating layer has either pinched out or become very thin receives a certain amount of vertical flow and behaves as part of aquifer 1. However, the main source of replenishment for aquifer 2 is lateral horizontal flow. As a consequence of this situation the nature of aquifer 2 ranges from confined to leaky-confined. All the four remaining deeper aquifers reflect true confined conditions as they are sandwiched between thick clay/shale layers and are entirely recharged by lateral horizontal-flow from precipitation on the outcrops in the eastern hilly areas where all these deeper aquifers are exposed to heavy rainfall (see rainfall distribution map, Fig. 1.2).

The present work is entirely devoted to the delineation of the ground water resources potential of aquifer 1, since the depth considered in this study rarely exceeds 500 feet (>150 m) (data below this depth are not available) and only in few cases does the recorded depth of the available lithological log exceed 1000 ft (300 m). The wells having this greater depth are concentrated in the southern Laksmipur, Begumganj and Noakhali upazillas where the estimated depth of the base of aquifer 1 is well above 1000 ft (300 m). All over the studied area, aquifer 1 is covered by a clay/silt layer of varying thickness which has created an aquifer condition that ranges from leaky confined to fully confined. A detailed description of the nature of aquifer 1 is given in the following section.
Fig. 3.3: Idealized W - E cross-sectional view of the main aquifer across the Lahnai hills showing recharge pattern.
3.3 Main aquifers:

3.3.1 Upper Semi-Confining Layer:

The surface clay/silt layer contour map (Fig. 3.4) was prepared using most of the available lithological logs to minimise confusion and to obtain a better description of the overlying semi-confining layer. Though the thickness contour map shows considerable variations, yet it reveals quite a lot of information about the thickness pattern and the distribution of this aquiclude.

The map suggests the general presence of a clay/silt layer all over the study area which is also reflected in several geological cross-sections (Figs. 2.8 to 2.12). This aquiclude, depending on its thickness and lithological characteristics and recharge ability, gives rise to the range from leaky confined to fully confined conditions.

The thickness contour map is characterized by two centrally-located closed-type low thickness areas separated by higher thickness in all other directions. The smaller closed low thickness area is confined in the north-central area covering most of Devidwar and parts of Burichong and Banchharampur upazillas. The larger closed thickness area is located in the south-central area covering most parts of Barura and Laksam and part of Nangalkot upazilla. Towards its southern edge, this low thickness area extends across the study area along a NW-SE strip covering part of Matlab Bazar, Haziganj, Sharasti, Begumganj, Senbagh, Dagonbhuiya and Sonagazi upazillas, separating the south and south-western part as the largest higher-thickness area. Apart from these closed areas, the thickness also decreases towards the west in the north-western part along the Meghna river bank covering part of Sarail and Nabinagar upazillas to give one of the lowest thicknesses encountered in the area.

A distinct increase in thickness is encountered in three different areas separated by intermediate low-thickness areas. In the north the
Fig. 3.4: Thickness distribution of the surficial clay/silt (aquiclude) layers.
thickness starts rising to the north of Nasirnagar upazilla and continues to do so beyond the study area towards the Sylhet basin. In the mid-western part, the thickness increases towards the west covering part of Banchharampur, Homna, Chandina and Kasba upazillas though the highest thickness is encountered in the Daudkandi area (>210 ft) and continues increasing into the Meghna river. Notably, the thickness of the aquiclude increases enormously in the south and south-western part of the study area and keeps on increasing towards the Meghna estuary where the thickness exceeds 350 ft in Laksmipur upazilla and 400 ft in Noakhali sadar upazilla before ultimately continuing into the Bay of Bengal. In this part of the project area, the aquiclude characteristically includes several thin layers of fine to medium sand and all these sand inter layers have limited aquifer potential. However, the extension of these inter-bedded sand layers within the aquiclude is not clearly known because of insufficient lithological information.

3.3.2 Physical Characteristics and Extent:

A detailed lithological study has been carried out using all the available and identifiable lithological logs to define and correlate the aquifer. It appears from such work that the aquifer is distributed throughout the project area and beyond as a continuous thick layer of sand. It is unconsolidated and moderately sorted in nature. In most places the aquifer is identified as a thick single unit but in some places, especially in the Lalmai deltaic plain area and in the southern part (Figs. 2.8 to 2.12), the aquifer is separated into two or more layers by the Madhupur Clay Formation and inter-bedded clay/silt layers, respectively. The south-western, western and southern parts of the study area are less well known because of limited lithological information. In the southern part, the aquifer is situated at much greater depth and the thickness of the aquifer also varies over small horizontal distances which is clearly revealed in the thickness contour map.
More sub-surface lithological information is needed for a clear delineation of the aquifer nature, especially for the southern part. Yet certain characteristic changes in lithology can be recognised. The lithological logs which were used to prepare geological cross-sections (Figs. 2.8 to 2.12) clearly demonstrate a gradation in grain size in the aquifer material with the finer being at the top and the grain size gradually increasing towards the base of the aquifer. This gradation is less clearly defined in the southern part though it can be recognised vaguely. The aquifer can be divided roughly into three main parts: 1) an upper finer part mainly composed of finer sand with little medium sand, 2) a middle part mainly composed of medium-grained sand finer at the top and coarser at the bottom and (3) a basal main part which is composed of medium to coarse sand occasionally with gravels and pebbles. These three parts of the aquifer must not be confused with the subdivisions of the previously recognised aquifer 1.

3.3.3 Aquifer Thickness:

The thickness contour map (Fig. 3.5) has been prepared using all the available borehole log information to demonstrate the natural thickness distribution of the aquifer all over the project area. It also reveals the prevailing trend of change in the thickness of the aquifer.

The thickness distribution of the aquifer in the relatively narrow northern part is quite different from that in the larger southern part. In the northern part, the general thickening of the aquifer occurs from east to west centring the B’Baria area, while in the southern larger part the aquifer represent a three-fold increase. All these changes were found beneath the west ward wedge-shaped 300 ft contour extending towards the Nabinagar area from the Akhaura area. In the southern part, the thickness of the aquifer decreases in west and south-
Fig. 3.5: Thickness distribution map of the main aquifer
western directions over the region covering Daudkandi, Chandpur, Haimchar and Raipur upazillas until it encounters the elongated 250 ft contour line wedging towards north-east directions. From this 250 ft contour line a thinning of the aquifer has been recognized in a south-eastern direction along a thin band covering parts of Senbagh, Begumganj and most of Sonagazi area. This 250 ft wedge shaped contour gradually opens-up towards the south, sharply increasing the aquifer thickness towards the Meghna estuary. At the southern extremity of the Noakhali region, the thickness of the aquifer exceeds 445 ft and appears to be increasing farther into the deeper sub-surface part beyond the limits of the mainland.

The aquifer reaches a thickness less than 150 ft only in two small areas. In the north, it covers the central part of the B'Baria upazilla where the lowest thickness obtained is about 114 ft and in the south-west it covers parts of Chandpur, Raipur and most parts of Haimchar upazilla where the lowest thickness encountered is as low as 82 ft. With these exceptions, the entire aquifer shows a thickness of more than 200 ft which controls and regulates the ground water resources in that region.

The need for more borehole logs was particularly felt for most parts of the southern region of the study area. On several occasions the entire upazilla has only one single borehole log (namely, Haimchar, Faridganj, Ramganj, Raipur and Chatkhil upazilla). In other instances, four lithological logs (from Laksmipur, Companiganj, Parshupram, Dagonbhuiya and Chhagalnaiya upazilla) and five lithological logs (from Begumganj, Sonagazi and fulgazi upazilla) were available for the sub-surface interpretation. The absence of this essential lithological information has forced limitations on the interpretation of the aquifer system with gross simplification of the complicated distribution in the southern part. When more sub-surface information would becomes available, the appearance of the thickness contour map could change significantly.
3.3.4 Aquifer Nature:

It is apparent from the preceding sections that a thick sandy aquifer is present throughout the entire project area and beyond (Fig. 3.5). It is also obvious that the aquifer is overlain by a clay/silt layer of variable thickness (Fig. 3.4) covering the entire extent of the aquifer. Underneath the thick main aquifer there is another clay/silt layer (Figs. 2.8 to 2.12) which is not as prominent as the upper semi-confining layer and also not clearly revealed from the present interpretation of lithological logs though was more clearly interpreted by Jones (1985, Fig. 3.1 and 3.2).

The presence of the overlying aquiclude and the lower bounding clay layer suggest a confined aquifer condition. But it has been found that a considerable amount of recharge takes place through the upper confining layer in the form of deep percolation of infiltrated water in addition to the recharge from lateral horizontal flow originating in the eastern hilly region beyond the Bangladesh-India border. Such vertical flow conforms to the definition of a leaky-confined condition. This typical nature of the aquifer is more thoroughly tested in chapter-5 (aquifer test analysis) where the hydraulic parameters suggest a fully confined condition for the smaller south-eastern part and leaky-confined conditions for the rest of the studied area.

3.4 Deep Aquifers:

On the basis of the Jones (1985) classification (Section 3.2) aquifers 3 to 6 inclusive are considered as the deeper aquifer series (Figs. 3.1 and 3.2). All these four major aquifers shows strong to very strong artesian characteristics. Using borehole geophysical techniques Jones demonstrated that in those areas for which information is available, ground water is fresh at depths greater than 1500 m (5000 ft) in the eastern part of the Surma basin and at depths
greater than 1200 m (4000 ft) throughout north-eastern Bangladesh, north of the confluence of the Meghna and Padma rivers. Throughout most of the Bengal foredeep, fresh ground water occurs at depths greater than 600 m (2000 ft). The maximum depth of occurrence of fresh ground water in the south-eastern part (Feni and Chauddagram upazilla) is more than 600 m (2000 ft) underneath the present project area and this depth increases to more than 760 m (2,500 ft) in the northern part (B'Baria and Muradnagar upazilla) of the study area.

As mentioned previously, the only source of replenishment for these deeper aquifers is from the lateral horizontal flow via the outcrop section, and it has also been found that because of the basinal configuration the depth of the aquifers increases from both eastern and western sides towards the central part of the basin in the vicinity of the capital city of Dhaka (Kamta 1 well) where the depth to fresh ground water is more than 1000 metres (Figs. 2.3 to 2.5). It follows that the artesian head also increases for deeper aquifers with increasing depth of burial. The area of outcrop of the deeper aquifers in the Tripura and Chittagong Hill Tracts occurs at increasingly higher altitude eastwards from the margin of the deltaic plain. Therefore, it is more likely that the artesian head also increases with depth because of increased overburden pressure which makes positive contribution in making the aquifer condition more and more strongly overflowing. An interpretation of this artesian head in terms of Ghyben-Herzberg relationships has been made which shows that when the depth of the fresh ground water is 600 m (the depth of fresh ground water underneath the present project area) then the fresh water head (potentiometric head) in the aquifer should be at least (600/40) = 15 m (50 ft) above sea level. The maximum altitude around the project area is less than 12 m (40 ft) which is less than the altitude of the potentiometric surface. When the altitude of the land surface is lower than the altitude of the potentiometric surface then the penetrated well in that aquifer should have an overflowing artesian
The difference between the altitude of the potentiometric surface and the altitude of the land surface is called the closed-in artesian pressure. If the difference is positive then it is called the closed-in artesian pressure at the land surface and higher number indicates a stronger artesian overflowing conditions. Jones demonstrated that natural overflowing conditions prevail almost anywhere to the east of the Brahmaputra River in the deltaic plain for aquifers ranging from 3 to 6. For this particular well depth and altitude condition the closed-in pressure at the land surface is (15-11.6) = 3.4 m (11.16 ft) indicative of an overflowing condition.

A rough calculation can be made to demonstrate theoretically how much water would be available from an overflowing well installed at a depth of 600 m (2000 ft) below sea level. If the well is 8 inch in diameter and with a measured specific capacity of 0.05 ft³/sec/ft, then the rate of artesian flow of the well would be:

\[
\text{flow rate} = 11.16 \times 0.05 \text{ ft}^3/\text{sec} = 0.558 \text{ ft}^3/\text{sec} = 4821.2 \text{ ft}^3/\text{d}
\]

\[
= 1365.2 \text{ m}^3/\text{d} = 15.7954 \text{ l/s} \quad [1 \text{ m}^3/\text{d} = 0.01115 \text{ l/s}]
\]

\[
= 300344 \text{ gpd} \quad [1 \text{ m}^3/\text{d} = 220 \text{ gpd}] = 208.6 \text{ gpm}.
\]

This amount of flow minus the frictional losses would be sustained by the well if a balance can be maintained between recharge and withdrawal by means of an efficient water management. This, of course, is based on a clear understanding of the hydrogeological regime.
CHAPTER 4  GROUND WATER FLOW

4.1 Water Level Monitoring System.
4.2 Water Level Data Used
4.3 Ground Water Level Fluctuation.
4.4 Water Table Contour Map and Flow-Net Analysis.
   4.4.1 Introduction.
   4.4.2 Low Elevation.
   4.4.3 High Elevation.
   4.4.4 Annual Fluctuation Map.
4.5 Replenishment Calculation.
4.6 Comments on Ground Water Movement and Flow Pattern.
4.1 Water Level Monitoring System:

The application and use of ground water in Bangladesh started on a small scale as early as the 1960's because of increasing demand for a variety of purposes e.g. municipal, irrigation and industrial. Initially a directorate of the then Water and Power Development Authority (WAPDA) was responsible for the development, monitoring and application of both surface water and ground water. With the passage of time and because of the inadequacy of surface water during the dry season (winter period), the need and demand for ground water has become of paramount importance both for increased nationwide irrigation practices and to make available more ground water for drinking purposes. To ensure the better management of water resources a separate organization called Bangladesh Water Development Board (BWDB) was formed in the early 1970's. A ground water division has been established within the major Hydrology sub-division of the greater BWDB establishment and has built up a good data storage section.

A second major organization which deals entirely with the irrigation usage of both ground water and surface water is called the Bangladesh Agricultural Development Corporation (BADC). Their data storage programme is more irregular and at the same time monitoring is also not continuous. Therefore most interpretation is mainly based on the BWDB data.

The most efficiently organized and up-to-date computer based data storage centre has been created by the Master Plan Organization (MPO) under the Ministry of Irrigation, Water Management and Flood Control. This organization is dedicated to preparing the National Water Planning Project under the advice of Dr. G.T.K. Pitman, with the overall supervision of the Harza Engineering Company International, a U.S. consulting engineering firm. The MPO has collected-collated basic water-related data from every possible public and private organization involved in water related projects. Most of the ground water data for the present work were
taken from the MPO with the direct help of Dr. Pitman, though the data centre is mainly based on BWDB data. Lately the MPO itself has expanded its own data generating network by installing its own permanent monitoring wells and by other means.

In the 1960's the water level measurements were necessarily taken from shallow and hand-dug wells but since the early 1970's these have been replaced by purpose-built deep boreholes. By September 1986, there were about 95 monitoring wells drilled by BWDB scattered throughout the present project area, from which water levels were and still are measured systematically and regularly once a week. The monitoring of ground water is essential for any assessment of the origin and movement of ground water and the nature of the aquifer system. Regular monitoring over long periods of time is vital to identify and control the effects of dry and wet years, if present.

As in many other parts of the country, the monitoring wells are constructed in the elevated ground of the villages and urban areas usually above the maximum flooding level to avoid the inundation and contamination of the well. Thus the water level (piezometric surface) does not rise above the ground level.

4.2 Water Level Data Used:

Changes in ground water level with time and space as a consequence of both long term and short term changes of ground water level due to both natural and artificial causes are demonstrated in several sections of this chapter. Long term changes in ground water level i.e. the changes of ground water level with time are explained using continuous eleven years data (from 1976-1986) and are presented in section 4.3 in the form of long term ground water fluctuation (Fig. 4.1).
The short term changes preferably called the changes of ground water level in space are explained using the weekly measurement of ground water level data for all the piezometric wells for the year 1985. Different types of contour map, fluctuation map and flow net maps were constructed to highlight the interpretation of the changes of water level in space. All the interpretation, both qualitative and quantitative assessments, including the behaviour of flow patterns are based on the 1985 data.

4.3 Ground Water Level Fluctuation:

The preparation of a ground water level fluctuation diagram is one of the standard methods of presenting long term changes of ground water level to demonstrate the changing behaviour under prevailing conditions. The diagram of figure 4.1 was prepared using the data recorded from January, 1986 to the end of December 1986. Three different monitoring wells were chosen to represent fluctuations from the area as a whole; these are monitoring wells 4, 58 and 142.

The upper limit of this fluctuation graph coincides with the measuring point level of monitoring well 4 (solid line) and the graduation scale for this graph is also prepared with respect to this well. The measuring point level for monitoring well 58 is actually at the 4 m marked level in the vertical scale. In the same way the measuring point level for the monitoring well 142 is actually 0.5 m above the upper bounding line of the figure. The measuring points for monitoring wells 58 (lower) and 142 (upper) is presented as broken lines and essentially indicate that maximum water levels come close to the surface. A brief description about the water level behaviour for each of these wells is presented below:
FIG. 4: GROUNDWATER LEVEL FLUCTUATION
Well Number 4: This well is located in the extreme northern part of the project area. It is mainly used for irrigation purposes but occasionally the villagers use the well as a source of potable water. This well shows no consistent long-term decline in ground water level during the last ten years. The rise of maximum water level in different years seems to be variable in nature therefore the incremental changes (Table 8.10) with respect to the previous years sometimes are positive and at other times become negative. An examination of the seasonal rise of maximum water level during the last ten years (Fig. 4.1) reveals the following facts. There was a steady decline of maximum water level for four years from 1975-76 to 1979-80 but during the next two water years (1980-81 and 1981-82) a rise of maximum water level was recorded. A brief fall of maximum water level in 1982-83 water year is followed by a rise during the next two water years (1983-84 and 1984-85) and again a fall in maximum water level is noticed during the 1985-86 water year. This alternate rise and fall of maximum water level is not at all affected by the continuously rising number of irrigation wells which is responsible for a steady increase in ground water withdrawal. This indicates that the amount of withdrawal is low in comparison with the perennial yield to be revealed by the response of ground water level.

Well Number 58: Monitoring well 58 is chosen as representative of the east-central part of the project area. It is installed in the highly populated Comilla town area. Because of the dense population in and around Comilla there is a great demand for ground water for both municipal and agricultural purposes which explains why the Comilla area (more specifically Kotwali thana) has the highest concentration of wells. Like many others, well 58 is under constant use throughout the year to meet the ground water requirements. Because of excessive annual abstraction this well produces the maximum amount of fluctuation (7.0 m or >23 ft). Like the well 4
an examination of the maximum water level during the last ten years (Fig. 4.1) reveals the following information. A steady decline of maximum water level was recorded for a period of four years from 1975-76 to 1979-80 and thereafter maximum water levels recorded a rise for the next two water years (1980-81 and 1981-82) followed by a brief fall during the 1982-83 water year. A substantial rise in maximum water level was recorded during the 1983-84 water year. Although not high enough to reach the level of 1976-77 water year it was higher than during the last six years of record and was followed by a decline of maximum water level during 1984-85 and 1985-86. These alternate declines and recovery of maximum water level are a positive indication that the seasonal dry period overdraft of ground water storage is recoverable in spite of the heavy withdrawal of ground water which is primarily a consequence of the existing management of ground water resources. The amount of fluctuation has also substantially increased locally as a result of increased withdrawal which has caused the lowering of ground water levels and can be regarded as a local phenomenon rather than of regional significance. This effect can easily be understood from the opposite behaviour of the maximum water level in the other two wells. The lowering of the water table also emphasises that the amount of ground water withdrawal is greater than the seasonal replenishment.

**Well Number 142:** is located in the extreme southern part of the study area in Noakhali town (Sudharam thana). The number of wells throughout the greater Noakhali district in the south is much lower than the other parts to the north. In some of the upazillas in the greater Noakhali district there is only one deep ground water well and they are mainly used for municipal purposes as sources of potable water. Ground water irrigation in the south takes place on a much smaller scale, there-by suggesting a much lower abstraction. All these facts are revealed in the form of the long term fluctuation (Fig. 4.1) for well 142. This shows a small but
continuous steady rise in maximum water levels during the six years from 1979-80 to 1985-86 in spite of the limited seasonal amount of artificial withdrawal of ground water. The seasonal dry period losses are fully recharged during the following wet period where the replenishment at the same time increases the perennial yield from this particular well.

4.4 Water Table Contour Maps:

4.4.1 Introduction:

Until August 1985, there were in the project area about 95 BWDB monitoring wells (Fig. 4.2) in which ground water levels were constantly monitored. Ground water level measurements from all these wells have been used to construct various potentiometric maps (e.g-water table contour map of minimum elevation, water table contour map of maximum elevation, and annual fluctuation map) as well as the construction of major flow direction maps for both periods of minimum and maximum elevation. In two of the monitoring wells (Well 60 in Comilla town and Well 144 in Noakhali town) the water levels have been recorded continuously using an automatic recording device, but in all other piezometric wells the ground water levels were measured manually once a week.

The initial depth measurements to the water table are made not from ground level but from a convenient elevated point called the measuring point (MP). The height from the ground level to the measuring point is commonly called the parapet. The parapet height was carefully taken into consideration when the depth to the water table was converted into elevation (Appendix. 4.1) for the preparation of different types of potentiometric maps. The initial measurements were made in metric units and the depths are expressed in metres. The contours were drawn using a one metre interval, Each contour line represents the point of equal elevation.
Using the standard procedure of construction with the flow lines perpendicular to the equipotential lines and the direction of flow from higher elevation (potential) to lower elevation (potential), a flow net was produced. An idealised flow net will produce many 'squares' depending on the number of flow lines and equipotential lines. The square appearance of a flow net tends to be distorted and is modified into a rectangular shapes depending on the degree of complication of the flow pattern which also largely depends on the inherent complex distribution of the water bearing system.

An interpretation of a water table contour map can reveal several useful features of the properties of ground water. The most useful are: a) it allows measurement of the hydraulic gradient which is a measure of the ground water potential, b) it allows the location of the best possible sources of ground water supply-using the assumption that a wider contour spacing represents a decreasing hydraulic gradient, which in turn suggest a more permeable condition and hence is a better ground water source, and c) a flow net can only be constructed from a completed contour map which enables the identification of the major flow direction.

4.4.2 Minimum Elevation Contour Map:

The contour map of minimum elevation (Fig. 4.2) has been prepared for one of the most dry periods (March, 1985) data. During this period of the year the water table reaches its minimum elevation as a result of a long dry sunny winter (November to March) which is a consequence of the monsoonal climate. At the same time, a maximum amount of ground water is also withdrawn from ground water storage.

A minimum elevation as low as -1 m is recorded at well 79 and less than +1 m at well 8. At the same time a maximum elevation of the
FIG: 4.2: WATER TABLE CONTOUR MAP OF MINIMUM ELEVATION (DRY PERIOD) MARCH 1985.

LEGENDS

INTERNATIONAL BOUNDARY CHANNELS
PRIMARY SECONDARY WELL LOCATION
PIEzOMETRIC WELLS AUTOPiEzOMETRIC WELLS PUMP TEST WELLS PIEZ-PI. WELLS UNDP QUALITY STATIONS GWC QUALITY STATIONS BASIC QUALITY STATIONS UNDP-GWC QUALITY STATIONS UNDP-PIEZ Q. WELLS GWC QUALITY-PIEZ WELLS GWC QUALITY-PIEZ WELLS BASIC QUALITY-PIEZ WELLS GWC QUALITY-AUTO-PIEZ WELLS UNDP-QUALITY-AUTO-PIEZ WELLS UNDP-QUALITY-AUTO-PIEZ WELLS

Elevation in metres.

Hydraulic gradient measuring points A, B, C, D and E

BAY OF BENGAL
potentiometric surface greater than +6 m is recorded at wells 2 and 13, and greater than +7 m at well 52. In the north, well 8 produced the lowest elevation measurement being located somewhat in between wells 2 and 13, and both these wells showed the maximum elevation. Well 79 in the east-central part gave the lowest elevation measurement even being located adjacent to well 52 which produced the other maximum elevation. This abnormal close disposition of two extreme elevations should not in theory occur under normal circumstances.

It is apparent from knowledge of geomorphology and geology that the area has a gently sloping land surface and the present studied aquifer has not suffered any major structural evolution. The eastern boundary has a higher elevation and from there the land surface gently slopes in all other directions until it meets the Meghna river. It is also an established fact that the ground water table is a subdued replica of the land surface, therefore any major changes in morphology should also be reflected in the water table. Since such major changes in the morphology seem to be absent, and since all the wells under consideration (Nos. 2, 8, 13, 52, 79 and 99) are located along the eastern elevated section therefore the wells 8, 79 and 99 should have produced higher ground water elevation than the measured value. In view of the above interpretation, a further checking of surface topography and surface elevation including the depth measurement of the water table is recommended during any future study which may significantly reduce the complication of the flow behaviour because the possibility of erroneous measurements-either of water level or elevation can not be discounted, though no proof is available.

The construction of a flow net showing flow directions (Fig. 4.3) provides useful information about the response of ground water and also its possible relationship with river flow. Although the constructed flow pattern is very complicated and makes extremely difficult any analysis of the possible relationship
FIG-4-3: MAJOR FLOW DIRECTION
BASED ON MINIMUM ELEVATION
CONTOUR MAP.

LEGENDS
INTERNATIONAL BOUNDARY
CHANNELS
PRIMARY
SECONDARY
WELL LOCATION
PIEZOMETRIC WELLS
AUTO PIEZOMETRIC WELLS
PUMP TEST WELLS
PIEDPIT WELLS
UNDP QUALITY STATIONS
GWC QUALITY STATIONS
BADQ QUALITY STATIONS
UNDP-GWC QUALITY STATIONS
UNDP-BADQ QUALITY-PIED WELLS
UNDP QUALITY-PIED WELLS
GWC QUALITY-PIED WELLS
BADQ QUALITY-PUMP TEST WELLS
GWC QUALITY-AUTO PIEZ WELLS
BADQ QUALITY-AUTO PIEZ WELLS
UNDP QUALITY-AUTO PIEZ WELLS

NOTE: 20 KM
between the ground water and surface water, useful information can still be obtained. In the northern region, the northern part of the Titas river behaves like a gaining stream while the southern part that merges with the Meghna river provides clear indication of a losing stream. The contribution to or from the Gumti river is some what unclear. The upstream part of the Dakatia and most parts of the Little Feni rivers show clear indications of a losing stream. The flow pattern of the Noakhali canal provides clear indication of a gaining stream.

There is a clear contrast in the distribution of contours between the eastern and western parts of the studied area. The contours in the western part are sparsely (thinly) distributed in comparison with those of the eastern part. The extreme closeness of the contours around Comilla town (wells 49, 52 and 60) is mainly because of excessive withdrawal of ground water from storage rather than because of poor aquifer conditions. The hydraulic gradient has been calculated for five different locations (Table 4.1) covering the main contrasting regions indicated in Fig. 4.2. Locations A, C and E were selected from the eastern densely distributed contoured area. On the other hand locations B and D were chosen from the sparsely distributed contoured area. The maximum and minimum hydraulic gradient values are recorded respectively at locations C and D which have a difference of more than two orders of magnitude. A number of reasons could be advanced to account for the steeper gradient in the eastern region and particularly at location C (around Comilla town). Firstly, the town is a densely populated area which has a high demand for water for municipal purposes all the year round. Secondly, the urban area is surrounded by highly fertile crop lands which also require constant irrigation during the dry season for which the major source is ground water. Thirdly, a considerable amount of ground water is also abstracted for industrial purposes.
<table>
<thead>
<tr>
<th>Period</th>
<th>Location</th>
<th>Hydraulic gradient dh/dl = i</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRY</td>
<td>A</td>
<td>$3.26 \times 10^{-4}$</td>
<td>1.3070</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>$1.09 \times 10^{-4}$</td>
<td>1.9140</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>$1.27 \times 10^{-3}$</td>
<td>1.790</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>$7.18 \times 10^{-5}$</td>
<td>1.13930</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>$2.86 \times 10^{-4}$</td>
<td>1.3500</td>
</tr>
<tr>
<td>WET</td>
<td>A</td>
<td>$3.18 \times 10^{-4}$</td>
<td>1.3140</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>$2.08 \times 10^{-4}$</td>
<td>1.4780</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>$3.50 \times 10^{-4}$</td>
<td>1.2860</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>$2.75 \times 10^{-4}$</td>
<td>1.3640</td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>$2.72 \times 10^{-4}$</td>
<td>1.3680</td>
</tr>
</tbody>
</table>

Table 4.1: Comparison of hydraulic gradient in the two seasons.
Because of all these demands the area has the highest concentration of deep tube wells (DTW) and shallow tube wells (STW) which abstract large amounts of ground water every year, especially during the dry season. As a consequence the hydraulic gradient sharply increases within the zone of influence of this cluster of wells.

On the other hand, the crop lands in and adjacent to the flood plain areas in the western regions require smaller amounts of ground water or none at all for irrigation as substantial quantities of surface water is available for this purpose. As a result, only a small number of deep tube wells have been installed in this part of the project area and a smaller fraction of the ground water resource is withdrawn during summer, which is also reflected by the contour distribution.

4.4.3 Maximum Elevation (Wet Period) Contour Map:

The water table contour map for maximum elevation (Fig. 4.4) has been prepared using the water table measurements for August, 1985 when the maximum amount of rainfall occurs. During this period of time the highest possible amount of recharge takes place and in a few cases, particularly close to the flood plain area, some land surface occasionally becomes inundated.

During this wet period minimum elevations of <0 m have been recorded at wells 8 and 99 whereas elsewhere the minimum elevations are >4 m in all other places except the south-western Haimchar, Faridganj, Raypur and Laksmipur areas. Here the elevation progressively decreases to <2 m which is expected and logical since the land surface elevation decreases towards the west.

The general direction of flow (Fig. 4.5) obtained from flow net analysis is much improved and less complicated in comparison with the flow net map analysis for the dry period. In this map the general flow is more clearly defined. An interesting feature about the ground water flow is observed within the
FIG.-4: WATER TABLE CONTOUR MAP OF MAXIMUM ELEVATION (WET PERIOD) AUGUST, 1985.

Hydraulic gradient measuring points A, B, C, D and E

Elevation in metres.
FIG. 4.5: MAJOR FLOW DIRECTION BASED ON MAXIMUM ELEVATION CONTOUR MAP.
4 m closed contour surrounding the Nabinagar and Muradnagar areas in the north-west (see Fig. 4.4). Here it looks as if ground water is pouring in from all directions. This 4 m contour surrounds the down stream part of the Gumti river suggesting the river is being fed by the ground water but the reverse is true for the upstream part of the same river. Previously the relationship of the Gumti river with the ground water was quite unclear in the dry period flow-net map (Fig. 4.3). The wet period flow-net map shows the Titas river to have characteristics of a losing stream throughout its entire length. The downstream section of the Dakatia river and most parts of the Noakhali canal show the characteristics of a gaining river. The losing characteristics of the Little Feni river are consistent with the dry period flow-net interpretation. The Feni river in the light of this flow-net analysis has characteristics of a gaining river.

The equipotential lines are much more uniformly distributed and the spacing of the contours all over the project area is somewhat similar. Even in the urban areas (around Comilla town) the contour spacing has also increased significantly to give a better co-ordination with the other areas. The hydraulic gradient has been calculated for five different locations (Table 4.1) which are close to those considered previously. The wet period values are remarkably close to each other and they are also fairly small. Such a close correlation in hydraulic gradient suggests a similar distribution of resource potential in different regions. It also indicates that the entire or most parts of the aquifer is well connected and the permeability does not change abruptly. This in turn also indicates that the lithological variation is minimal. An increase in contour spacing, particularly in urban areas (around Comilla town), indicates some augmentation in ground water storage during the summer time.
4.4.4 Annual Fluctuation Map:

The fluctuation in ground water elevation has been determined at the points of intersection by subtracting the elevation of minimum water table contours (Fig. 4.2) from the elevation of the maximum water table contours (Fig. 4.4) by superimposition of the two maps with additional fluctuations obtained as the difference between dry and wet periods in all the available wells. The resultant data were used to prepare the annual fluctuation map (Fig. 4.6) for the year 1985. The use of both types of fluctuation values allowed a greater number of points to be taken into consideration for the better preparation of the map and the more accurate the contours are drawn so also will be the interpretation.

The maximum amount of fluctuation (>10 m) is recorded around the Comilla town where the maximum amount of ground water is withdrawn during dry period. The minimum amount of fluctuation as low as zero (0) m is recorded in the northern part of Nasirnagar area. Further north, close to the boundary, an area of negative fluctuation (-1 m) is recorded which implies a rise in water level during dry period. This seems to be unlikely on the basis of the prevailing condition, when the water table elevation is expected to be declining. A possible explanation for the rising water table could be that more water is coming into storage via horizontal flow and deep percolation as well as from the effluent Titas river than the amount of water that is flowing out naturally and/or taken out from storage by pumping through the existing large number of wells.

The changing fluctuation pattern in the north is quite different from those in the south. In the north, the maximum fluctuation is intermediate and gradually decreases in all directions. However, for the larger southern part the reverse is true i.e.-the central part gave rise to the lowest fluctuation and increases on all other direction except the south-eastern narrow strip where the fluctuation decreases into the Feni river, which itself behaves as a gaining river. The change
FIG. 4.6: CONTOUR MAP SHOWING ANNUAL FLUCTUATION FOR 1985.

Fluctuation in metres.
in fluctuation is large in the Comilla town area and consequently the gradient of the increasing fluctuation is also very high in the town area. The contour spacing of the annual fluctuation contour map increases in west, north-west and south-western directions, in similar fashion to the contour spacing of the dry period elevation contour map (Fig. 4.2).

In all locations the increased amount of fluctuation has coincided with the higher amount of ground water withdrawal. A high withdrawal is not necessarily harmful for the aquifer. In fact a controlled high withdrawal in relation to the annual recharge makes more ground water available for use. On the other hand, the excess amount of recharge which was previously unable to be taken into storage because of early saturation could now be accepted by the aquifer by virtue of the creation of more space by excessive withdrawal.

4.5 Replenishment Calculation:

The yearly replenishment for the year 1985 is calculated using the prepared fluctuation contour map (Fig. 4.6). The replenishment is calculated in the form of volumetric changes multiplying the area involved by the average fluctuation. Since the amount of fluctuation ranges from -2 m to +11 m and the map has a contour interval of 1 m, the volumetric changes between every two consecutive contours were calculated separately to obtain better results which are displayed in Table 4.2.

The total volumetric change in the contours between the extremes of -2 and +11 m is equivalent to some 28,500 million [= 2.85335 x 10^{10} m^{3} ].

Finally the total amount of recharge in the form of effective infiltration (I_{e}) is calculated using the following relationship:

1) I_{e} = [(W_{y} x S_{r})/a] to get the results in terms of height in (mm/year), and
2) I_{e} = (W_{y} x S_{r}) to get the results in volume in (m^{3}/year).
<table>
<thead>
<tr>
<th>Contour interval (m)</th>
<th>Area between contours (m²)</th>
<th>Average fluctuation (m)</th>
<th>Volumetric change ($V_i$) (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2 to -1</td>
<td>$8.95 \times 10^7$</td>
<td>1.5</td>
<td>$1.343 \times 10^8$</td>
</tr>
<tr>
<td>-1 to 0</td>
<td>$1.80 \times 10^8$</td>
<td>0.5</td>
<td>$9.000 \times 10^7$</td>
</tr>
<tr>
<td>0 to +1</td>
<td>$5.49 \times 10^8$</td>
<td>0.5</td>
<td>$2.745 \times 10^8$</td>
</tr>
<tr>
<td>+1 to +2</td>
<td>$1.78 \times 10^9$</td>
<td>1.5</td>
<td>$2.670 \times 10^9$</td>
</tr>
<tr>
<td>+2 to +3</td>
<td>$4.15 \times 10^9$</td>
<td>2.5</td>
<td>$1.038 \times 10^{10}$</td>
</tr>
<tr>
<td>+3 to +4</td>
<td>$2.26 \times 10^9$</td>
<td>3.5</td>
<td>$7.910 \times 10^9$</td>
</tr>
<tr>
<td>+4 to +5</td>
<td>$6.42 \times 10^8$</td>
<td>4.5</td>
<td>$2.889 \times 10^9$</td>
</tr>
<tr>
<td>+5 to +6</td>
<td>$1.61 \times 10^8$</td>
<td>5.5</td>
<td>$8.855 \times 10^8$</td>
</tr>
<tr>
<td>+6 to +7</td>
<td>$1.34 \times 10^8$</td>
<td>6.5</td>
<td>$8.710 \times 10^8$</td>
</tr>
<tr>
<td>+7 to +8</td>
<td>$9.72 \times 10^7$</td>
<td>7.5</td>
<td>$7.290 \times 10^8$</td>
</tr>
<tr>
<td>+8 to +9</td>
<td>$7.40 \times 10^7$</td>
<td>8.5</td>
<td>$6.290 \times 10^8$</td>
</tr>
<tr>
<td>+9 to +10</td>
<td>$5.02 \times 10^7$</td>
<td>9.5</td>
<td>$4.769 \times 10^8$</td>
</tr>
<tr>
<td>+10 to +11</td>
<td>$5.66 \times 10^7$</td>
<td>10.5</td>
<td>$5.943 \times 10^8$</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>$1.02235 \times 10^9$</td>
<td>-</td>
<td>$2.85336 \times 10^9$</td>
</tr>
</tbody>
</table>

Table 4.2: Volumetric changes covering the entire region.
where,

\[ W_y = \text{total volumetric changes} = (2.85335 \times 10^{10} \text{ m}^3) \]

\[ a = \text{area over which recharge occurred} = (1.02235 \times 10^{10} \text{ m}^2) \]

\[ S_y = \text{specific yield} = 20 \text{ percent}. \]

The specific yield can be determined directly by analyzing pumping test data when the aquifer is unconfined; in this case the late storativity is equivalent to the specific yield. But when the aquifer condition is other than unconfined, which is true for the present study area, then the specific yield cannot be determined from pumping test data because in these circumstances the aquifer can not be dewatered. Hence, the specific yield has to be determined in an alternative fashion. The commonest way, however, is to determine from the porosity analysis result where the volume of linked porosity is taken as equivalent to specific yield.

Unfortunately neither the actual porosity of the aquifer material nor the specific yield has been estimated by any other means. In these circumstances one can experimentally establish a value of specific yield. Three different sources were considered before selection of a reasonable value of specific yield justifiable for the existing lithological conditions which are a mixture of different types of unconsolidated sands and gravels (Section 3.3.2). The specific yield determined by Poland et. al. (1959) for sand, sand and gravel, and gravel and sand is about 20 percent. In another study Walton (1970) experimentally established that the specific yield for the present type of materials ranges from 15 to 25 percent and this is reprinted by Driscoll (1987) in Johnson divisions book 'Groundwater and Wells'. In another instance, Fetter (1980) has compiled the value of specific yield from a large number of samples distributed in various geographic locations, where it is found that the value of specific yield ranges from 20 to 35 percent for sands and gravels with an average of 25 percent. The average of these three
published accepted values of specific yield is about 22 percent but to be on the safe side a specific yield value of 20 percent has been selected to calculate the ground water replenishment and other parameters in the subsequent chapters. Using this specific yield value the calculated value of effective infiltration \( I_e \) in both forms are:

\[
I_e = \left[ \frac{W_y \times S_y}{a} \right] = \left[ \frac{2.85335 \times 10^{10} \times 0.20}{1.02235 \times 10^{10}} \right]
\]

\[
= 558.22 \text{ mm} = 5.71 \times 10^9 \text{ m}^3.
\]

4.6 Comments on Ground Water Movement and Flow Pattern:

From the foregoing analysis of various water table contour maps and flow direction deductions, it can be concluded that in general ground water flow directions are mainly towards west, south-west, north-west and south with few exceptions where the flow of ground water is found to be towards eastern directions. This flow pattern has developed because of variable sloping directions of the land surface. The following comments can be made on the basis of analysis of various aspects of ground water flow:

1) all the perennial rivers maintain a direct relationship with the ground water. Most of them in their downstream sections show characteristics of a gaining river and the upstream sections show characteristics of a losing river, except the Little Feni river which shows the reverse characteristics. This feature is revealed in both the dry period and wet period flow net maps.

2) the uniform distribution of contours in the contour map (Fig. 4.4) suggest that enough water is available during the wet period and the ground water storage is full to its capacity. At the same time, it may also indicate that this uniform nature of the contours all over the places may also indicate minimal lithological variation.
3) the general concept that increasing spacing of the equipotential lines means smaller hydraulic gradients which in turn suggest greater ground water potential has again been proved to be true. But one has to be careful that an aquifer having good ground water potential can also produce a higher hydraulic gradient resulting in close contour spacing because of excessive withdrawal from storage.

4) the higher elevation (which also coincides with the higher fluctuation) of the water table around Comilla town to some extent could well be due to the partial blockage of ground water flow by the north-south trending Lalmai Hills located in the west of Comilla town, the only relics of the Tertiary structure.

5) the annual fluctuation is at a maximum near the places from where maximum amount of ground water is withdrawn during the dry period i.e.-amount of fluctuation maintains a direct relationship with the amount of withdrawal, which suggests that the minimum levels are not natural, but instead are accentuated by pumping effects. What is significant is that the seasonal replenishment commonly restores water levels to their natural maxima, this being indicative of high value of effective infiltration.
CHAPTER 5  AQUIFER TEST ANALYSIS.

5.1 Introduction
   5.1.1 General Information.
   5.1.2 Well Structure.
   5.1.3 Hydraulic Properties.

5.2 Analytical Solution.
   5.2.1 Validity of Measurement.
   5.2.2 Selection of Methods.
   5.2.3 Presentation and Discussion of Analyses.

5.3 Numerical Solution.
   5.3.1 Radial Flow Model.
   5.3.2 Presentation of Analyses.
   5.3.3 Discussion in Results.

5.4 Comparison of the Results.
   5.4.1 Comparison of Individual Sites.
   5.4.2 Overall Comparison.
5.1 Introduction:

5.1.1 General Information:

    Being a part of a deltaic plain, the study area shows rapid facies changes along with characteristic lack of lateral continuity. This characteristic change in lithology is reflected in the rapid changes of aquifer condition from confined to semi-confined over very short distances even from one observation well to another at the same pumping well site.

    A total of fourteen pump tests (see Fig. 5.1) were carried out by the Bangladesh Water Development Board (BWDB) in and around the present project area. Eleven of them are constant rate tests i.e. the well was pumped for a considerable period of time at a constant discharge rate; such a test is often called an aquifer test. Seven of them are step-drawdown tests (over-lapping in some of the wells) i.e. the well was pumped at successively greater discharges for relatively short periods of time. Such a pumping test is sometime called a well test. During the pumping test session three to four observation wells (OW) were used with the pumping well where the change in water level (drawdown) was also measured. These various drawdown-data measurements in the OWs facilitate the adoption of both time-drawdown and distance-drawdown solutions in the analysis of the important hydraulic parameters such as transmissivity (T), storativity (S), hydraulic conductivity (K), leakage factor (L), and others depending on the hydrogeological nature of the aquifer (i.e. whether it is confined, leaky-confined or unconfined). All these aquifer parameters provide vital clues about the storage as well as the transmitting properties of the aquifer. The drawdown data from the pumping wells have not been used to analyze any of the hydraulic parameters since drawdown data for several OWs are available.

    When the well is pumped during the aquifer test the position of the potentiometric surface declines with time producing the drawdown response which
Fig. 5.1: Map showing the location of aquifer testing wells.
is measured in the pumping well and in the nearby observation well at specified times. This recorded time-drawdown data allows the utilisation of various analytical and numerical methods for calculating the hydraulic parameters.

5.1.2 Well Structure:

From the top to the bottom of the hole the well is given a metallic structure for all cases in the study area because of the unconsolidated nature of the aquifer. Depending on the shape, size and use of the well, the total structure is divided into five different segments (Fig. 5.2). According to their position from top to bottom they are:

1. **Housing pipe**: In most cases the housing pipe is around 80 feet (about 24 metres) in length with a width of 14 inches (about 36 cm). It is wide enough to accommodate a turbine pump.

2. **Reducing Socket**: This part connects the housing pipe to the bottom part of the well pipe and at the same time reduces the well radius to the desired limit. Usually the vertical length of the reducing socket is around 2 feet (0.61 m) in length.

3. **Blind pipe, Strainer and Bail Plug**: From the reducer to the bottom of the well, the structure maintains a constant diameter in most of the wells; it is 0.25 ft (0.08 m) except for a few instances when it is 0.33 ft (0.1 m). Depending on the presence of prospective aquifer horizon(s), single or multiple strainer (screen) segments are set against the best horizon(s), rather than placing strainers throughout the entire length of the aquifer, in order to minimise the well construction costs and to increase the performance of the well. Except for the lowest 5 or 10 ft (1.5 or 3.0 m), depending on the depth of the well, the entire well fixture length is completed with blind pipe. The bottom 5 ft (3.0 m) is called the bail plug which marks the physical end of the well.
Fig. 5.2. Generalised structure of the constructed wells.
During the construction of the well in almost all cases the entire thickness of the aquifer was utilised to avoid partial penetration effects.

5.1.3 Hydraulic Properties:

The most important hydraulic properties of a potential aquifer are twofold in number. Firstly, the storage capacity (i.e. the water bearing formations should be capable of holding sufficient quantity of ground water within the pore spaces) which is reflected by a property called storativity (S) and is dimensionless. Secondly, the yielding capacity (i.e. the water bearing formation(s) should be able of transmitting a sufficient quantity of ground water through the linked porosity) and this property is represented by the parameters known as transmissivity (T) and hydraulic conductivity (K).

Storativity is defined as the quantity of water that an aquifer releases from or takes into storage per unit surface area of aquifer per unit change in the component of head normal to the surface. Two important properties are related to the storage function which are porosity (more precisely the linked porosity) and specific yield (Sₚ). Porosity is an index of how much ground water can be stored in a saturated medium, and specific yield is a measure of how much water can actually be taken out from that storage. The coarser the sediment the higher will be the specific yield. The storativity of an unconfined aquifer (equivalent to their specific yield) ranges from 0.01 to 0.30 while the storativity of a confined aquifer is much lower because it is not drained during pumping (hence specific yield can not be determined) any water released from storage is obtained primarily by the compaction of the aquifer and expansion of the water. In a confined aquifer, water is always stored under high pressure and because of pumping this pressure is reduced to some extent which allows the water to expand though the aquifer is not dewatered. Typical storativity values of a confined aquifer range from $10^{-4}$ to
The hydraulic conductivity (permeability) indicates the quantity of water that will flow through a unit cross sectional area of a porous medium per unit time under a hydraulic gradient of 1 (100 percent) at a specified temperature. A hydraulic gradient of one means a head fall of 1 ft or 1 m for every 1 ft or 1 m of flow travel. The common range of K is generally from 10 to 5000 gpd/ft² in the English units system (or 0.5 to 200 m/d in the metric system of units) for natural aquifer materials (Freeze & Cherry, 1979). The transmission of water through the entire thickness of the aquifer is more informative than the flow through the unit area of the aquifer. Theis (1935) introduced the concept of 'transmissivity' by using the product of K and b as a single term defining it as the rate of flow through the vertical section of an aquifer one feet (or other units) wide and extending the full saturated thickness of an aquifer under a hydraulic gradient of 1. It is expressed as m³/d/m or simply m²/d accordingly to the metric system and in the English unit system it is gpd/ft or ft²/d.

Among the several methods available for the determination of hydraulic parameters, the results obtained by analyzing pumping test data are the most accurate. When a well is pumped at a constant rate for a known time an exponential decrease in water table (or piezometric surface) takes place within the well and adjacent aquifer unless it intercepts a boundary (such as faults, rivers etc.) or induces a vertical flow of water through the overlying semi-pervious confining layer or receives gravity drainage equal to the amount of water being pumped from the bore hole. The horizontal distance up to which the lowering of water level takes place is called the zone of influence. The change in water level at a point during pumping is called the drawdown (s). This when plotted against time, either arithmetic scale or log-log scale, provides several values which then can be inserted into various analytical formulae developed by Theis, Jacob, Hantush, Walton, De
Glee and others. For confirmation purposes, a numerical technique can also be used to calculate various hydraulic parameters depending on the type of aquifer.

5.2 Analytical Solution:

5.2.1 Validity of Measurement:

During the conduct of pumping tests in the study area, three observation wells were used for every test site to obtain more accurate results. The distance to the observation wells from the pumping well was limited to between 50 and 1000 ft, and varies from one well site to another.

A careful study of the time-drawdown data plots of all 33 observation wells reveals various discrepancies within the data proper, and ignorance of these facts could have produced misleading results.

Good quality data when plotted on semi-log paper or on double logarithmic paper, should give a progressive increase in drawdown or a decrease in the case of recovery. This rule is not maintained in two cases. Firstly, the short time increase and decrease in drawdown during the first 30 minutes observed at Burichong O.W. at r = 100 ft (30.48 m) in Fig. 5.8.A and Kotwali O.W. at r = 400 ft (121.92 m) in Fig. 5.10.C. These irregularities could be due to inefficient measurement of data or could be due to rapid changes in sedimentary facies i.e. alternating thin bands of clay/silt lenses within the aquifer. It is not due to an uncontrolled rate of pumping because this effect is absent in other observation wells. Secondly, the long-term fluctuation (increase and decrease) in drawdown and/or recovery through-out the entire length of pumping session seen in Nabinagar O.W., at r = 400 ft (121.92 m) Fig. 5.4.B; r = 1000 ft (304.8 m) Fig. 5.4.C; and Kotwali O.W., r = 50 ft (15.24 m) Fig. 5.10.A and r = 400 ft (121.92 m) Fig. 5.10.C suggest that this could be due to inefficient measurement of data or more likely to slight variations in pumping rate.
The unexpected sudden rises in drawdown seen in Daudkandi O.W., \( r = 150 \text{ ft (45.72 m)} \) Fig. 5.7.B; Chandina O.W., \( r = 50 \text{ ft (15.24 m)} \) Fig. 5.9.A; Chandina O.W., \( r = 150 \text{ ft (45.72 m)} \) Fig. 5.9.B; Chandina O.W., \( r = 400 \text{ ft (121.92 m)} \) Fig. 5.9.C1 and Barura O.W., \( r = 150 \text{ ft (45.72 m)} \) Fig. 5.10.B when the wells were attaining steady state conditions indicates interference drawdowns due to the pumping of a neighbouring well. Some rises in water level return to their steady state conditions, indicating that the interference wells were pumped only for a short time and then stopped before the cessation of the pumping test session.

The cone of influence should produce a greater drawdown in the nearer observation wells and a smaller drawdown at the farthest wells. This rule is maintained for the two O.W. \([r = 150 \text{ ft (45.72 m)} \) Fig. 5.9.B and \( r = 400 \text{ ft (121.92 m)} \) Fig. 5.9.C\] of the Chandina test site, but a surprisingly small drawdown was recorded at the well at \( r = 50 \text{ ft (15.24 m)} \) (Fig. 5.9.A) which is smaller than the recorded drawdown for the farthest observation well. Therefore the time-drawdown data of the nearest observation well cannot be used for calculating the hydraulic parameters.

A negative drawdown is only expected in the presence of a barrier boundary condition. How many times the plotted data will change gradient will depend on the number of boundaries in the vicinity of the well site. The drawdowns produced at the Barura O.W. with \( r = 50 \text{ ft (15.24 m)} \) Fig. 5.11.A indicate the presence of a double boundary condition whereas the observation wells with \( r = 150 \text{ ft (45.72 m)} \) Fig. 5.11.B and \( r = 400 \text{ ft (121.92 m)} \) Fig. 5.11.C at the same pumping site produce no negative effects. If it were a true boundary condition then all the observation wells should have the same effect. Alternatively, it might be that a true boundary condition exists which is present close to the affected observation well and the unaffected wells are present on the opposite side of the pumping well from the boundary. Since the lay out of the test wells is not
available, this problem cannot be resolved, and also suggests that the data from \( r = 50 \text{ ft (15.24 m)} \) cannot be used for the final calculation of hydraulic parameters. With all these difficulties in mind, the pump test data were analyzed using several types of solution to avoid confusion.

5.2.2 Selection of Methods:

It is desirable that a pumping test should be continued until steady state flow conditions have been reached i.e. the recharge to the aquifer is equal to the pumping rate. In practice it is found that a steady state condition cannot be reached for all types of aquifer condition. It is very difficult for example to achieve a steady state condition for a truly confined aquifer because no actual dewatering takes place. Also constraints on time and costs mean that most pumping tests have a duration shorter than ideal. An advantage of longer pumping of well is that it may reveal the presence of boundary condition previously unknown.

The drawdowns observed in each well and/or piezometer during pumping are then plotted against the corresponding time either on a semi-log paper or on a double logarithmic paper to produce time-drawdown or distance-drawdown curves. Analytical solutions are of two basic types (a) time-drawdown and (b) distance-drawdown solution both of which can be analyzed by the straight-line method (semi-log plot) and the type curve method (double-log plot). A few methods such as that of Hantush (1956) require both time-drawdown and distance-drawdown data for all the piezometers. For the present project, time-drawdown and distance-drawdown solutions were both applied to analysis of the data since one method is complementary to the other.

The shape of the time-drawdown plot (both straight-line and type-curve method) provides important guidelines for understanding the nature and condition (whether confined, semi-confined or water table) of the aquifer. A confined aquifer
condition produces a steep curve with constant gradient. A leaky confined condition initially produces a steep curve with high constant gradient which with increasing time gradually flattens so that if the duration of pumping is long enough then it reaches a steady-state condition. An unconfined aquifer, on the other hand, produces a plot with three distinct segments. The first segment is analogous to the curve of a confined aquifer since initially water is released instantaneously from storage by the compaction of the aquifer and by the expansion of water. The second segment shows a decrease in slope because of the replenishment by gravity drainage from the horizon above the depression cone. The third segment again shows a rise in the gradient and maintains a slope almost similar to the first segment. If the time-drawdown is plotted on double logarithmic paper then the first and third segments closely conform to the Theis type-curve when it reaches an equilibrium between the gravity drainage and the rate of pumping.

In the light of knowledge of the geology and the above mentioned aquifer responses, the data plots produced for all the pumping test sites suggest leaky confined condition except in two wells (Feni well 117 and Senbagh well 130). After a careful screening, the Theis (1935) and Jacob & Cooper (1946) non-steady state solutions were used to analyze the confined condition. The Walton (1962) and Hantush (1956) non-equilibrium and De Glee (1930,1951) equilibrium methods were used to analyze the leaky confined conditions. Though each method is based on the Theis formula, every solution has additional conditions to fulfil. Yet some basic assumptions are common to many method of solutions:-

1. the aquifer has an infinite lateral extent,
2. the aquifer is homogeneous, isotropic and of uniform thickness over the area influenced by pumping,
3. prior to pumping, the potentiometric surface is nearly horizontal over the area influenced by pumping,
(4) it should be an efficient pumping well and pumped at a constant rate,

(5) the pumping well penetrates the entire thickness of the aquifer and receive water by means of horizontal flow, and

(6) the well diameter is infinitely small i.e. the storage in the well can be neglected.

A brief outline of the methods used are given below:

**Theis Method:**

The non-steady state solution was first introduced by C. V. Theis (1935) and derived from an analogy of ground water flow with that of heat conduction. In doing that he took into account the related parameters of pumping duration and the storativity of the aquifer. This is a type curve solution so that the time-drawdown data is plotted on double-logarithmic paper and requires matching of the data with a specially prepared Theis type-curve to obtain values of \( W(u) \), \( u \), \( t \) and \( s \) which are known as the 'match point' co-ordinates. The formulae he developed to calculate the transmissivity \( (T) \) and storativity \( (S) \) are:

\[
T = \frac{Q \cdot W(u)}{4 \pi s} \quad \text{and} \quad S = \frac{4 \cdot T \cdot t \cdot u}{r^2}
\]

This solution needs to satisfy the following conditions and general assumptions;

(1) the aquifer is confined i.e. the water bearing zone is bounded by impervious layers both at top and at bottom,

(2) the flow to the well is unsteady i.e. the drawdown difference with time is not negligible nor is the hydraulic gradient constant with time, and

(3) the water removed from storage is discharged instantaneously with the decline of head.
**Jacob and Cooper Method:**

This method is also based on Theis method but it depends on the relationship that when sufficient time has elapsed for a discharging well then the drawdown at a fixed distance increases approximately in proportion to the logarithm of time since the pumping started and decreases in proportion to the logarithm of the distance from the well.

Jacob’s approximation of the Theis formula in the form of the straight-line equations he derived employ both time-drawdown and distance-drawdown solutions for the calculation of 'T' and 'S', provided the value of 'u' remains less than 0.02. In this connection, to check that the value of 'u' is appropriate requires the calculation of 't_u', which indicates how much time should elapsed before the method is valid for a particular set of data.

One technique requires the time-drawdown plot (semi-log scale) and uses the following formulae to calculate the hydraulic parameters:

\[
T = \frac{0.183 Q}{ds} \times \log \left( \frac{t_f}{t_i} \right)
\]

\[
S = \frac{2.25 T}{r^2} \quad \text{and} \quad t_u = \frac{12.5 r^2 S}{T}
\]

The second technique uses a distance-drawdown plot (semi-log scale) and the following formulae to calculate the hydraulic parameters:

\[
T = \frac{0.366 Q}{ds} \times \log \left( \frac{r_f}{r_1} \right) \quad \text{and} \quad S = \frac{2.25 T t}{(r_o)^2}
\]

**Walton Method:**

This type curve method for analyzing the hydraulic properties of a
leaky confined aquifer combines the ideas of Theis and Hantush in the preparation of a family of type curves depending on the degree of leakage. Along with the previous general assumptions this method must also satisfy the following additional limitations:

1. the aquifer is semi-confined,
2. the flow to the well is unsteady, and
3. instantaneous removal of storage water takes place with the decline of hydraulic head.

After obtaining a satisfactory match with one of the family of type curves the match point co-ordinates of W(u), u, s and t_m are recorded to calculate the following hydraulic parameters:

\[
T = \frac{Q \cdot W(u)}{4 \pi s}
\]

\[
S = \frac{4 \cdot T \cdot t_m \cdot u}{r^2} \quad \text{and} \quad L = \frac{r}{(r/L)}
\]

**Hantush Method:**

Hantush (1956) developed several methods, some dedicated to steady state conditions and others applicable for non-steady state conditions. Therefore selection of procedures depends on the nature of aquifer. Two of his procedures were adopted for analyzing the aquifer parameters.

Firstly, with his time-drawdown procedure, the accuracy of the results depends on the extrapolation of the maximum drawdown value (s_max) and the correct positioning of the associated inflection point. This method requires fulfilment of all the additional assumptions applicable for the Walton method.

Calculation of the different hydraulic parameters using the following formulae requires values for r/l and e^na from a tabulation produced by Hantush.
(1956):

\[ e^{(n)} K_0 (r/L) = \frac{2.303 \, s_i}{d s_i} \quad L = \frac{r}{\lambda (r/L)} \]

\[ T = \frac{0.183 \, Q}{d s_i} \times e^{(n)} \quad S = \frac{4 \, T \, t_i}{2 \, r \, L} \quad \text{and} \quad t_{st} = \frac{12.5 \, r^2 S}{T} \]

The second procedure is a distance-drawdown solution using a straight line method for determining the hydraulic parameters which requires at least two observation wells (but greater the number of OW’s the better the results) as well as the time-drawdown data for each observation well. A second semi-log plot with the change of drawdown per log cycle of time over the distances of the observation wells is also required. This method requires all the same additional assumptions to be fulfilled as for Walton’s method including the general assumptions.

De Glee Method:

Unlike the confined aquifer, a steady state condition can be achieved for a leaky confined aquifer after pumping the well for a long enough period of time when the discharge rate of pumping well equals the recharge rate from the overlying semi-pervious layer in the form of vertical flow. De Glee’s method of solution requires steady state drawdown for each observation well. As it is a distance-drawdown type-curve solution, a number of observation wells is always desirable to obtain more accurate results. The following extra conditions are needed to be fulfilled in addition with the general assumptions:

(1) the aquifer is leaky-confined,

(2) the flow to the well is steady state i.e. there is no change in drawdown with time,
(3) the phreatic surface remains constant (drawdown of the phreatic surface < 5% of the saturated part of the semi-pervious layer) so that leakage through the covering layer takes place in proportion to the drawdown of the piezometric level, and

(4) leakage factor is more than three times the aquifer thickness i.e.

\[ L = > 3b. \]

Unfortunately this method is incapable of giving any storativity value but the match point co-ordinates of \( K_0(r/L), r/L=1, \) and \( s \) allows \( T \) and \( L \) to be determined with the following equations:

\[
T = \frac{Q}{2 \pi s} \times K_0(r/L) \quad r/L = 1 \text{ or } r = L.
\]

5.2.3 Presentation and Discussion of analyses:

The result of the pumping test analysis for the project area are presented in this section individually and systematically from north to south (Fig. 5.1). Detailed calculations of one test result are presented below from each group of aquifer conditions with the main calculations for the other test sites only the final results are tabulated. The Feni Pumping test site is selected to represent confined condition and the Nabinagar pumping test site is taken as the representative of the leaky-confined conditions. The pump test data are presented in Appendix 5.1.

Theoretically speaking, the results of the analysis of a pumping test obtained from the different methods of solution used should normally show little variation. However, since a good agreement in the results very much depends on the successful conduct of the test, the accurate measurement of time-drawdown data is of utmost importance. The variation in the results also depends to some extent on the variation of the lithology in the vicinity of the pumping and observation wells. Since a frequent change in lithofacies is an important characteristic of the
sediments deposited under deltaic conditions, therefore a variation in the results from different observation wells at the same site may not be unexpected.

**Feni Pumping Test Site:**

The well has a depth of 191.58 ft (58.4 m) with a well radius (r) of 0.25 ft (7.6 m). During the pumping test, the well was pumped with a constant discharge (Q) = 4574 m³/d (161,553 ft³/d) for a period of 4300 minutes (3 days). The observation wells are spaced at distances of 50 ft (15 m), 400 ft (120 m) and 1000 ft (305 m) respectively. The estimated thickness of the aquifer is about 110 ft (33 m) and the overlying aquiclude has an estimated thickness of 82 ft (25 m). Static water level (SWL) is 11.33 ft (3.45 m) below measuring point (bmp). The results of analysis of the pumping test data are summarised in Table 5.1.

1) **NSS/NLC/Time-Drawdown Solution:**

**Feni O.W. (r = 50 ft):**

(a) **Type Curve Method:**

The log-log plot of Figure 5.3.A(a) was used to obtain the indicated match point co-ordinates for the calculation of the following hydraulic parameters:

\[
T = \frac{Q W(u)}{4 \pi s} = \frac{61553 \times 1}{4 \pi 1.10} = 11687.25 \text{ ft}^2/\text{d}
\]

or 1090 m²/d.

\[
K = \frac{T}{b} = \frac{11687.25}{110} = 106.25 \text{ ft}/\text{d} \text{ or } 32 \text{ m}/\text{d}.
\]

\[
S = \frac{4 T t u}{r^2} = \frac{4 \times 11687.25 \times 5.2 \times 0.01}{(50)^2 \times 1440} = 6.8 \times 10^4.
\]
### (a) SOLUTION: TIME - DRAWDOWN

<table>
<thead>
<tr>
<th>DISTANCE OF PIEZOMETER</th>
<th>METHOD</th>
<th>( T (m^3/d) )</th>
<th>( S(\cdot) )</th>
<th>( S_1(\cdot) )</th>
<th>( S_2(\cdot) )</th>
<th>( K=\frac{T}{b} (m/d) )</th>
<th>( L (m) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 ft.</td>
<td>SL</td>
<td>930</td>
<td>1.7(3)</td>
<td>-</td>
<td>-</td>
<td>28</td>
<td>-</td>
</tr>
<tr>
<td>15.24 m.</td>
<td>TC</td>
<td>1090</td>
<td>6.8(4)</td>
<td>-</td>
<td>-</td>
<td>32</td>
<td>-</td>
</tr>
<tr>
<td>400 ft.</td>
<td>SL</td>
<td>890</td>
<td>1.8(3)</td>
<td>-</td>
<td>-</td>
<td>27</td>
<td>-</td>
</tr>
<tr>
<td>121.92 m.</td>
<td>TC</td>
<td>900</td>
<td>6.8(4)</td>
<td>-</td>
<td>-</td>
<td>32</td>
<td>-</td>
</tr>
<tr>
<td>1000 ft.</td>
<td>SL</td>
<td>930</td>
<td>8.5(4)</td>
<td>-</td>
<td>-</td>
<td>28</td>
<td>-</td>
</tr>
<tr>
<td>304.80 m.</td>
<td>TC</td>
<td>870</td>
<td>9.5(4)</td>
<td>-</td>
<td>-</td>
<td>26</td>
<td>-</td>
</tr>
</tbody>
</table>

**AVERAGE VALUES**

|                      |        | 940             | 1.1(-3)       | -              | -              | 29                   | -       |

**INFERRED CONDITIONS**

FULLY CONFINED

### (b) SOLUTION: DISTANCE - DRAWDOWN

<table>
<thead>
<tr>
<th>METHOD</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
<th>( r (m) )</th>
<th>( T (m^3/d) )</th>
<th>( S_1 (\cdot) )</th>
<th>( S_2 (\cdot) )</th>
<th>( S_3 (\cdot) )</th>
<th>( K (m/d) )</th>
<th>( L (m) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SL (II)</td>
<td>15.24</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>121.92</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>304.80</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TC (SS)</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TC (NSS)</td>
<td></td>
<td>-</td>
<td>1190</td>
<td>8.6(4)</td>
<td>-</td>
<td>36</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SL (II)</td>
<td></td>
<td>-</td>
<td>1140</td>
<td>8.7(4)</td>
<td>-</td>
<td>34</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**AVERAGE VALUES**

|                      |        | 1170           | 8.7(4)        | -               | 35              | -             | -           |

**INFERRED CONDITIONS**

FULLY CONFINED

Table 5.1. Pumping test analysis results (analytical) of Feni Well; (a) Time-Drawdown and (b) Distance-Drawdown.
Fig. 5.3.A: Aquifer test analysis for OW1 at Feni; (a) Type Curve and (b) Straight Line.
(b) Straight Line Method:

The 'ds' and 't_o' values were taken from the semi-log plot [Fig. 5.3.A(b)] to calculate the following parameters:

\[
\frac{0.183 \times Q}{ds} = \frac{0.183 \times 161553}{2.95} = 10021.76 \text{ ft}^2/\text{d}
\]

or 930 m\(^2\)/d.

\[
K = \frac{T}{b} = \frac{10021.76}{110} = 91.11 \text{ ft/d. or 28 m/d.}
\]

\[
S = \frac{2.25 \times T \times t_o}{r^2} = \frac{2.25 \times 10021.76 \times 0.27}{(50)^2 \times 1440} = 1.7 \times 10^3.
\]

or 7.6 minutes.

Feni O.W. (r = 400 ft):

(a) Type Curve Method:

The match point co-ordinates of W(u), u, t and s are obtained from the log-log plot [Fig. 5.3.B(a)] to calculate the following hydraulic parameters:

\[
T = \frac{Q \times W(u)}{4 \pi s} = \frac{161553 \times 1}{4 \pi \times 1.31} = 9813.72 \text{ ft}^2/\text{d.}
\]

or 910 m\(^2\)/d.

\[
K = \frac{T}{b} = \frac{9813.72}{110} = 89.22 \text{ ft/d or 27 m/d.}
\]

\[
S = \frac{4 \times T \times u}{r^2} = \frac{4 \times 9813.72 \times 9.00 \times 1}{(400)^2 \times 1440} = 1.5 \times 10^3.
\]
Fig. 5.3.B: Aquifer test analysis for OW2 at Feni; (a) Type Curve and (b) Straight Line.
(b) **Straight Line Method:**

The 'ds' and 't₀' values were taken from the time-drawdown plot [Fig. 5.3.B(b)] to calculate the following hydraulic parameters:

\[
T = \frac{0.183 \times 161553}{0.183} = 9598.76 \text{ ft}^2/\text{d}
\]

or 890 m²/d.

\[
K = \frac{T}{b} = \frac{9598.76}{110} = 87.26 \text{ ft/d or } 27 \text{ m/d.}
\]

\[
S = \frac{2.25 \times 9598.76 \times 19}{(400)^2 \times 1440} = 1.8 \times 10^3.
\]

\[
t_u = \frac{12.5 \times (400)^2 \times 1.8 \times 10^3}{9598.76} = 0.37 \text{ days or } 540 \text{ mins.}
\]

Feni O.W. (r = 1000 ft):

(a) **Type Curve Method:**

The match point co-ordinates of W(u), u, t and s are obtained from the log-log plot [Fig. 5.3.C(a)] to calculate the following hydraulic parameters:

\[
T = \frac{161553 \times 1}{4 \pi s} = \frac{9383.93 \times 1}{4 \pi 1.37} = 9383.93 \text{ ft}^2/\text{d}
\]

or 870 m²/d.

\[
K = \frac{T}{b} = \frac{9383.93}{110} = 85.31 \text{ ft/d or } 26 \text{ m/d.}
\]

\[
S = \frac{4 \times 9383.93 \times 36.5 \times 1}{(1000)^2} = 9.51 \times 10^4.
\]

(b) **Straight Line Method:**

The 'ds' and 't₀' values were taken from the time-drawdown plot [Fig. 5.3.C(b)] to calculate the following parameters:
Fig. 5.3.C: Aquifer test analysis for OW3 at Feni; (a) Type Curve and (b) Straight Line.
\[ T = \frac{0.183 \times 161553}{2.95} = 10021.76 \text{ ft}^2/\text{d} \]

or 930 m$^2$/d.

\[ K = \frac{T}{b} = \frac{10021.76}{110} = 91.11 \text{ ft/d or 28 m/d} \]

\[ S = \frac{2.25 \times 10021.76 \times 54}{(1000)^2 \times 1440} = 8.5 \times 10^4 \]

\[ t_u = \frac{12.5 \times (1000)^2 \times 8.5 \times 10^4}{10021.76} = 1.06 \text{ days} \]

or 1526.7 mins.

2) NSS/NLC/Distance-Drawdown Solution:

Feni site:

(a) Type Curve Method:

The match point co-ordinates of $W(u)$, $u$, $s$ and $r$ were taken from the log-log plot [(Fig. 5.3D(a)] to calculate the following hydraulic parameters:

\[ T = \frac{Q \times W(u)}{4 \times \pi \times s} = \frac{161553 \times 1}{4 \times \pi \times 1.0} = 12856.00 \text{ ft}^2/\text{d} \]

or 1190 m$^2$/d.

\[ K = \frac{T}{b} = \frac{12856.00}{110} = 116.90 \text{ ft/d or 36 m/d} \]

(b) Straight line Method:

The semi-log plot [Fig.- 5.3D(b)] of distance-drawdown data were used to obtain the values of $ds$ and $r_0$ for the calculation of following hydraulic parameters:
Fig. 5.3.D. Aquifer test analysis for Feni; (a) Type Curve and (b) Straight Line.
\[
\frac{0.366 \times Q}{ds} = \frac{0.366 \times 16153}{4.825} = 12254.59 \text{ ft}^2/\text{d}
\]

or 1140 m\(^2\)/d.

\[K = \frac{t}{b} = \frac{12254.59}{110} = 111.4 \text{ ft/d} \text{ or} \ 34 \text{ m}^2/\text{d}.
\]

\[
\frac{2.25 \times T \times t}{(r_0)^3} = \frac{2.25 \times 12254.59 \times 200}{(2100)^3 \times 1440} = 8.7 \times 10^4.
\]

3) Discussion:

Feni well is an ideal example of a non-leaky confined condition indicated by the results obtained from all the methods (Table. 5.1). Strikingly close results were obtained for T, S and K from all the different methods.

Maximum and minimum transmissivity values range from 1190 m\(^2\)/d obtained by the distance-drawdown solution to 870 m\(^2\)/d obtained by a time-drawdown solution for OW3.

Storativity values range from 1.7 \times 10^{-3} for OW1 to 6.8 \times 10^{-4} for both OW1 and OW2.

The permeability values range from 26 m/d to 36 m/d.

Nabinagar Pumping Test Site:

The test well has a depth of 301.5 ft (92 m) and a well radius of 0.25 ft (7.62 cm). During the test programme, the well was pumped at a \(Q\) of 2446 m\(^3\)/d (86400 ft\(^3\)/d) for a time period of 4100 mins (2.85 days). The piezometers were placed at distances of 50 ft (15 m), 400 ft (122 m) and 1000 ft (305 m) from the pumping well. The observed thickness of the aquifer \(b\) is 140 ft (43 m) with an overlying aquiclude that has a thickness of 161.5 ft (49 m). Pumping test results are summarised in Table 5.2.
SITE: NABINAGAR  WELL No:- 9

(a) SOLUTION:- TIME - DRAWDOWN

<table>
<thead>
<tr>
<th>DISTANCE OF PIEZOMETER</th>
<th>METHOD</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>T (m²/d)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D'down REC.</td>
</tr>
<tr>
<td>50 ft.</td>
<td>SL</td>
<td>420</td>
</tr>
<tr>
<td>15.24 m.</td>
<td>TC</td>
<td>360</td>
</tr>
<tr>
<td>400 ft.</td>
<td>SL</td>
<td>430</td>
</tr>
<tr>
<td>121.92 m.</td>
<td>TC</td>
<td>280</td>
</tr>
<tr>
<td>1000 ft.</td>
<td>SL</td>
<td>580</td>
</tr>
<tr>
<td>304.80 m.</td>
<td>TC</td>
<td>410</td>
</tr>
<tr>
<td>AVERAGE VALUES</td>
<td></td>
<td>410</td>
</tr>
<tr>
<td>INFERRED CONDITIONS</td>
<td></td>
<td>LEAKY CONFINED</td>
</tr>
</tbody>
</table>

(b) SOLUTION:- DISTANCE - DRAWDOWN

<table>
<thead>
<tr>
<th>METHOD</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r (m)</td>
</tr>
<tr>
<td>SL (II)</td>
<td>15.24</td>
</tr>
<tr>
<td></td>
<td>121.92</td>
</tr>
<tr>
<td></td>
<td>304.80</td>
</tr>
<tr>
<td>TC (SS)</td>
<td>-</td>
</tr>
<tr>
<td>TC (NSS)</td>
<td>-</td>
</tr>
<tr>
<td>SL (II)</td>
<td>-</td>
</tr>
<tr>
<td>AVERAGE VALUES</td>
<td>360</td>
</tr>
<tr>
<td>INFERRED CONDITIONS</td>
<td>LEAKY CONFINED</td>
</tr>
</tbody>
</table>

Table. 5.2. Pumping test analysis results (analytical) of Nabinagar Well; (a) Time-Drawdown and (b) Distance-Drawdown.
1) NSS/LC/Time-Drawdown Solution:

Nabinagar O.B. (r = 50 ft):

(a) Type Curve Method:

The match point co-ordinates of W(u), u, t and s along with the \((r/L)\) value obtained from the type curve plot [Fig. 5.4.A(a)] were used to calculate the following hydraulic parameters:

\[
T = \frac{Q \cdot w(u)}{4 \pi s} = \frac{86400 \times 1}{4 \times \pi \times 1.78} = 3862.63 \text{ ft}^2/\text{d.}
\]

or \(360 \text{ m}^2/\text{d.}\)

\[K = \frac{T}{b} = \frac{3862.63}{140} = 27.59 \text{ ft/d or } 8 \text{ m/d.}\]

\[\frac{r}{L} = 0.3 \times 10^{-1}.\]

\[
L = \frac{r}{(r/L)} = \frac{50}{0.3 \times 10^{1}} = 1666.67 \text{ ft.}
\]

\[
S = \frac{4 \cdot T \cdot t \cdot u}{r^2} = \frac{4 \times 3862.63 \times 14.3 \times 0.01}{(50)^2 \times 1440} = 6.1 \times 10^{-4}.
\]

(b) Straight Line Method:

The necessary parameters obtained from the time-drawdown plot [Fig. 5.4.A(b)] with the other values taken from the Hantush (1956) table of functions specially prepared for this solution were used to calculate the following parameters:

\[
e^{\rho t} \cdot K_0 \left(\frac{r}{L}\right) = \frac{2.303 \times s_i}{d s_i} = \frac{2.303 \times 6.8}{3.45} = 4.54.
\]

\[e^{\nu t} = 0.987, \frac{r}{L} = 0.013,\]

\[
L = \frac{r}{(r/L)} = \frac{50}{0.013} = 3846 \text{ ft. or } 1172 \text{ m.}
\]
Fig. 5.4.A: Aquifer test analysis for OW1 at Nabinagar; (a) Type Curve and (b) Straight Line.
\[ T = \frac{0.183 \times Q}{ds_i} \times e^{-\frac{Q}{86400 \times 0.987}} = \frac{0.183 \times 86400 \times 0.987}{3.45} = 4523.38 \text{ ft}^2/\text{d.} \]

or \( 420 \text{ m}^2/\text{d.} \)

\[ K = \frac{T}{b} = \frac{4523.38}{140} = 32.31 \text{ ft/d or } 10 \text{ m/d.} \]

\begin{align*}
S &= \frac{4 \times 4523.38 \times 16}{2 \times 50 \times 3846 \times 1440} = 5.2 \times 10^4. \\
12.5 \times r^2 \cdot s &= \frac{12.5 \times (50)^2 \times 5.2 \times 10^4}{4523.38} = 3.59 \times 10^3 \text{ days} \\
&= 5.17 \text{ mins.} \\
\end{align*}

Nabinagar O.W. (r = 400 Ft):

(a) Type Curve Method:

The match point co-ordinates of W(u), u, t and s along with the \((r/L)\) value obtained from the type curve plot [Fig. 5.4.B(a)] were used to calculate the following hydraulic parameters:

\[ T = \frac{Q \cdot w(u)}{4 \pi s} = \frac{86400 \times 1}{4 \pi \times 2.25} = 3055.77 \text{ ft}^2/\text{d.} \]

or \( 280 \text{ m}^2/\text{d.} \)

\[ K = \frac{T}{b} = \frac{3055.77}{140} = 21.83 \text{ ft/d or } 7 \text{ m/d.} \]

\begin{align*}
S &= \frac{4 \times 4 \times 3055.77 \times 14.5 \times 1}{(400)^2 \times 1440} = 7.7 \times 10^4. \\
\end{align*}

(b) Straight Line Method:

The necessary parameters obtained from the time-drawdown plot [Fig. 5.4.B(b)] and the Hantush (1956) function tables were used to calculate the
Fig. 5.4.B: Aquifer test analysis for OW2 at Nabinagar; (a) Type Curve and (b) Straight Line.
following hydraulic parameters:

\[ e^{nl} \cdot K_{o}(r/L) = \frac{2.303 \times s_i}{3.05} \]

\[ e^{nl} = 0.89 \quad \text{and} \quad r/L = 0.11 \quad \text{(From the table)}.

\[ L = \frac{400}{(r/L)(0.11)} = 3636.36 \text{ ft}.
\]

\[ T = \frac{0.183 \times Q}{d_s} \times e^{nl} = \frac{0.183 \times 86400 \times 0.89}{3.05} = 4613.73 \text{ ft}^2/\text{d}.
\]

or 430 m$^2$/d.

\[ S = \frac{4 \times T \cdot t_m}{2 \cdot r \cdot L} = \frac{4 \times 4613.73 \times 145}{2 \times 400 \times 3636.36 \times 1440} = 6.4 \times 10^4
\]

\[ K = \frac{T}{b} = \frac{4613.77/140}{140} = 32.96 \text{ ft/d. or 10 m/d}.
\]

\[ t_s = \frac{12.5 \times r^2 \cdot s}{T} = \frac{12.5 \times (400)^2 \times 6.4 \times 10^4}{4613.73} = 0.27 \text{ days}.
\]

\[ = 399 \text{ mins}.
\]

**Nabinagar O.W. (r = 1000 ft):**

(a) **Type Curve Method:**

The match point co-ordinates of W(u), u, t and s and the matching (r/L) value were taken from the type curve plot [Fig. 5.4.C(a)] to calculate the following hydraulic parameters:

\[ T = \frac{Q \cdot w(u)}{4 \pi s} = \frac{86400 \times 1}{4 \times \pi \times 1.55} = 4435.80 \text{ ft}^2/\text{d}.
\]

or 410 m$^2$/d.

\[ K = \frac{T}{b} = \frac{4435.80/140}{140} = 31.68 \text{ ft/d. or 10 m/d}.
\]

\[ L = \frac{r}{(r/L)(1000/0.4)} = 2500 \text{ ft}.
\]
**Fig. 5.4.C:** Aquifer test analysis for OW3 at Nabinagar; (a) Type Curve and (b) Straight Line.
or \( L = 762 \text{ m/d.} \)

\[
S = \frac{4 \times 4435.80 \times 76 \times 1}{(1000)^2 \times 1440} = 9.4 \times 10^4.
\]

(b) Straight Line Method:

The necessary parameters were obtained from the time-drawdown plot [Fig. 5.4.C(b)] and also from the Hantush (1956) function tables to calculate the following hydraulic parameters:

\[
e^{rt} \cdot K_0(r/L) = \frac{2.303 \times 1.60}{2.02} = 2.303 s_i = \frac{2.303}{L} \cdot K_0 \cdot (r/L) = 1.824
\]

\[
e^{-r\ell} = 0.733 \quad \text{and} \quad r/L = 0.31. \quad \text{(From function table)}
\]

\[
L = \frac{1000}{0.31} = 3225.81 \text{ ft. or 983 m.}
\]

\[
T = \frac{0.183 \times Q \times e^{r\ell}}{ds_i} = \frac{0.183 \times 86400 \times 0.733}{2.02}
\]

\[
= \frac{5737.43 \text{ ft}^2/\text{d.}}{\text{or 530 m}^2/\text{d.}}
\]

\[
K = \frac{5737.43}{140} = 40.98 \text{ ft/d. or 12 m/d.}
\]

\[
4 \times \frac{t_i}{r L} = \frac{4 \times 5737.43 \times 360}{2 \times 1000 \times 3225.81 \times 1440} = 8.9 \times 10^4.
\]

\[
12.5 \times r^2 \times S = \frac{12.5 \times (1000)^2 \times 8.5 \times 10^4}{5737.43} = 1.939 \text{ days.}
\]

or 2792 mins.

2) SS/LC/Nabinagar Distance-Drawdown solution:
(a) Type Curve Method:

The match point co-ordinates were obtained from the distance-drawdown Plot [Fig. 5.4.D(a)] to calculate the following hydraulic parameters:

\[
\frac{r}{L} = 1 \quad \text{or} \quad r = L = 1980 \text{ ft. or } 604 \text{ m.}
\]

\[
T = \frac{Q K_0 \left( \frac{r}{L} \right)}{2 \pi s} = \frac{84600 \times 1}{2 \times \pi \times 3.60} = 3819.72 \text{ ft}^2/\text{d.}
\]

or \(360 \text{ m}^2/\text{d.}\)

\[
K = \frac{T}{b} = \frac{3819.72}{140} = 27.28 \text{ ft/d. or } 8 \text{ m/d.}
\]

(b) Straight Line Method:

The necessary parameters were taken from the previous time-drawdown plots of all the observation wells and also from the distance-ds (per log cycle) plot [Fig. 5.4.D(B)] to calculate the following hydraulic parameters:

\[
L = \frac{dr}{2.303} = \frac{2803.3}{2.303} = 1217.20 \text{ ft. or } 371 \text{ m.}
\]

\[
\frac{r_1}{L} = \frac{50}{1217.2} = 0.04, \quad K_0 \left( \frac{r_1}{L} \right) = 3.312 \text{ (table).}
\]

\[
\frac{r_2}{L} = \frac{400}{1217.2} = 0.329, \quad K_0 \left( \frac{r_2}{L} \right) = 1.286 \text{ (table).}
\]

\[
\frac{r_3}{L} = \frac{1000}{1217.2} = 0.82, \quad K_0 \left( \frac{r_3}{L} \right) = 0.548 \text{ (table).}
\]

\[
T = \frac{0.183 Q}{ds_0} = \frac{0.183 \times 86400}{4.22} = 3746.73 \text{ ft}^2/\text{d.}
\]

or \(350 \text{ m}^2/\text{d.}\)

\[
s_{(1)} = \frac{Q}{4 \pi T} \times K_0 \left( \frac{r_1}{L} \right) = \frac{86400}{4 \times \pi \times 3746.73} \times 3.312 = 1.835 \times 3.312 = 6.08 \text{ ft. and from the plot the corresponding } t_{(1)} \text{ value is } 0 \text{ mins.}
\]

\[
s_{(2)} = \frac{Q}{4 \pi T} \times K_0 \left( \frac{r_2}{L} \right) = \frac{86400}{4 \times \pi \times 3746.73} \times 1.286
\]
Fig. 5.4.D: Aquifer test analysis Nabinagar site; (a) Type Curve and (b) Straight Line.
\[ s_{t(0)} = \frac{Q}{4 \pi T} \times K_0 \cdot \frac{r^2}{L} = \frac{86400}{4 \pi x 3746.73} \times 0.548 \]

\[ = 1.835 \times 0.548 = 1.01 \text{ ft. and from the plot the corresponding } t_{t(0)} \text{ value is 190.0 mins.} \]

\[ 2 \frac{T}{T} \frac{t_{t(0)}}{t_{t(0)}} = \frac{2 \times 3746.73 \times 10.0}{50 \times 1217.2 \times 1440} = 8.6 \times 10^{-4}. \]

\[ S_1 = \frac{2 \times 3746.73 \times 190}{400 \times 1217.2 \times 1440} = 7.3 \times 10^{-4}. \]

\[ S_2 = \frac{2 \times 3746.73 \times 190}{400 \times 1217.2 \times 1440} = 8.1 \times 10^{-4}. \]

3) Discussion:

All the observation wells show the characteristics of a leaky confined aquifer indicating minimum lithologic variation. The maximum amount of leakage \((L = 371 \text{ m})\) is obtained from the straight line distance-drawdown solution for OW1 while the minimum amount of leakage \((L = 1172 \text{ m})\) is given by SL time-drawdown for the same well.

The transmissivity values obtained do not show any great deal of difference except the single low value \((280 \text{ m}^2/\text{d})\) obtained by the type curve time-drawdown solution for OW2. The highest \(T\) value \((530 \text{ m}^2/\text{d})\) is given by the straight line time-drawdown solution for OW3.

Striking similarities were obtained in storativity values. The lowest value \((5.2 \times 10^{-4})\) was obtained by the straight line time-drawdown solution for OW1 and the highest value \((9.4 \times 10^{-4})\) is given by the type curve time-drawdown solution.
solution for OW3.

The permeability values range from 7 m/d obtained by use of the type curve time-drawdown solution for OW2 to 12 m/d obtained from the straight line time-drawdown solution for OW3 (Table 5.2).

B'Baria Pumping Test Site:

The well has a depth of 302 ft (92 m) with a well radius \( r \) = 0.33 ft (10 cm). During the test the well was pumped at a discharge \( Q \) = 76997 ft\(^3\)/d (2180 m\(^3\)/d) for a period of \( t \) = 3000 minutes (2.083 days). The observation wells were spaced at \( r \) = 50 ft (15 m), 150 ft (45 m), and 400 ft (122 m). The estimated thickness of the aquifer is 200 ft (60 m) and the overlying semi-pervious layer has a thickness of 102 ft (31 m). The static water level at the pumping well is 4.39 ft (1.34 m) below the measuring point. The result of analysis of pumping test data are summarised in Table 5.3 calculated on the basis of the match point co-ordinates and other necessary parameters obtained from the relevant figures.

1) Time-Drawdown Solution:

(a) Type Curve Method: The match-point co-ordinates for OW1 \( (r = 50 \text{ ft}) \), OW2 \( (r = 150 \text{ ft}) \) and OW3 \( (r = 400 \text{ ft}) \) were obtained from the type-curve plots of Figures 5.5.A(a), 5.5.B(a) and 5.5.C(a) respectively.

(b) Straight Line Method: The necessary parameters for OW1, OW2 and OW3 were obtained from the time-drawdown plots of Figures 5.5.A(b), 5.5.B(b), and 5.5.C(b), respectively.

2) B'Baria Distance-Drawdown Solution:

(a) Type Curve Method: The match-point co-ordinates were obtained from the distance-drawdown log-log plot (figure not included).
### (a) SOLUTION: TIME-DRAWDOWN

<table>
<thead>
<tr>
<th>DISTANCE OF PIEZOMETER</th>
<th>METHOD</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>T (m²/d)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D'down REC.</td>
</tr>
<tr>
<td>50 ft.</td>
<td>SL</td>
<td>950</td>
</tr>
<tr>
<td>15.24 m.</td>
<td>TC</td>
<td>1020</td>
</tr>
<tr>
<td>150 ft.</td>
<td>SL</td>
<td>810</td>
</tr>
<tr>
<td>45.72 m.</td>
<td>TC</td>
<td>59*</td>
</tr>
<tr>
<td>400 ft.</td>
<td>SL</td>
<td>1020</td>
</tr>
<tr>
<td>121.92 m.</td>
<td>TC</td>
<td>410*</td>
</tr>
<tr>
<td>AVERAGE VALUES</td>
<td></td>
<td>950</td>
</tr>
<tr>
<td>INFERRED CONDITIONS</td>
<td></td>
<td>LEAKY CONFINED</td>
</tr>
</tbody>
</table>

* Results not included

### (b) SOLUTION: DISTANCE-DRAWDOWN

<table>
<thead>
<tr>
<th>METHOD</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r (m)</td>
</tr>
<tr>
<td>SL (II)</td>
<td>15.24</td>
</tr>
<tr>
<td></td>
<td>45.72</td>
</tr>
<tr>
<td></td>
<td>121.92</td>
</tr>
<tr>
<td>TC (SS)</td>
<td>-</td>
</tr>
<tr>
<td>TC (NSS)</td>
<td>-</td>
</tr>
<tr>
<td>SL (II)</td>
<td>-</td>
</tr>
<tr>
<td>AVERAGE VALUES</td>
<td>830</td>
</tr>
<tr>
<td>INFERRED CONDITIONS</td>
<td>LEAKY CONFINED</td>
</tr>
</tbody>
</table>

Table 5.3. Pumping test analysis results (analytical) of B'Baria Well; (a) Time-Drawdown and (b) Distance-Drawdown.
Fig. 5.5.A: Aquifer test analysis for OW1 at B' Baria; (a) Type Curve and (b) Straight Line.
Fig. 5.5.B: Aquifer test analysis for OW2 at B' Baria; (a) Type Curve and (b) Straight Line.
Fig. 5.5.C. Aquifer test analysis for OW3 at B'Baria; (a) Type Curve and (b) Straight Line.
(b) **Straight Line Method**: The necessary parameters were obtained from the previous time-drawdown plots of all the observation wells and the distance-drawdown semi-log plot (figure not included).

3) **Discussion:**

Both the type curve (TC) and straight line (SL) solution for OW1 (r = 50 ft) and the SL solution for OW3 (r = 400 ft) suggest a non-leaky confined condition whereas both the type curve and straight line solution for OW2 (r = 150 ft) and the type curve solution for OW3 produces enough leakage to qualify as a leaky confined condition. The highest leakage (L = 183 m) was calculated by the type curve time-drawdown solution for OW2 and the lowest leakage (L = 1166 m) was produced by the straight line distance-drawdown solution (Table. 5.3).

A high transmissivity (T) value (2014 m²/d) is obtained by the straight line distance-drawdown solution with a low T value (410 m²/d) given by the type curve time-drawdown solution for OW3, and these values are not included for further interpretation.

All the storativity values obtained for the different OWs indicate a confined condition. The highest storativity value (5.7 x 10⁻³) is given by a type curve time-drawdown solution for OW2 and the lowest value (1.6 x 10⁻⁴) is obtained by a straight line distance-drawdown solution for OW1.

The maximum (34 m/d) and minimum (7 m/d) permeability (hydraulic conductivity) values correspond to the highest and lowest transmissivity values.

**Daudkandi Pumping Test Site:**

The well structure has a depth of 342 ft (104 m) with a well radius of 0.25 ft (7.6 cm). During the pumping test the well was pumped with an average discharge (Q) = 172785 ft³/d (4892 m³/d) for a period of 1800 minutes (1.25 days).
The observation wells are spaced at 50 ft (15 m), 150 ft (45 m), and 400 ft (122 m) from the pumping well. The estimated aquifer thickness is 140 ft (40 m) which is underlain by a semi-pervious layer of 195 ft (60 m) thick. S.W.L. = 8.08 ft. The result of the analysis is present in the Table. 5.4 calculated on the basis of the match-point co-ordinates and other necessary parameters obtained from the relevant figures.

1) Time-Drawdown and Time-Calculated Recovery Solution:

(a) Type-Curve Method: The match-point co-ordinates for OW1 (r = 50 ft), OW2 (r = 150 ft) and OW3 (r = 400 ft) were obtained from the type-curve plots of Figures 5.6.A(a), 5.6.B(a) and 5.6.C(a), respectively.

(b) Straight Line Method: The necessary parameters for OW1, OW2, and OW3 were obtained from the time-drawdown plots of Figures 5.6.A(b), 5.6.B(b), and 5.6.C(b), respectively and the Hantush function tables.

2) Daudkandi Distance-Drawdown Solution:

(a) Type-Curve Method: The match point co-ordinates were obtained from the distance-drawdown log-log plot (figure not included).

(b) Straight Line Method: The necessary parameters were obtained from the previous time-drawdown plots of all the observation wells and the distance-ds (drawdown per log cycle) semi-log plot (figure not included).

3) Discussion:

In addition to the time-drawdown data, the recovery data were also available for this particular test site. The results obtained by analyzing both drawdown and recovery data (Table. 5.4) suggest a leaky confined condition. The recovery data suggests a lower leakage. The highest leakage (L = 192 m) is given
## (a) SOLUTION: TIME-DRAWDOWN

### VALUES OF HYDRAULIC PARAMETERS

<table>
<thead>
<tr>
<th>DISTANCE OF PIEZOMETER</th>
<th>METHOD</th>
<th>$T$ (m$^2$/d)</th>
<th>$S_1$ (-)</th>
<th>$S_2$ (-)</th>
<th>$S_3$ (-)</th>
<th>$K = T/b$ (m/d)</th>
<th>$L$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 ft.</td>
<td>SL</td>
<td>1010</td>
<td>860</td>
<td>50(-4)</td>
<td>68(-3)</td>
<td>24</td>
<td>20</td>
</tr>
<tr>
<td>15.24 m.</td>
<td>TC</td>
<td>1090</td>
<td>26(-4)</td>
<td>26(-4)</td>
<td>35(-4)</td>
<td>29</td>
<td>1219</td>
</tr>
<tr>
<td>150 ft.</td>
<td>SL</td>
<td>1320</td>
<td>1030</td>
<td>30(-4)</td>
<td>81(-3)</td>
<td>31</td>
<td>1999 581</td>
</tr>
<tr>
<td>400 ft.</td>
<td>SL</td>
<td>1320</td>
<td>1030</td>
<td>30(-4)</td>
<td>81(-3)</td>
<td>31</td>
<td>1999 581</td>
</tr>
<tr>
<td>121.92 m.</td>
<td>TC</td>
<td>1240</td>
<td>35(-4)</td>
<td>29(-4)</td>
<td>85(-4)</td>
<td>25</td>
<td>1219</td>
</tr>
</tbody>
</table>

### AVERAGE VALUES

<table>
<thead>
<tr>
<th></th>
<th>T (10$^5$)</th>
<th>S$1$ (-)</th>
<th>S$2$ (-)</th>
<th>S$3$ (-)</th>
<th>K (m/d)</th>
<th>L (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1050</td>
<td>51(-4)</td>
<td></td>
<td></td>
<td>25</td>
<td>553</td>
</tr>
</tbody>
</table>

### INFERRED CONDITIONS

Leaky Confined

* Results not included

## (b) SOLUTION: DISTANCE-DRAWDOWN

### VALUES OF HYDRAULIC PARAMETERS

<table>
<thead>
<tr>
<th>METHOD</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$r$ (m)</td>
</tr>
<tr>
<td>SL (II)</td>
<td>15.24</td>
</tr>
<tr>
<td></td>
<td>45.72</td>
</tr>
<tr>
<td></td>
<td>121.92</td>
</tr>
<tr>
<td>TC (SS)</td>
<td>-</td>
</tr>
<tr>
<td>TC (NSS)</td>
<td>-</td>
</tr>
<tr>
<td>SL (II)</td>
<td>-</td>
</tr>
</tbody>
</table>

### AVERAGE VALUES

<table>
<thead>
<tr>
<th></th>
<th>T (10$^5$)</th>
<th>S$1$ (-)</th>
<th></th>
<th></th>
<th></th>
<th>K (m/d)</th>
<th>L (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1050</td>
<td>51(-4)</td>
<td></td>
<td></td>
<td></td>
<td>25</td>
<td>553</td>
</tr>
</tbody>
</table>

### INFERRED CONDITIONS

Leaky Confined

Table 5.4. Pumping test analysis results (analytical) of Daudkandi Well; (a) Time-Drawdown and (b) Distance-Drawdown.
Fig. 5.6.A: Aquifer test analysis for OW1 at Daudkandi; (a) Type Curve and (b) Straight Line.
Fig. 5.6.B: Aquifer test analysis for OW2 at Daudkandi; (a) Type Curve and (b) Straight Line.
Fig. 5.6.C: Aquifer test analysis for OW3 at Daudkandi; (a) Type Curve and (b) Straight Line.
by the straight line distance-drawdown solution and the lowest leakage (L = 1999 m) is recorded by the straight line time-drawdown solution for OW3.

The transmissivity values obtained for all the observation wells employing all the methods shows little variation except that the lowest value (770 m$^2$/d) obtained by the type curve time-drawdown solution for OW1 which is much lower than all other values. The highest transmissivity value (1320 m$^2$/d) is given by the straight line time-drawdown solution for OW3.

Storativity values obtained are representative of confined conditions. The highest and lowest storativity values ranged from $1.0 \times 10^3$ obtained by a type curve time-drawdown solution for OW1 to $1.7 \times 10^4$ obtained by the straight line distance-drawdown solution for OW2.

The permeability values show no great deal of difference and vary from 18 m/d obtained by the type curve time-drawdown solution for OW1 to 31 m/d obtained by the straight line distance-drawdown solution for OW3.

**Burichong Pumping Test Site:**

The test well was drilled a depth of 327 ft (100 m) with a radius (r) = 0.25 ft (7.6 cm). During the testing session the well was pumped with a constant discharge (Q) = 76962 ft$^3$/d (2179 m/d) and the test was continued for a period of 3000 mins (2.083 days). The observation wells were placed at r = 100 ft (30 m), 150 ft (45 m), and 250 ft (76 m). The aquifer has an estimated thickness (b) of 192 ft (60 m) and the thickness of the overlying semi-pervious bed (b') is 135 ft. (40 m). The static water level is measured at 5.42 ft (1.65 m) below measuring point. The test results are summarised in Table. 5.5 calculated on the basis of the match-point co-ordinates and necessary parameters obtained from the relevant figures.
### (a) SOLUTION: TIME-DRAWDOWN

<table>
<thead>
<tr>
<th>DISTANCE OF PIEZOMETER</th>
<th>METHOD</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>T (m²/d)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D'down</td>
</tr>
<tr>
<td>100 ft.</td>
<td>SL</td>
<td>570</td>
</tr>
<tr>
<td>30.48 m.</td>
<td>TC</td>
<td>325</td>
</tr>
<tr>
<td>150 ft.</td>
<td>SL</td>
<td>560</td>
</tr>
<tr>
<td>45.72 m.</td>
<td>TC</td>
<td>420</td>
</tr>
<tr>
<td>250 ft.</td>
<td>SL</td>
<td>550</td>
</tr>
<tr>
<td>76.20 m.</td>
<td>TC</td>
<td>490</td>
</tr>
</tbody>
</table>

**AVERAGE VALUES**

| | | | | | |
|---|---|---|---|---|
| 505 | 23(3) | 9 | 523 |

**INFERRED CONDITIONS**

LEAKY CONFINED

* Results not included

### (b) SOLUTION: DISTANCE-DRAWDOWN

<table>
<thead>
<tr>
<th>METHOD</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r (m)</td>
</tr>
<tr>
<td>SL (II)</td>
<td>30.48</td>
</tr>
<tr>
<td></td>
<td>45.72</td>
</tr>
<tr>
<td></td>
<td>76.20</td>
</tr>
<tr>
<td>TC (SS)</td>
<td>-</td>
</tr>
<tr>
<td>TC (NSS)</td>
<td>-</td>
</tr>
<tr>
<td>SL (II)</td>
<td>-</td>
</tr>
</tbody>
</table>

**AVERAGE VALUES**

| | | | | |
|---|---|---|---|
| 340 | 4.9(3) | 6 | 131 |

**INFERRED CONDITIONS**

LEAKY CONFINED

Table 5.5. Pumping test analysis results (analytical) of Burichong Well; (a) Time-Drawdown and (b) Distance-Drawdown.
1) Time-Drawdown Solution:

(a) **Type-Curve Method**: The match-point co-ordinates for OW1 \( (r = 100 \text{ ft}) \), OW2 \( (r = 150 \text{ ft}) \) and OW3 \( (r = 250 \text{ ft}) \) were obtained from the time-drawdown plots of Figures 5.7.A(a), 5.7.B(a), and 5.7.C(a), respectively.

(b) **Straight Line Method**: The necessary parameters for OW1, OW2, and OW3 were obtained from the time-drawdown plots of Figures 5.7.A(b), 5.7.B(b), and 5.7.C(b), respectively and the Hantush function tables.

2) Burichong Distance-Drawdown solution:

(a) **Type Curve Method**: The match-point co-ordinates were obtained from the distance-drawdown log-log plot (figure not included).

(b) **Straight Line Method**: The necessary parameters were obtained from the previous semi-log time-drawdown plots of all the observation wells and the distance-drawdown semi-log plot (figure not included).

3) Discussion:

The results obtained by using both time-drawdown and distance-drawdown solutions for OW1 are abnormally high and are not included for further interpretation. Analytical results for other observation wells are reasonably acceptable (Table. 5.5).

Highly variable leakage values \( (L) \) are obtained ranging from 113 to 1088 m for OW2.

Confined storage values for the aquifer were obtained from all solutions for OW2 and OW3. The storativity values range from \( 4.4 \times 10^{-4} \) for OW2 to \( 9.2 \times 10^{-3} \) for OW3.

Little variation in transmissivity values were found with a range from 240 m\(^2\)/d to 560 m\(^2\)/d.
BURICHONG PIEZO. WELL AT A DISTANCE R = 100.0 FT Q = 76962 FT³/D

Fig. 5.7.A: Aquifer test analysis for OW1 at Burichong; (a) Type Curve and (b) Straight Line.
Fig. 5.7.B: Aquifer test analysis for OW2 at Burichong; (a) Type Curve and (b) Straight Line.
Fig. 5.7.C: Aquifer test analysis for OW3 at Burichong; (a) Type Curve and (b) Straight Line.
The permeability values range from 4 m/d to 10 m/d.

Chandina Pumping Test Site:

The well has a depth of 295 ft (90 m) and the structure has a radius of 0.25 ft (7.6 cm). During the test the well was pumped with a discharge \( Q = 84662 \text{ ft}^3/\text{d} \) \((2397 \text{ m}^3/\text{d})\) for a period of \( t = 3600 \text{ mins} \) (2.5 days). Three observation wells were placed at 50 ft (15 m), 150 ft (45 m), and 400 ft (122 m) from the pumping well. The aquifer has an estimated thickness \( b \) of 135 ft (41 m) and the overlying semi-pervious confining layer has a thickness \( b' \) of 160 ft (50 m). Static water level = 11.04 ft (3.36 m) below measuring point. The results are summarized in Table. 5.6 calculated on the basis of the match-point co-ordinates and other necessary parameters obtained from the relevant figures.

1) Time-Drawdown and Time-Calculated Recovery Solution:
(a) **Type-Curve Method:** The match-point co-ordinates for OW1 \((r = 50 \text{ ft})\), OW2 \((r = 150 \text{ ft})\), and OW3 \((r = 400 \text{ ft})\) were obtained from the log-log plots of Figures 5.8.A(a), 5.8.B(a), 5.8.C1(a), and 5.8.C2(a), respectively.
(b) **Straight Line Method:** The necessary parameters for OW1, OW2, and OW3 were obtained from the time-drawdown semi-log plots of Figures 5.8.A(b), 5.8.B(b), 5.8.C1(b), and 5.8C2(b), respectively and the Hantush function tables.

2) Chandina Distance-Drawdown Solution:
(a) **Type Curve Method:** The match-point co-ordinates were obtained from the distance-drawdown log-log plot (figure not included).
(2) **Straight Line Method:** The necessary parameters were obtained from the previous time-drawdown and time-calculated recovery plots of all the observation wells and the relevant distance-drawdown and distance-recovery semi-log plots
### (a) Solution: Time-Drawdown

<table>
<thead>
<tr>
<th>Distance of Piezometer</th>
<th>Method</th>
<th>Values of Hydraulic Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$T$ (m$^2$/d)</td>
</tr>
<tr>
<td>50 ft.</td>
<td>SL</td>
<td>62.60</td>
</tr>
<tr>
<td>15.24 m.</td>
<td>TC</td>
<td>41.70</td>
</tr>
<tr>
<td>150 ft.</td>
<td>SL</td>
<td>N.I</td>
</tr>
<tr>
<td>45.72 m.</td>
<td>TC</td>
<td>N.I</td>
</tr>
<tr>
<td>400 ft.</td>
<td>SL</td>
<td>1620</td>
</tr>
<tr>
<td>121.92</td>
<td>TC</td>
<td>1530</td>
</tr>
<tr>
<td><strong>Average Values</strong></td>
<td></td>
<td>1580</td>
</tr>
</tbody>
</table>

**Inferred Conditions**: Leaky Confined

---

### (b) Solution: Distance-Drawdown

<table>
<thead>
<tr>
<th>Method</th>
<th>Values of Hydraulic Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$r$ (m)</td>
</tr>
<tr>
<td>SL (II)</td>
<td>15.24</td>
</tr>
<tr>
<td></td>
<td>45.72</td>
</tr>
<tr>
<td></td>
<td>121.92</td>
</tr>
<tr>
<td>TC (SS)</td>
<td>-</td>
</tr>
<tr>
<td>TC (NSS)</td>
<td>-</td>
</tr>
<tr>
<td>SL (II)</td>
<td>-</td>
</tr>
<tr>
<td><strong>Average Values</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Inferred Conditions**: Leaky Confined

Table 5.6. Pumping test analysis results (analytical) of Chandina Well; (a) Time-Drawdown and (b) Distance-Drawdown.
Fig. 5.8.A: Aquifer test analysis for OW1 at Chandina; (a) Type Curve and (b) Straight Line.
Fig. 5.8.B: Aquifer test analysis for OW2 at Chandina; (a) Type Curve and (b) Straight Line.
Fig. 5.8.C1: Aquifer test analysis for OW3 at Chandina; (a) Type Curve and (b) Straight Line.
Fig. 5.8.C2: Aquifer test analysis for OW3 at Chandina; (a) Type Curve and (b) Straight Line.
3) Discussion:

The results obtained by analyzing the time-drawdown data for OW1 are abnormally high and misleading, therefore these results are not included in the final interpretation of the results (Table. 5.6).

For OW2 and OW3, both the time-drawdown and recovery data were available for analysis. But the time-drawdown data measured for OW2 are not amenable to analytical solution and therefore were not included. Recovery results for OW2 and the distance-drawdown result are much different from those obtained for OW3.

The leakage values (L) ranges from 91 m to 1340 m for OW3.

Transmissivity values range from 510 m²/d to 1750 m²/d for OW3 with recovery data.

Noticeable differences were found in the storativity values obtained by different methods of solution. The range of values are $8.9 \times 10^3$ (obtained from recovery data) for OW2 to $5.5 \times 10^4$ (obtained from drawdown data) for OW3.

Considerable variations were also observed in the permeability values obtained by different methods. They range from 12 m/d obtained from distance-drawdown solution to 43 m/d obtained from the time-drawdown solution for OW3.

Kotwali Pumping Test Site:

The well has a depth of 135 ft (41 m) and the structure was constructed with a radius (r) = 0.25 ft (7.6 cm). During the test the well was pumped with a discharge (Q) = 76982 ft³/d (2179 m³/d) for a period t = 2960 minutes (2.06 days). The observation wells were placed at 50 ft (15 m), 150 ft (45 m), and 400 ft (122 m) from the pumping well. The estimated thickness of the
aquifer \( b = 50 \) ft (15 m) while the thickness of the overlying aquiclude \( (b') = 85 \) ft (26 m). Static water level \( (swl) = 4.54 \) ft (1.38 m) below measuring point. The results of pump test data analysis by various analytical methods are summarized in Table. 5.7 calculated on the basis of the match-point co-ordinates and other necessary parameters obtained from the relevant figures.

1) **Time-Drawdown Solution:**

(a) **Type Curve Method:** The match-point co-ordinates for OW1 \((r = 50 \) ft), OW2 \((r = 150 \) ft), and OW3 \((r = 400 \) ft) were obtained from the log-log plots of Figures 5.9.A(a), 5.9.B(a), and 5.9.C(a), respectively.

(b) **Straight Line Method:** The necessary parameters for OW1, OW2, and OW3 were obtained from the semi-log plots of Figures 5.9.A(b), 5.9.B(b), and 5.9.C(b), respectively and the Hantush function tables.

2) **Kotwali Distance-Drawdown Solution:**

(a) **Type-Curve Method:** The match-point co-ordinates were obtained from the distance-drawdown log-log plot (figure not included).

(b) **Straight Line Method:** The necessary parameters were obtained from the previous time-drawdown plots of all the observation wells and the distance-ds (drawdown per log cycle) semi-log plot (figure not included).

3) **Discussion:**

The results obtained show all the characteristics of a leaky confined condition. Unusually low leakage values \((L = 4572 \) m) were obtained for OW2 and the maximum leakage \((L = 203 \) m) is obtained for OW3 (Table. 5.7).

The transmissivity values show noticeable differences among themselves. They range from \(1040 \) m\(^2\)/d obtained for OW2 to \(320 \) m\(^2\)/d obtained for
(a) **SOLUTION:- TIME-DRAWDOWN**

<table>
<thead>
<tr>
<th>DISTANCE OF PIEZOMETER</th>
<th>METHOD</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>T (m²/d)</td>
</tr>
<tr>
<td>50 ft.</td>
<td>SL</td>
<td>810</td>
</tr>
<tr>
<td>15.24 m.</td>
<td>TC</td>
<td>470</td>
</tr>
<tr>
<td>150 ft.</td>
<td>SL</td>
<td>1040</td>
</tr>
<tr>
<td>45.72 m.</td>
<td>TC</td>
<td>790</td>
</tr>
<tr>
<td>400 ft.</td>
<td>SL</td>
<td>340</td>
</tr>
<tr>
<td>121.92 m.</td>
<td>TC</td>
<td>320</td>
</tr>
</tbody>
</table>

**AVERAGE VALUES**

|                      |        | 630      | -1.12(-3) | 41       | 768  |

**INFERRED CONDITIONS**

Leaky Confined

---

(b) **SOLUTION:- DISTANCE-DRAWDOWN**

<table>
<thead>
<tr>
<th>METHOD</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r (m)</td>
</tr>
<tr>
<td>SL (II)</td>
<td>15.24</td>
</tr>
<tr>
<td></td>
<td>45.72</td>
</tr>
<tr>
<td></td>
<td>121.92</td>
</tr>
<tr>
<td>TC (SS)</td>
<td>-</td>
</tr>
<tr>
<td>TC (NSS)</td>
<td>-</td>
</tr>
<tr>
<td>SL (II)</td>
<td>-</td>
</tr>
</tbody>
</table>

**AVERAGE VALUES**

|                      | 470   | -1.2(-3) | -31    | 365    |

**INFERRED CONDITIONS**

Leaky Confined

---

Table 5.7. Pumping test analysis results (analytical) of Kotwali Well; (a) Time-Drawdown and (b) Distance-Drawdown.
Fig. 5.9.A: Aquifer test analysis for OW1 at Kotwali; (a) Type Curve and (b) Straight Line.
Fig. 5.9.B: Aquifer rest analysis for OW2 at Kotwali; (a) Type Curve and (b) Straight Line.
Fig. 5.9.C: Aquifer test analysis for OW3 at Kotwali; (a) Type Curve and (b) Straight Line.
The storativity values are representative of confined conditions. Most values are close together except the lowest value $4.8 \times 10^3$ which was obtained for OW3, the highest storativity value $1.4 \times 10^4$ was obtained for OW2.

Like the transmissivity values, the permeability values also show marked differences. Maximum and minimum values calculated are 68 m/d and 21 m/d.

**Barura Pumping Test Site:**

The penetrated depth of the well is 305 ft (93 m) and the structure has an effective well radius of 0.25 ft (7.6 cm). During the test, the well was pumped for a period of 3000 minutes (2.083 days) with a constant discharge ($Q = 76982$ ft$^3$/d (2179 m$^3$/d). The estimated thickness of the aquifer is 140 ft (40 m) and the thickness of the overlying semi-confining layer is 170 ft (50 m) The static water level at the pumping well is 5.08 ft (1.55 m). The piezometers were placed at distances of 50 ft (15 m), 150 ft (45 m), and 400 ft (122 m) from the pumping well. Test analysis results are summarised in Table. 5.8 calculated on the basis of the match-point co-ordinates and other necessary parameters obtained from the relevant figures.

1) **Time-Drawdown and Time-Calculated Recovery Solution:**

(a) **Type Curve Method:** The match-point co-ordinates for OW1 ($r = 50$ ft), OW2 ($r = 150$ ft), and OW3 ($r = 400$ ft) were obtained from the log-log plots of Figures 5.10.A(a), 5.10.B(a), and 5.10.C(a), respectively.

(b) **Straight Line Method:** The necessary parameters for OW1, OW2, and OW3 were obtained from the time-drawdown plots of Figures 5.10.A(b), 5.10.B(b), and 5.10.C(b), respectively and the Hantush function tables.
### (a) Solution: Time-Drawdown

<table>
<thead>
<tr>
<th>Distance of Piezometer</th>
<th>Method</th>
<th>( T ) (m²/d)</th>
<th>( S ) (-)</th>
<th>( K = T/b ) (m/d)</th>
<th>( L ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 ft.</td>
<td>SL</td>
<td>615(*)</td>
<td>2.5(*)</td>
<td>144*</td>
<td></td>
</tr>
<tr>
<td>15.24 m.</td>
<td>TC</td>
<td>1770(*)</td>
<td>2.3(*)</td>
<td>41*</td>
<td></td>
</tr>
<tr>
<td>150 ft.</td>
<td>SL</td>
<td>700 1060 5.9(-2) 23(-2)</td>
<td>16</td>
<td>25</td>
<td>352 762</td>
</tr>
<tr>
<td>45.72 m.</td>
<td>TC</td>
<td>460 980 3.5(-4) 1.9(-3)</td>
<td>11</td>
<td>23</td>
<td>114* 572</td>
</tr>
<tr>
<td>400 ft.</td>
<td>SL</td>
<td>1170 1150 3.5(-4) 3.4(-4)</td>
<td>27</td>
<td>27</td>
<td>1108 762</td>
</tr>
<tr>
<td>121.92</td>
<td>TC</td>
<td>1460 900 8.5(-4) 4.3(-4)</td>
<td>34</td>
<td>21</td>
<td>305 406</td>
</tr>
</tbody>
</table>

**Average Values**

|                  | 1110 1023 5.4(-4) 7.3(-4) | 22 | 24 | 586 626 |

**Inferred Conditions**: Leaky Confined

### (b) Solution: Distance-Drawdown

<table>
<thead>
<tr>
<th>Method</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( r ) (m) ( T ) (m²/d) ( S_1 ) (-) ( S_2 ) (-) ( S_3 ) (-) ( K ) (m/d) ( L ) (m)</td>
</tr>
<tr>
<td>SL (II)</td>
<td>15.24 600 5.8(-1) - - 14 154</td>
</tr>
<tr>
<td></td>
<td>45.72 600 - 5.9(-4) - 14 154</td>
</tr>
<tr>
<td></td>
<td>121.92 600 - 3.4(-4) 14 154</td>
</tr>
<tr>
<td>TC (SS)</td>
<td>- 860 - - - 20 533</td>
</tr>
<tr>
<td>TC (NSS)</td>
<td>- - - - - -</td>
</tr>
<tr>
<td>SL (II)</td>
<td>- - - - - -</td>
</tr>
</tbody>
</table>

**Average Values**

|                  | 730 4.7(-4) 17 344 |

**Inferred Conditions**: Leaky Confined

Table 5.8. Pumping test analysis results (analytical) of Barura Well; (a) Time-Drawdown and (b) Distance-Drawdown.
Fig. 5.10.A: Aquifer test analysis for OW1 at Barura; (a) Type Curve and (b) Straight Line.
Fig. 5.10.B: Aquifer test analysis for OW2 at Barura; (a) Type Curve and (b) Straight Line.
Fig. 5.10.C: Aquifer test analysis for OW3 at Barura; (a) Type Curve and (b) Straight Line.
2) **Barura Distance-Drawdown Solution:**

(a) **Type Curve Method:** The match-point co-ordinates were obtained from the distance-drawdown log-log plot (figure not included).

(b) **Straight Line Method:** The necessary parameters were obtained from the previous time-drawdown plots of all the observation wells and the distance-drawdown per log cycle) semi-log plot (figure not included).

3) **Discussion:**

The time-drawdown data recorded for OW1 is not amenable to analytical solution because of its negative draw-down characteristics (see section 5.2.1) and this well is therefore not included for further interpretation (Table. 5.8).

Drawdown and recovery data are available for OW2 and OW3. The results obtained by analyzing both types of data suggest an ideal leaky confined condition. Maximum leakage \((L = 114 \text{ m})\) is given for OW2 and the minimum leakage \((L = 1108 \text{ m})\) for OW3.

Comparatively high transmissivity values are recorded for OW3. But the lowest transmissivity value \((460 \text{ m}^2/\text{d})\) is for OW2. On the other hand, the highest transmissivity value \((1460 \text{ m}^2/\text{d})\) is for OW3.

The permeability values range from 11 m/d to 34 m/d and correspond to the highest and lowest transmissivity values.

**Haziganj Pumping Test Site:**

The depth of the pumping well is 391.66 ft (120 m) with a well radius of \((r = 0.25 \text{ ft} \ (7.6 \text{ cm})\). During the test the well was pumped at a discharge of \((Q = 180273 \text{ ft}^3/\text{d} \ (5104 \text{ m}^3/\text{d})\) for a period of 3000 minutes (2.083 days). The observation wells are located at distances of 50 ft (15 m), 150 ft (45 m), and 1000
ft (300 m) from the pumping well. The estimated thickness of the aquifer (b) is 120 ft (35 m) while the thickness of the overlying aquiclude (b') is 265 ft (80 m). Static water level is 13.21 ft (4.03 m) below measuring point. The analyzed results by the different analytical methods are summarized in Table. 5.9 calculated on the basis of the match-point co-ordinates and other necessary parameters obtained from the relevant figures.

1) Time-Drawdown Solution:
(a) Type Curve Method: The match-point co-ordinates for OW1 (r = 50 ft), OW2 (r = 150 ft), and OW3 (r = 1000 ft) were obtained from the log-log plots of Figures 5.11.A(a), 5.11.B(a), and 5.11.C(a), respectively.
(b) Straight Line Method: The necessary parameters for OW1, OW2, and OW3 were obtained from the semi-log plots of Figures 5.11.A(b), 5.11.B(b), and 5.11.C(b) and the Hantush function tables.

2) Haziganj Distance-Drawdown Solution:
(a) Type Curve Method: The match-point co-ordinates were obtained from the distance-drawdown log-log plot (figure not included).
(b) Straight Line Method: The necessary parameters were obtained from the previous time-drawdown Plots of all the observation wells and the distance-ds (drawdown per log cycle) semi-log plot (figure not included).

3) Discussion:
The OW1 and OW3 show enough leakage to qualify as a leaky confined condition but OW2 does not produce any leakage and hence suggests a non-leaky confined condition. Maximum leakage (L = 381 m) was produced for OW1 while the minimum leakage (L = 3048 m) was obtained for OW3 (Table.
Table. 5.9. Pumping test analysis results (analytical) of Haziganj Well; (a) Time-Drawdown and (b) Distance-Drawdown.
Fig. 5.11.A: Aquifer test analysis for OW1 at Hazigang; (a) Type Curve and (b) Straight Line.
Fig. 5.11.B: Aquifer test analysis for OW2 at Hazigang; (a) Type Curve and (b) Straight Line.
Fig. 5.11.C. Aquifer test analysis for OW3 at Hazigang; (a) Type Curve and (b) Straight Line.
Small variations were found in the transmissivity values calculated using various solutions except the lowest value of 970 m$^2$/d obtained for OW1. The maximum T value (1710 m$^2$/d) is given for both OW2 and OW3.

Typical storativity values were obtained which suggest a confined condition. The values also show little variation among themselves obtained by the different methods. Highest and lowest storativity values obtained are $8.8 \times 10^{-4}$ for OW1 and $8.0 \times 10^{-5}$ for OW2.

The permeability values, like transmissivity values, also show little variation. The minimum K values 26 m/d is the only very low value but the other values are quite close to each other of which the maximum K value is 47 m/d.

Chauddagram Pumping Test Site:

The pumping well has a depth of 326.66 ft (100 m) which has a structural radius (r) = 0.25 ft (7.6 cm). During the test the well was pumped at a discharge (Q) = 86604 ft$^3$/d (2450 m$^3$/d) for a period of $t = 4290$ minutes (3 days). The observation wells were spaced at distances of 50 ft (15.24 m), 150 ft (45 m), and 1000 ft (300 m) from the pumping well. The aquifer has an estimated thickness (b) of 241 ft (70 m) while the thickness of the overlying confining layer (b') is about 95 ft (30 m). Static water level = 7.83 ft (2.39 m) below measuring point. The analyzed results are presented in Table 5.10 calculated on the basis of the match-point co-ordinates and other necessary parameters obtained from the relevant figures.

1) Time-Drawdown Solution:
(a) Type Curve Method: The match-point co-ordinates for OW1 (r = 50 ft), OW2 (r = 150 ft), and OW3 (r = 1000 ft) were obtained from the log-log plots of
### SOLUTION:-  TIME - DRAWDOWN

<table>
<thead>
<tr>
<th>DISTANCE OF PIEZOMETER</th>
<th>METHOD</th>
<th>T (m²/d)</th>
<th>S(-)</th>
<th>K = Tb (m/d)</th>
<th>L (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 ft.</td>
<td>SL</td>
<td>230</td>
<td>20(-2)</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>15.24 m.</td>
<td>TC</td>
<td>200</td>
<td>23(-2)</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>150 ft.</td>
<td>SL</td>
<td>250</td>
<td>30(-3)</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>45.72 m.</td>
<td>TC</td>
<td>142</td>
<td>13(-3)</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>1000 ft.</td>
<td>SL</td>
<td>320</td>
<td>60(-4)</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>304.80 m.</td>
<td>TC</td>
<td>270</td>
<td>19(-3)</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>AVERAGE VALUES</td>
<td></td>
<td>240</td>
<td>17(-3)</td>
<td>3</td>
<td>-</td>
</tr>
</tbody>
</table>

**INFERRED CONDITIONS**  FULLY CONFINED

### SOLUTION:- DISTANCE - DRAWDOWN

Table. 5.10. Pumping test analysis results (analytical) of Chauddagram Well; (a) Time-Drawdown and (b) Distance-Drawdown.
Figures 5.12.A(a), 5.12.B(a), and 5.12.C(a), respectively.

(b) **Straight Line Method:** The necessary parameters for OW1, OW2, and OW3 were obtained from the semi-log plots of Figures 5.12.A(b), 5.12.B(b), and 5.12.C(b), respectively.

2) **Chauddagram Distance-Drawdown Solution:**

(a) **Type Curve Method:** The match-point co-ordinates were obtained from the distance-drawdown log-log plot (figure not included).

(b) **Straight Line Method:** The necessary parameters were obtained from the distance-drawdown semi-log plot (figure not included).

3) **Discussion:**

This is an ideal example of a non-leaky confined condition exclusively suggested by both the type curve and straight line method. Hence there is no leakage (Table. 5.10).

The distance-drawdown solution gave much higher transmissivities in comparison with the time-drawdown solution. The highest value of 840 m²/d was obtained from the distance-drawdown solution by comparison with a low transmissivity value of 142 m²/d determined for OW2 by a time-drawdown solution.

The storativity value $2.0 \times 10^2$ obtained for OW1 is much too high for a non-leaky confined condition. The values obtained by the time-drawdown solution showed that storativity decreases with increasing distance of the observation wells. The lowest storativity value $3.5 \times 10^4$ is given by the distance-drawdown solution.

The maximum and minimum permeability values obtained are 11.0 m/d and 2 m/d respectively.
Fig. 5.12.A: Aquifer test analysis for OW1 at Chauddagram; (a) Type Curve and (b) Straight Line.
Fig. 5.12.B: Aquifer test analysis for OW2 at Chauddagram; (a) Type Curve and (b) Straight Line.
Fig. 5.12.C: Aquifer test analysis for OW3 at Chauddagram; (a) Type Curve and (b) Straight Line.
Senbagh Pumping Test Site:

The well has a depth of 295 ft (90 m) and the structure has an effective well radius of \( r = 0.33 \) ft (10 cm). During the test the well was pumped at a discharge \( Q = 86604 \) ft\(^3\)/d (2450 m\(^3\)/d) for a period of \( t = 4100 \) minutes (2.85 days). The observation wells are located at distances of 50 ft (15 m), 150 ft (45 m) and 400 ft (122 m) from the pumping well. The estimated thickness of the aquifer \( b \) is about 136 ft (40 m) while the thickness of the overlying aquiclude \( b' \) is 157 ft (48 m). Depth of static water level is 5.17 ft (1.57 m) below the measuring point. All the observation wells were put down to a similar range of depths which is 247 ft (75 m). The analytical results are summarised in Table. 5.11 calculated on the basis of the match-point co-ordinates and other necessary parameters obtained from the relevant figures.

1) Time-Drawdown Solution:

(a) Type Curve Method: The match-point co-ordinates for OW1 \( (r = 50 \) ft or 15 m), OW2 \( (r = 150 \) ft or 45 m), and OW3 \( (r = 400 \) ft or 120 m) were obtained from the log-log plots of figures 5.13.A(a), 5.13.B(a), and 5.13.C(a), respectively.

(b) Straight Line Method: The necessary parameters for OW1, OW2, and OW3 were obtained from the semi-log plots of Figures 5.13.A(b), 5.13.B(b), and 5.13.C(b), respectively and the Hantush function tables.

2) Senbagh Distance-Drawdown Solution:

(a) Type Curve Method: The match-point co-ordinates were obtained from the distance-drawdown log-log plot (figure not included).

(b) Straight Line Method: The necessary parameters were obtained from the previous time-drawdown plots of all the observation wells and the distance-ds (drawdown per log cycle) semi-log plot (figure not included).
### (a) SOLUTION: TIME-DRAWDOWN

<table>
<thead>
<tr>
<th>DISTANCE OF PIEZOMETER</th>
<th>METHOD</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$T$ ($m^3/d$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D'down REC</td>
</tr>
<tr>
<td>50 ft.</td>
<td>SL</td>
<td>690</td>
</tr>
<tr>
<td>15.24 m.</td>
<td>TC</td>
<td>680</td>
</tr>
<tr>
<td>150 ft.</td>
<td>SL</td>
<td>780</td>
</tr>
<tr>
<td>45.72 m.</td>
<td>TC</td>
<td>750</td>
</tr>
<tr>
<td>400 ft.</td>
<td>SL</td>
<td>990</td>
</tr>
<tr>
<td>121.92 m.</td>
<td>TC</td>
<td>750</td>
</tr>
</tbody>
</table>

**AVERAGE VALUES**

|              |        | 770 | 7.1(-4) | 19 | 844 |

**INFERRED CONDITIONS**

*LEAKY CONFINED*

### (b) SOLUTION: DISTANCE-DRAWDOWN

<table>
<thead>
<tr>
<th>METHOD</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$r$ (m)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>SL (II)</td>
<td>15.24</td>
</tr>
<tr>
<td></td>
<td>45.72</td>
</tr>
<tr>
<td></td>
<td>121.92</td>
</tr>
<tr>
<td>TC (SS)</td>
<td></td>
</tr>
<tr>
<td>TC (NSS)</td>
<td></td>
</tr>
<tr>
<td>SL (II)</td>
<td></td>
</tr>
</tbody>
</table>

**AVERAGE VALUES**

|              |        | 630 | 66(3) | 15 | 397 |

**INFERRED CONDITIONS**

*LEAKY CONFINED*

---

Table. 5.11. Pumping test analysis results (analytical) of Senbagh Well; (a) Time-Drawdown and (b) Distance-Drawdown.
Fig. 5.13.A. Aquifer test analysis for OW1 at Senbagh; (a) Type Curve and (b) Straight Line.
Fig. 5.13.B: Aquifer test analysis for OW2 at Senbagh; (a) Type Curve and (b) Straight Line.
Fig. 5.13.C: Aquifer test analysis for OW3 at Senbagh; (a) Type Curve and (b) Straight Line.
3) Discussion:

Senbagh well is a typical example of a leaky confined condition (Table 5.11). Minimum variation between the results for different hydraulic parameters were found except for the unusually low leakage value ($L = 6100 \text{ m}$) obtained for OW3. The maximum leakage was $L = 367 \text{ m}$.

The transmissivity values range from $990 \text{ m}^2/\text{d}$ obtained for OW3 to $580 \text{ m}^2/\text{d}$. Extreme permeability values of $24 \text{ m/d}$ and $14 \text{ m/d}$ correspond to the maximum and minimum transmissivity values.

The storativity values unanimously suggest a confined condition. The values range from $9.2 \times 10^3$ for OW1 to $3.0 \times 10^4$ for OW2.
5.3 Numerical Solution:

5.3.1 Radial Flow Model:

It is well known that the analytical solutions (both type-curve and straight line methods) are based on many simplified assumptions. It frequently happens that one or more of these assumptions are not valid and although the range of problems that can be analyzed by these classical solutions are impressive yet many features which are known to have a significant effect on the response of an aquifer cannot be included in the analytical solution. Where this is the case an alternative numerical method can be used known as the radial flow modelling technique. This method has the advantage that a variety of variables can be introduced in a single numerical solution. A full description of the numerical technique is available in several books and journals [Rushton and Chan (1976), Jones and Rushton (1981), Rushton and Booth (1976) and Rushton and Redshaw (1979)] however a brief outline is given below:

This method is based on a discrete space-discrete time approximation to the differential equation of two-dimensional, radial, time-variant flow in the aquifer. When analyzing pumping test data using a numerical technique, the flow is assumed to be radial (Fig. 5.15). Depending on the nature of the problem two alternative idealizations are adopted:

(1) For confined Situation:

In such situation the general three-dimensional differential equation is integrated in the vertical direction and takes the following form:-

\[
\frac{d}{dx} b \frac{dh}{dx} + \frac{d}{dy} b \frac{dh}{dy} = S_0 b \frac{dh}{dt}
\]  

(5.1)

Where,

\[ b = \text{aquifer thickness.} \]
In many instances vertical flow of water occur into the aquifer (Fig. 5.14) which is called the inflow "q(x, y, t)". As a consequence equation (1) becomes:

\[
\frac{d}{dr} \left( b \frac{dh}{dr} \right) + \frac{b}{r} \frac{dh}{dr} = S \frac{dh}{dt} - q(r,t) \quad (5.2)
\]

substituting \( r^2 = x^2 + y^2 \) at the same time, which is known as the governing differential equation.

Rather than working in terms of ground water potential "h", it is usually convenient to consider the drawdown 's' since \( s = (H - h) \) where 'H' is the elevation of the rest water level. After this substitution, equation (5.2) becomes:

\[
\frac{d}{dr} \left( b \frac{ds}{dr} \right) + \frac{b}{r} \frac{ds}{dr} = S \frac{ds}{dt} + q(r,t) \quad (5.3)
\]

which is known as the governing differential equation for a radial flow due to pumping under a non-leaky confined condition.

where,

\[ s = \text{drawdown below an arbitrary datums}, \]
\[ r = \text{radial co-ordinate}, \]
\[ b = \text{saturated thickness of the aquifer}, \]
\[ K_r = \text{radial permeability}, \]
\[ t = \text{duration of pumping}, \]
\[ S = \text{storativity, and} \]
\[ q = \text{inflow per unit area}. \]

It has been pointed out by Rushton and Redshaw (1979) that when the radial ordinate is divided into a discrete mesh which increases logarithmically by an amount of 'da' then it is usually more convenient to analyze radial flow towards a well.

Introducing the variable 'a' such that \( a = \log_r r \)
Fig. 5.14: Inflow due to leakage in a Confined aquifer.

Fig. 5.15(a): Basis of Numerical technique for radial flow model (Confined aquifer).

Fig. 5.15(b): Discrete space - discrete time grid with radial distance increasing logarithmically (After: Rushton 1979).
and substituting for it in equation (5.3) and multiplying through by \( r^2 \) leads to the equation

\[
\frac{d^2 s}{d a^2} b. k \frac{d s}{d t} = \frac{S r^2}{r} + q r^2 \quad (5.4)
\]

A solution to equation (5.4) with appropriate boundary and initial conditions can be obtained using the finite difference technique. The use of mesh-spacing with a constant increment of 'da' results in a fine mesh in the vicinity of the well with the distance between mesh points becoming larger with increasing radius. By considering a time increment from \( t \) to \( (t+dt) \) as shown in the Figure 5.15 and using the backward difference approximation (fully implicit), the finite difference approximation to equation (5.4) allows the expression to be written for drawdown centred at nodes \( j \) as:

\[
\frac{b. k}{d a^2} [s_{(j-1)} - 2s_{(j)} + s_{(j+1)}] \quad \text{(5.5)}
\]

For an accurate representation at the smallest radius, according to Rushton and Redshaw (1979), the initial time step should be kept very small and that can be done by setting the initial value of the time step as:

\[
dt = \frac{0.0025 \ r^2 \ S_c}{T} \quad (5.6)
\]

where '\( S_c \)' is the confined storativity and \( r_w \) is the radius of the pumping well.

The finite difference method leads to a series of simultaneous equations. These are solved efficiently by simple matrix routines.

(2) For Unconfined Situation:

When the vertical component of flow is significant then the differential
equation for radial flow towards a well takes the following form:

$$\frac{d}{dx} \frac{ds}{dr} b \frac{ds}{dr} + \frac{d^2 s}{dz^2} = \frac{ds}{dt}$$  \hspace{1cm} (5.7)

Where,

- $s$ = drawdown,
- $r$ = radial ordinate,
- $z$ = vertical ordinate,
- $k_r$ & $k_z$ = radial and vertical permeability,
- $b$ = saturated aquifer thickness,
- $t$ = pumping time, and
- $S$ = storativity.

As in the confined situation, the radial mesh also increases logarithmically and in addition the drawdowns are defined at the free surface and at distance $Z = 0.25$ m above the base of the aquifer, these drawdowns are denoted as $s_r$ and $s_b$ respectively (Fig. 5.16). Using the two successive time steps of $t$ and $(t+dt)$ the finite difference approximation for drawdown is written as:

$$\frac{s_{r(j+1)} - s_{r(j)}}{H \ U_{(j)}} + \frac{s_{r(j-1)} - s_{r(j)}}{H \ U_{(j+1)}} + \frac{s_{b(j)} - s_{b(j)}}{V_{(j)}} = \frac{s_{r(j+1)} - s_{r(j)}}{T_j} + qr_j^2$$  \hspace{1cm} (5.8)

Where,

- $H U_j = H L_j = \frac{2.d.a^2}{b.k_r}$
- $V_j = \frac{0.46875.b}{k_r r_j^2}$ and $T = \frac{d.t}{S \ r_j^2}$

'q' refers to the recharge per unit area. At present there are no exact analytical
Fig. 5.16(a). Pictorial definition of drawdown $S_f$ and $S_b$.  

Fig. 5.16(b) : Problems involving variable saturated depth.
solutions for time-variant unconfined radial-flow problems.

5.3.2 Presentation of Analysis:

The aquifer condition for all the observation wells was simulated with the time drawdown data (in some cases the recovery data) using the modified Rushton Radial flow modelling program (Appendix. 5.2) to obtain the numerical solution.

With the modified Rushton radial flow program the well can be modelled using the exact distance of the observation well which brings more accuracy to the results. During the running of the model it was found that some parameters are more sensitive than the others. For confined condition the sensitive parameters are permeability (K) and storativity (S). For leaky confined conditions the sensitive parameters are permeability, storativity and the leakage factor (L). For unconfined conditions, permeability, storativity and the delay index (alpha) are important.

During the simulation exercise the model was run several times with different values for the parameters starting with the manually derived results. The parameters are fed into the computer in the form of a data file that is linked to the model with changes to values of hydraulic parameters made after every run with the aim of finding the closest possible match between the plot of the field time-drawdown data and the model interpretation. The plots with the trial values are displayed on a graphics terminal and the plots for the final results were printed for presentation when the best agreement was achieved. Crosses (+) represent the field data while the continuous unbroken line represent the model data plot. The simulated values of all the parameters are printed at the bottom of every numerical modelling plot.

The simulated final model plot along with the results and the model
plot produced by the best analytical results (some with straight line method and others with type curve method) with the results at the bottom of the plot for one observation well of a particular pumping test site are presented together to demonstrate the variation of the results obtained by the two different approaches. The plots of the two representative test sites (Feni OW1 (Fig. 5.17.A), OW2 (Fig. 5.17.B) and OW3 (Fig. 5.17.C) and Nabinagar OW1 (Fig. 5.18.A), OW2 (Fig. 5.18.B) and OW3 (Fig. 5.18.C) are presented below and the plots for all other test sites are attached in Appendix. 5.3 as tabulated in the next page.

The movement of the model plot during simulation is controlled by changing the more sensitive parameters. An increase in $K$ value, for example, decreases the gradient of the curve and vice versa (Fig. 5.19.a).

A change in the confined storativity value moves the curve either upward or downward without changing the gradient. A positive change takes the curve upwards while a negative change brings the curve downwards (Fig. 5.19.b). A change in the leakage factor (BL) modifies the tail end of the curve (Fig. 5.19.c). An increase in the BL value (lower leakage) produces a downward deviation whereas a decrease in BL value (higher leakage) moves the tail upwards. A variation in the Boulton delay index ($\alpha$), modifies the wavy nature of the typical elongated S-shaped curve that represent the three section of a true water table condition (Fig. 5.19.d).

During simulation with the radial flow modelling the true well radius was used. A very large $R_{max}$ was adopted to avoid any boundary effect. Lithological logs for the pumping wells were not available, and the length of screen was used as the effective aquifer thickness to run the model. It is also assumed that the well is 100 percent efficient.
<table>
<thead>
<tr>
<th>TEST SITE</th>
<th>OBSERVATION WELL</th>
<th>APPENDICES</th>
</tr>
</thead>
<tbody>
<tr>
<td>B'Baria</td>
<td>OW1.</td>
<td>Appendix 5.3.1.A</td>
</tr>
<tr>
<td></td>
<td>OW2.</td>
<td>Appendix 5.3.1.B</td>
</tr>
<tr>
<td></td>
<td>OW3.</td>
<td>Appendix 5.3.1.C</td>
</tr>
<tr>
<td>Daudkandi</td>
<td>OW1.</td>
<td>Appendix 5.3.2.A</td>
</tr>
<tr>
<td></td>
<td>OW2.</td>
<td>Appendix 5.3.2.B</td>
</tr>
<tr>
<td></td>
<td>OW3.</td>
<td>Appendix 5.3.2.C</td>
</tr>
<tr>
<td>Burichong</td>
<td>OW1.</td>
<td>Appendix 5.3.3.A</td>
</tr>
<tr>
<td></td>
<td>OW2.</td>
<td>Appendix 5.3.3.B</td>
</tr>
<tr>
<td></td>
<td>OW3.</td>
<td>Appendix 5.3.3.C</td>
</tr>
<tr>
<td>Chandina</td>
<td>OW1.</td>
<td>Appendix 5.3.4.A</td>
</tr>
<tr>
<td></td>
<td>OW2.</td>
<td>Appendix 5.3.4.B</td>
</tr>
<tr>
<td></td>
<td>OW3.</td>
<td>Appendix 5.3.4.C1</td>
</tr>
<tr>
<td></td>
<td>OW3.</td>
<td>Appendix 5.3.4.C2</td>
</tr>
<tr>
<td>Kotwali</td>
<td>OW1.</td>
<td>Appendix 5.3.5.A</td>
</tr>
<tr>
<td></td>
<td>OW2.</td>
<td>Appendix 5.3.5.B</td>
</tr>
<tr>
<td></td>
<td>OW3.</td>
<td>Appendix 5.3.5.C</td>
</tr>
<tr>
<td>Barura</td>
<td>OW1.</td>
<td>Appendix 5.3.6.A</td>
</tr>
<tr>
<td></td>
<td>OW2.</td>
<td>Appendix 5.3.6.B</td>
</tr>
<tr>
<td></td>
<td>OW3.</td>
<td>Appendix 5.3.6.C</td>
</tr>
<tr>
<td>Haziganj</td>
<td>OW1.</td>
<td>Appendix 5.3.7.A</td>
</tr>
<tr>
<td></td>
<td>OW2.</td>
<td>Appendix 5.3.7.B</td>
</tr>
<tr>
<td></td>
<td>OW3.</td>
<td>Appendix 5.3.7.C</td>
</tr>
<tr>
<td>Chauddagram</td>
<td>OW1.</td>
<td>Appendix 5.3.8.A</td>
</tr>
<tr>
<td></td>
<td>OW2.</td>
<td>Appendix 5.3.8.B</td>
</tr>
<tr>
<td></td>
<td>OW3.</td>
<td>Appendix 5.3.8.C</td>
</tr>
<tr>
<td>Senbagh</td>
<td>OW1.</td>
<td>Appendix 5.3.9.A</td>
</tr>
<tr>
<td></td>
<td>OW2.</td>
<td>Appendix 5.3.9.B</td>
</tr>
<tr>
<td></td>
<td>OW3.</td>
<td>Appendix 5.3.9.C</td>
</tr>
</tbody>
</table>
Fig. 5.17.A: Comparison of (a) Manual and (b) Model result from Feni OW1.
Fig. 5.17.B: Comparison of (a) Manual and (B) Model result from Feni OW2.
Fig. 5.17.C: Comparison of (a) Manual and (b) Model result from Feni OW3.
Fig. 5.18.A: Comparison of (a) Manual and (b) Model result from Nabinagar OW1.
Fig. 5.18.B: Comparison of (a) Manual and (b) Model result from Nabinagar OW2.
Fig. 5.18.C: Comparison of (a) Manual and (b) Model result from Nabinagar OW3.
Fig. 5.19; Response of the simulation with different values of sensitive parameters.
5.3.3 Discussion in results:

The model plots themselves are self explanatory. The better the match the more accurate is the analysis. In some cases excellent matching was obtained but in others difficulties arise in obtaining good agreement between the model and field data plots.

B’Baria Well Site:

Excellent matching is obtained for OW1 (Appendix. 5.3.1.A) and OW3 (Appendix. 5.3.1.C) without requiring any leakage though a little leakage was essential for OW2 (Appendix. 5.3.1.B) in order to get the excellent match with the field condition. In the case of OW1 and OW2, the first few data measurements show higher drawdowns than the model, while the reverse is true for OW3. No remarkable differences between K values are found. The storativity value for OW2 is one order of magnitude greater than the others but still valid for a leaky confined condition.

Nabinagar Well site:

A very good simulation is obtained for all three OWs (Fig. 5.18.A, 5.18.B & 5.18.C) by introducing leakage for every well. For OW2 (Fig. 5.18.B) and OW3 (Fig. 5.18.C) the very last few field data points were ignored (see Section 5.2.1). No major differences are found in storativity values. A little higher permeability value is obtained for OW3.

Daudkandi Well Site:

A reasonably good model match was obtained for all the observation wells by ignoring the very last few data measurements in all the observation wells. For OW1 (Appendix. 5.3.2.A) and OW2 (Appendix. 5.3.2.B) the
first few data points shows lower drawdown than expected. The storativity values were all very close to each other. A little higher K value was recorded for OW3 (Appendix. 5.3.2.C) than the other two wells. A similar range of leakage was given by all the observation wells.

Burichong Well Site:

Excellent model simulation is obtained for OW2 (Appendix. 5.3.3.B) and OW3 (Appendix. 5.3.3.C) but for OW1 (Appendix. 5.3.3.A) simulation was possible only with the middle part of the field data because of its unstable nature (see Section 5.2.1). An unacceptably high simulated storativity and leakage values were also obtained for OW1 and these results are not included for further interpretation. Much different leakage values were obtained for OW2 and its storativity value is one order of magnitude lower than the simulated storativity for OW3 but they are all within the acceptable limit.

Chandina Well Site:

The exponential distribution of drawdown caused by the pumping of a well is such that the greatest drawdown occurs at the well and the drawdown decreases with the increasing distance from the well. But the reverse is happening at Chandina OW1 (Appendix. 5.3.4.A) where the recorded drawdown is much lower than the drawdown recorded for OW2 (Appendix. 5.3.4.B) and OW3 (Appendix. 5.3.4.C1 and C2).

Reasonably good results were obtained for OW2 (recovery data only) and OW3 (both recovery and drawdown). The results obtained for OW2 suggest more vertical leakage and a less permeable situation, while OW3 suggests the opposite condition. Results obtained from OW1 are altogether ignored. Except for the recovery data of OW3 the simulation was done ignoring the very last few
data points.

Kotwali Well Site:

The unstable data measurement for OW3 (Appendix. 5.3.5.C) made it extremely complicated to obtain an accurate simulation. However, the results obtained are quite acceptable. The best simulation was achieved for OW2 (Appendix. 5.3.5.B) and moderate matching was possible for OW1 (Appendix. 5.3.5.A). Differences between the permeability results are quite noticeable. The storativity value for OW3 is one order of magnitude higher than the others and for the same well a high leakage is also observed. During the simulation of OW1, the initial and last few data points had to be ignored to obtain a reasonable matching. Only the initial few data points were away from the simulated curve for OW2 but for OW3 only an average simulation was possible.

Barura Well Site:

The negative drawdown observed for OW1 (Appendix. 5.3.6.A) made it impossible to simulate the data. For OW2 (Appendix. 5.3.6.B) and OW3 (Appendix. 5.3.6.C) simulation was done primarily on the middle portion of the data plot ignoring both the tail end portion and the first few data points. The results obtained for storativity and leakage are quite close for OW2 and OW3 but the permeability value obtained for OW3 is much higher than that obtained for OW2.

Haziganj Well Site:

Excellent simulation results were obtained for all the OWs by introducing some leakage for OW1 (Appendix. 5.3.7.A) and OW3 (Appendix. 5.3.7.C) but without any leakage for OW2 (Appendix. 5.3.7.B). The very
last few data points for OW1 were ignored during the simulation. The storativity value obtained for OW2 is one order of magnitude lower than the other two OWs. The drawdown data recorded for the initial 30 minutes are higher than the values produced by the simulated curve.

Chauddagram Well Site:

Excellent matching between the field data and the numerically obtained data plot has been obtained for all the OWs (Appendix. 5.3.8.A, 5.3.8.B, and 5.3.8.C) without requiring any leakage. Interestingly it was noticed that higher permeability values were needed to simulate data points with increasing distances of the OWs. The simulation has also indicated that the storativity decreases with increasing distance. The storativity value obtained for OW1 is very high for a confined aquifer.

Senbagh Well Site:

A very good simulation was obtained for all the OWs (Appendix. 5.3.9.A, 5.3.9.B, and 5.3.9.C) covering the entire field data measurement under leaky confined conditions. The permeability value obtained for OW3 (Appendix. 5.3.9.C) is slightly higher than the value obtained for the other OWs. The calculated and simulated transmissivity values show a fair amount of closeness. The storativity value for OW2 (Appendix. 5.3.9.B) is much lower than the other two OWs.

Feni Well Site:

Excellent simulation is obtained for all the OWs (Fig. 5.17.A, 5.17.B, and 5.17.C) under typical non-leaky confined conditions. Both the field and model data plots for OW2 (Fig. 5.17.B) and OW3 (Fig. 5.17.C) show
virtually no deviation in any part of the plot. Striking similarities were obtained for
the results from both the analytical method and simulated results.

5.4 Comparison of the Results:

5.4.1 Comparison of Individual Sites:

The comparison is made considering all the results obtained from the time-drawdown solution (both straight line and type curve method), the distance-drawdown solution and the numerical solution. The comments were made on the basis of the average results obtained for each individual well site. The results obtained from both the time drawdown and distance drawdown solutions for an individual well site are presented in a single table such as Table. 5.1 while the numerical results as well as the comparison of the average results obtained from all the methods are presented in another table such as Table. 5.12. Those results with an asterisk indicate that these values are excluded from the overall average results. It can be concluded that the aquifer condition varies from confined to leaky confined conditions. When the same well site indicates both confined and leaky confined conditions, the general condition is considered to be leaky confined. It is observed that when leaky confined conditions are found, the transmissivity values show noticeable decreases.

5.4.2 Overall Comparison:

A rapid change in aquifer condition from leaky confined to confined was noticed for different OWs of the same test site (B’Baria OW1 & OW3 shows nonleaky-confined but B’Baria OW2 gives rise leaky-confined and Haziganj OW2 represents nonleaky-confined but Haziganj OW1 & OW3 suggests leaky-confined condition). In such a situation the non-leaky confined condition furnished higher transmissivity and lower storativity and the opposite is
### (a) Pumping Test Analysis Results

**Site:** Feni  
**Well No:** 117  
**Solution:** Numerical

<table>
<thead>
<tr>
<th>Position of Piezometers</th>
<th>Values of Hydraulic Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( T ) (( m^2/d ))</td>
</tr>
<tr>
<td>50 ft. (15.24 m.)</td>
<td>940</td>
</tr>
<tr>
<td>400 ft. (121.92 m.)</td>
<td>840</td>
</tr>
<tr>
<td>1000 ft. (304.80 m.)</td>
<td>890</td>
</tr>
<tr>
<td>Average Values</td>
<td>890</td>
</tr>
<tr>
<td>Inferred Conditions</td>
<td><strong>FULLY CONFINED</strong></td>
</tr>
</tbody>
</table>

### (b) Comparison of Hydraulic Parameters Obtained from Different Solutions

<table>
<thead>
<tr>
<th>Method of Solution</th>
<th>Values of Hydraulic Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( T ) (( m^2/d ))</td>
</tr>
<tr>
<td></td>
<td>( \text{D'down} ) REC. AVE.</td>
</tr>
<tr>
<td>Time-Drawdown</td>
<td>940</td>
</tr>
<tr>
<td>Distance-Drawdown</td>
<td>1170</td>
</tr>
<tr>
<td>Numerical</td>
<td>890</td>
</tr>
<tr>
<td>Average Values</td>
<td>1000</td>
</tr>
<tr>
<td>Inferred Conditions</td>
<td><strong>FULLY CONFINED</strong></td>
</tr>
</tbody>
</table>

Table 5.12. Aquifer test results of Feni Well; (a) Numerical results and (b) Overall comparison of results obtained by all the methods.
(a) PUMPING TEST ANALYSIS RESULTS

SITE: NABINAGAR WELL No: 9

SOLUTION: NUMERICAL

<table>
<thead>
<tr>
<th>POSITION OF PIEZOMETERS</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T (m²/d)</td>
</tr>
<tr>
<td>50 ft. (15.24 m.)</td>
<td>430</td>
</tr>
<tr>
<td>400 ft. (121.92 m.)</td>
<td>520</td>
</tr>
<tr>
<td>1000 ft. (304.80 m.)</td>
<td>400</td>
</tr>
<tr>
<td>AVERAGE VALUES</td>
<td>450</td>
</tr>
<tr>
<td>INFERRED CONDITIONS</td>
<td>LEAKY CONFINED</td>
</tr>
</tbody>
</table>

(b) COMPARISON OF HYDRAULIC PARAMETERS OBTAINED FROM DIFFERENT SOLUTIONS

<table>
<thead>
<tr>
<th>METHOD OF SOLUTION</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T (m²/d)</td>
</tr>
<tr>
<td></td>
<td>D'down REC. AVE.</td>
</tr>
<tr>
<td>TIME-DRAWDOWN</td>
<td>410</td>
</tr>
<tr>
<td>DISTANCE-DRAWDOWN</td>
<td>360</td>
</tr>
<tr>
<td>NUMERICAL</td>
<td>450</td>
</tr>
<tr>
<td>AVERAGE VALUES</td>
<td>410</td>
</tr>
<tr>
<td>INFERRED CONDITIONS</td>
<td>LEAKY CONFINED</td>
</tr>
</tbody>
</table>

Table. 5.13. Aquifer test results of Nabinagar Well; (a) Numerical results and (b) Overall comparison of results obtained by all the methods.
(a) PUMPING TEST ANALYSIS RESULTS

SITE: B'BARIA WELL No: 6
SOLUTION: NUMERICAL

<table>
<thead>
<tr>
<th>POSITION OF PIEZOMETERS</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T (m²/d)</td>
</tr>
<tr>
<td>50 ft. (15.24 m.)</td>
<td>950</td>
</tr>
<tr>
<td>150 ft. (45.72 m.)</td>
<td>800</td>
</tr>
<tr>
<td>400 ft. (121.92 m.)</td>
<td>960</td>
</tr>
<tr>
<td>AVERAGE VALUES</td>
<td>900</td>
</tr>
</tbody>
</table>

INFERRED CONDITIONS
LEAKY CONFINED

(b) COMPARISON OF HYDRAULIC PARAMETERS OBTAINED FROM DIFFERENT SOLUTIONS

<table>
<thead>
<tr>
<th>METHOD OF SOLUTION</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T (m²/d)</td>
</tr>
<tr>
<td></td>
<td>D'down REC.</td>
</tr>
<tr>
<td>TIME-DRAWDOWN</td>
<td>950</td>
</tr>
<tr>
<td>DISTANCE-DRAWDOWN</td>
<td>830</td>
</tr>
<tr>
<td>NUMERICAL</td>
<td>900</td>
</tr>
<tr>
<td>AVERAGE VALUES</td>
<td>890</td>
</tr>
</tbody>
</table>

INFERRED CONDITIONS
LEAKY CONFINED

Table. 5.14. Aquifer test results of B'Baria Well; (a) Numerical results and (b) Overall comparison of results obtained by all the methods.
(a) PUMPING TEST ANALYSIS RESULTS

SITE: DAUDKANDI  
WELL No: 43

SOLUTION: NUMERICAL

<table>
<thead>
<tr>
<th>POSITION OF PIEZOMETERS</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T (m²/d)</td>
</tr>
<tr>
<td>50 ft. (15.24 m.)</td>
<td>1200</td>
</tr>
<tr>
<td>150 ft. (45.72 m.)</td>
<td>1210</td>
</tr>
<tr>
<td>400 ft. (121.92 m.)</td>
<td>1370</td>
</tr>
<tr>
<td>AVERAGE VALUES</td>
<td>1260</td>
</tr>
</tbody>
</table>

INFERRED CONDITIONS: LEAKY CONFINED

(b) COMPARISON OF HYDRAULIC PARAMETERS OBTAINED FROM DIFFERENT SOLUTIONS

<table>
<thead>
<tr>
<th>METHOD OF SOLUTION</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T (m²/d)</td>
</tr>
<tr>
<td></td>
<td>D'down</td>
</tr>
<tr>
<td>TIME-DRAWDOWN</td>
<td>1100</td>
</tr>
<tr>
<td>DISTANCE-DRAWDOWN</td>
<td>1050</td>
</tr>
<tr>
<td>NUMERICAL</td>
<td>1260</td>
</tr>
<tr>
<td>AVERAGE VALUES</td>
<td>1140</td>
</tr>
</tbody>
</table>

INFERRED CONDITIONS: LEAKY CONFINED

Table 5.15. Aquifer test results of Daudkandi Well; (a) Numerical results and (b) Overall comparison of results obtained by all the methods.
**PUMPING TEST ANALYSIS RESULTS**

SITE: BURICHONG  WELL No: 46

SOLUTION: NUMERICAL

<table>
<thead>
<tr>
<th>POSITION OF PIEZOMETERS</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T$ ($m^2/d$)</td>
</tr>
<tr>
<td>100 ft. (30.48 m.)</td>
<td>340*</td>
</tr>
<tr>
<td>150 ft. (45.72 m.)</td>
<td>470</td>
</tr>
<tr>
<td>250 ft. (76.20 m.)</td>
<td>540</td>
</tr>
<tr>
<td>AVERAGE VALUES</td>
<td>510</td>
</tr>
<tr>
<td>INFERRED CONDITIONS</td>
<td>LEAKY CONFINED</td>
</tr>
</tbody>
</table>

**COMPARISON OF HYDRAULIC PARAMETERS OBTAINED FROM DIFFERENT SOLUTIONS**

<table>
<thead>
<tr>
<th>METHOD OF SOLUTION</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T$ ($m^2/d$)</td>
</tr>
<tr>
<td></td>
<td>D'down</td>
</tr>
<tr>
<td>TIME-DRAWDOWN</td>
<td>505</td>
</tr>
<tr>
<td>DISTANCE-DRAWDOWN</td>
<td>340</td>
</tr>
<tr>
<td>NUMERICAL</td>
<td>510</td>
</tr>
<tr>
<td>AVERAGE VALUES</td>
<td>450</td>
</tr>
<tr>
<td>INFERRED CONDITIONS</td>
<td>L E A K Y C O N F I N E D</td>
</tr>
</tbody>
</table>

Table 5.16. Aquifer test results of Burichong Well; (a) Numerical results and (b) Overall comparison of results obtained by all the methods.
(a) PUMPING TEST ANALYSIS RESULTS

SITE: CHANDINA
WELL No: 55

SOLUTION: NUMERICAL

<table>
<thead>
<tr>
<th>POSITION OF PIEZOMETERS</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T (m²/d)</td>
</tr>
<tr>
<td>50 ft. (15.24 m.)</td>
<td>6371*</td>
</tr>
<tr>
<td>150 ft. (45.72 m.)</td>
<td>560</td>
</tr>
<tr>
<td>400 ft. (121.92 m.)</td>
<td>1430</td>
</tr>
<tr>
<td>AVERAGE VALUES</td>
<td>1000</td>
</tr>
</tbody>
</table>

INFERRED CONDITIONS: LEAKY CONFINED

(b) COMPARISON OF HYDRAULIC PARAMETERS OBTAINED FROM DIFFERENT SOLUTIONS

<table>
<thead>
<tr>
<th>METHOD OF SOLUTION</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T (m²/d)</td>
</tr>
<tr>
<td></td>
<td>D’down</td>
</tr>
<tr>
<td>TIME-DRAWDOWN</td>
<td>1580</td>
</tr>
<tr>
<td>DISTANCE-DRAWDOWN</td>
<td>600</td>
</tr>
<tr>
<td>NUMERICAL</td>
<td>1000</td>
</tr>
<tr>
<td>AVERAGE VALUES</td>
<td>1060</td>
</tr>
</tbody>
</table>

INFERRED CONDITIONS: LEAKY CONFINED

Table. 5.17. Aquifer test results of Chandina Well; (a) Numerical results and (b) Overall comparison of results obtained by all the methods.
(a) PUMPING TEST ANALYSIS RESULTS

SITE: KOTWALI      WELL No: 59

SOLUTION: NUMERICAL

<table>
<thead>
<tr>
<th>POSITION OF PIEZOMETERS</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T (m²/d)</td>
</tr>
<tr>
<td>50 ft. (15.24 m.)</td>
<td>680</td>
</tr>
<tr>
<td>150 ft. (45.72 m.)</td>
<td>790</td>
</tr>
<tr>
<td>400 ft. (121.92 m.)</td>
<td>370</td>
</tr>
<tr>
<td>AVERAGE VALUES</td>
<td>610</td>
</tr>
<tr>
<td>INFERRED CONDITIONS</td>
<td>LEAKY Confined</td>
</tr>
</tbody>
</table>

(b) COMPARISON OF HYDRAULIC PARAMETERS OBTAINED FROM DIFFERENT SOLUTIONS

<table>
<thead>
<tr>
<th>METHOD OF SOLUTION</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T (m²/d)</td>
</tr>
<tr>
<td></td>
<td>D_down REC.</td>
</tr>
<tr>
<td>TIME-DRAWDOWN</td>
<td>630</td>
</tr>
<tr>
<td>DISTANCE-DRAWDOWN</td>
<td>470</td>
</tr>
<tr>
<td>NUMERICAL</td>
<td>610</td>
</tr>
<tr>
<td>AVERAGE VALUES</td>
<td>570</td>
</tr>
<tr>
<td>INFERRED CONDITIONS</td>
<td>LEAKY Confined</td>
</tr>
</tbody>
</table>

Table. 5.18. Aquifer test results of Kotwali Well; (a) Numerical results and (b) Overall comparison of results obtained by all the methods.
(a) PUMPING TEST ANALYSIS RESULTS

SITE: - BARURA
WELL No: - 69

SOLUTION: - NUMERICAL

<table>
<thead>
<tr>
<th>POSITION OF PIEZOMETERS</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T (m²/d)</td>
</tr>
<tr>
<td>50 ft. (15.24 m.)</td>
<td>3642 *</td>
</tr>
<tr>
<td>150 ft. (45.72 m.)</td>
<td>1290</td>
</tr>
<tr>
<td>400 ft. (121.92 m.)</td>
<td>1630</td>
</tr>
<tr>
<td>AVERAGE VALUES</td>
<td>1460</td>
</tr>
</tbody>
</table>

INFERRED CONDITIONS: LEAKY CONFINED

(b) COMPARISON OF HYDRAULIC PARAMETERS OBTAINED FROM DIFFERENT SOLUTIONS

<table>
<thead>
<tr>
<th>METHOD OF SOLUTION</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T (m²/d)</td>
</tr>
<tr>
<td></td>
<td>D'down</td>
</tr>
<tr>
<td>TIME-DRAWDOWN</td>
<td>1110</td>
</tr>
<tr>
<td>DISTANCE-DRAWDOWN</td>
<td>730</td>
</tr>
<tr>
<td>NUMERICAL</td>
<td>1460</td>
</tr>
<tr>
<td>AVERAGE VALUES</td>
<td>1110</td>
</tr>
</tbody>
</table>

INFERRED CONDITIONS: LEAKY CONFINED

Table. 5.19. Aquifer test results of Barura Well; (a) Numerical results and (b) Overall comparison of results obtained by all the methods.
### (a) PUMPING TEST ANALYSIS RESULTS

**SITE:** HAZIGANJ  | **WELL No.:** 82  
**SOLUTION:** NUMERICAL

<table>
<thead>
<tr>
<th>POSITION OF PIEZOMETERS</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( T (m^2/d) )</td>
</tr>
<tr>
<td>50 ft. (15.24 m.)</td>
<td>1440</td>
</tr>
<tr>
<td>150 ft. (45.72 m.)</td>
<td>1660</td>
</tr>
<tr>
<td>1000 ft. (304.80 m.)</td>
<td>1440</td>
</tr>
<tr>
<td>AVERAGE VALUES</td>
<td>1510</td>
</tr>
<tr>
<td>INFERRED CONDITIONS</td>
<td>LEAKY CONFINED</td>
</tr>
</tbody>
</table>

### (b) COMPARISON OF HYDRAULIC PARAMETERS OBTAINED FROM DIFFERENT SOLUTIONS

<table>
<thead>
<tr>
<th>METHOD OF SOLUTION</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( T (m^2/d) )</td>
</tr>
<tr>
<td></td>
<td>D(d)</td>
</tr>
<tr>
<td>TIME-DRAWDOWN</td>
<td>1530</td>
</tr>
<tr>
<td>DISTANCE-DRAWDOWN</td>
<td>1410</td>
</tr>
<tr>
<td>NUMERICAL</td>
<td>1510</td>
</tr>
<tr>
<td>AVERAGE VALUES</td>
<td>1480</td>
</tr>
<tr>
<td>INFERRED CONDITIONS</td>
<td>LEAKY CONFINED</td>
</tr>
</tbody>
</table>

Table 5.20. Aquifer test results of Haziganj Well; (a) Numerical results and (b) Overall comparison of results obtained by all the methods.
(a) PUMPING TEST ANALYSIS RESULTS

SITE:- CHAUDDAGRAM WELL No:- 101

SOLUTION:- NUMERICAL

<table>
<thead>
<tr>
<th>POSITION OF PIEZOMETERS</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T (m²/d)</td>
</tr>
<tr>
<td>50 ft. (15.24 m.)</td>
<td>220</td>
</tr>
<tr>
<td>150 ft. (45.72 m.)</td>
<td>230</td>
</tr>
<tr>
<td>1000 ft. (304.80 m.)</td>
<td>280</td>
</tr>
</tbody>
</table>

AVERAGE VALUES

| INFERRED CONDITIONS | FULLY CONFINED |

(b) COMPARISON OF HYDRAULIC PARAMETERS OBTAINED FROM DIFFERENT SOLUTIONS

<table>
<thead>
<tr>
<th>METHOD OF SOLUTION</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T (m²/d)</td>
</tr>
<tr>
<td></td>
<td>D'down</td>
</tr>
<tr>
<td>TIME-DRAWDOWN</td>
<td>240</td>
</tr>
<tr>
<td>DISTANCE-DRAWDOWN</td>
<td>680</td>
</tr>
<tr>
<td>NUMERICAL</td>
<td>240</td>
</tr>
<tr>
<td>AVERAGE VALUES</td>
<td>390</td>
</tr>
</tbody>
</table>

| INFERRED CONDITIONS | FULLY CONFINED |

Table. 5.21. Aquifer test results of Chauddagram Well; (a) Numerical results and (b) Overall comparison of results obtained by all the methods.
### (a) PUMPING TEST ANALYSIS RESULTS

**SITE:** SENBAGH  \( \text{WELL No: - 130} \)

**SOLUTION:** NUMERICAL

<table>
<thead>
<tr>
<th>POSITION OF PIEZOMETERS</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( T (\text{m}^2/\text{d}) )</td>
</tr>
<tr>
<td>50 ft. (15.24 m.)</td>
<td>850</td>
</tr>
<tr>
<td>150 ft. (45.72 m.)</td>
<td>800</td>
</tr>
<tr>
<td>400 ft. (121.92 m.)</td>
<td>1060</td>
</tr>
<tr>
<td>AVERAGE VALUES</td>
<td>900</td>
</tr>
</tbody>
</table>

**INFERRED CONDITIONS**  \( \text{LEAKY CONFINED} \)

### (b) COMPARISON OF HYDRAULIC PARAMETERS OBTAINED FROM DIFFERENT SOLUTIONS

<table>
<thead>
<tr>
<th>METHOD OF SOLUTION</th>
<th>VALUES OF HYDRAULIC PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( T (\text{m}^2/\text{d}) )</td>
</tr>
<tr>
<td></td>
<td>D' down REC.</td>
</tr>
<tr>
<td>TIME-DRAWDOWN</td>
<td>770</td>
</tr>
<tr>
<td>DISTANCE-DRAWDOWN</td>
<td>630</td>
</tr>
<tr>
<td>NUMERICAL</td>
<td>900</td>
</tr>
<tr>
<td>AVERAGE VALUES</td>
<td>770</td>
</tr>
</tbody>
</table>

**INFERRED CONDITIONS**  \( \text{LEAKY CONFINED} \)

Table 5.22. Aquifer test results of Senbagh Well; (a) Numerical results and (b) Overall comparison of results obtained by all the methods.
true for leaky-confined condition. All these sequence of events are repeated by all
the method of solutions.

> It is observed that on many occasions the distance-
drawdown solutions produced much higher leakage (lower BL) values (Nabinagar, Burichong, Chandina, Kotwali & Senbagh test site) than the time-drawdown solution.

For some of the OWs the results obtained by the type
curve method provides better harmony with the numerical results, while for others
the results obtained by the straight line method exhibit closer correlation with numerically obtained results. In another situation it was found that all the results
obtained by the straight line method for the OWs of a particular test site
(Nabinagar and Chauthagram) were close to the numerical results. Similarly, it
was also found that for all the OWs of another site (Kotwali) the results given by
the type curve method closely resemble the numerically obtained results for that
particular well site. These sequence of events indicates that neither the straight line
nor the type curve method is superior to the other.

In some instances both the drawdown and recovery data
(all OWs of Daudkandi well site, Chandina OW2 and Barura OW2 & OW3)
and for Chandina OW2 only the recovery data were available for analysis. The
results obtained by analyzing the recovery data using the time-recovery solution
indicates more leakage than those obtained by the other methods.

For the B’Baria OW3, the straight line method indicated no
leakage whereas the type-curve method indicated significant leakage thereby
producing a great contrast in Transmissivity value. The numerical model results
however match with the non-leaky confined solution.

On many occasions the numerical model results show striking
similarity with the analytical results (B’Baria OW1, OW2 & OW3, Daudkandi
OW1 & OW3, Burichong OW3, Chandina OW3, Haziganj OW2, Chauddagram OW2, Feni OW2 & OW3 and Senbagh OW3) which strengthens the suitability of the methods even further and provides confirmation of the results and the interpretation of the hydraulic parameters.

**Transmissivity map:** Finally using the overall average of all the values obtained from different types of solutions, the following transmissivity distribution map (Fig. 5.20) was prepared which will be used to calculate the ground water resource potential. On the basis of the admittedly few reliable data points, the northern part has low transmissivity values in the range from <500 to >800 m$^2$/d, compared with a range from 600 to >1400 m$^2$/d.
Contour interval 100 m$^3$/d

Fig. 5.20: Distribution of transmissivity in the study area.
CHAPTER 6  WELL PERFORMANCE

6.1 Step-Drawdown Tests.
   6.1.1 General.
   6.1.2 Standard Procedures.
   6.1.3 Test Procedures Used.

6.2 Analysis of Step-Drawdown Tests.
   6.2.1 Method Used.
   6.2.2 Presentation of Analyses.
   6.2.3 Comments on the Results.

6.3 Well Efficiency.

6.4 Specific Capacity.
6.1 Step-Drawdown Tests:

6.1.1 General:

The drawdown that occurs when a well is pumped has several components as in the expression $s_t = (s_p + s_d + s_a - s_r + s_\gamma + s_w)$, where $s_t =$ total drawdown. The two primary components which constitute more than 90% of the drawdown are $s_\gamma$ and $s_w$ and the other components may be considered under special circumstances if identifiable but they are usually ignored.

The aquifer loss component is a function of both pumping rate and pumping period. It may be expressed as the product of the pumping rate $Q$ and an aquifer loss factor $B$ which is independent of $Q$ (Lennox, 1966). The lower the permeability of the aquifer, the higher the aquifer loss and virtually nothing can be done to modify this part of total loss. The well loss component, on the other hand, depends primarily on the pumping rate and does not vary with time. Well loss is associated with resistance to flow through the well screen and inside the well. When non-laminar flow occurs due to the higher pumping rate the magnitude of well loss also increases rapidly. Well loss may be expressed as the product of a well loss factor $C$ and some power of $Q$ dependent on the nature of flow in and around the well (Lennox, 1966). With efficient well design the well loss component can be improved.

Jacob (1946) pioneered the step-drawdown method, which was designed to distinguish the aquifer loss and well loss components of drawdown, though at that time priority was given to the determination of the effective well radius. The step-drawdown test is now widely used to determine well losses. Jacob suggested that the well loss is approximately proportional to the square of the discharge rate and that the relationship between the two components of drawdown is approximately as follows:
\[ s_t = BQ + CQ^2 \]  \hspace{1cm} (6.1)

where, \( BQ \) = aquifer loss and \( CQ^2 \) = well loss

and later on Bruin and Hudson (1955) and Bierschenk and Wilson (1961) also limited their interpretations on this assumption for solving the well loss component C. However Rorabaugh (1953) pointed out that with the increasing turbulent flow within the well the 'well loss' component is best calculated when the value of \( n \) may be greater than 2 and his analysis suggested that a representative value is about 2.5. The most accurate method for the analysis of step-drawdown test data must be that of Rorabaugh because it leads under ideal conditions to the unequivocal identification of the type of flow as laminar, turbulent or transitional from one to the other. Eden and Hazel (1973) were the first clearly to suggest that a step-drawdown test can also be used to determine aquifer characteristics.

### 6.1.2 Standard Procedure:

The present day practice in conducting a step-drawdown test is done in two different fashions. The first procedure is the original Jacob idea in which the drawdown of a well is observed while the discharge rate from the well is increased instantly in stepwise fashion without any recovery. In the second procedure, after every step the well is allowed to recover i.e. which is equivalent to a series of short tests with full recovery after each stage from a different discharge rate. The discharge rate in either of the methods is kept constant throughout each step and the time duration of the recommended stage or step must be kept identical (Jones and Rushton, 1981). The basic assumption in all step-drawdown test analysis is that the increase in discharge rate at the beginning of each step is equivalent to a new pump in the well having a discharge rate equal to the increase in the discharge rate. The total drawdown in a step-drawdown test is equal to the sum of the drawdowns caused by the theoretical pumps responsible.
for each discharge step in the test.

The specific drawdown-discharge rate graph (Fig. 6.6) is basic to most of the analysis done for understanding well performance and well efficiency. Therefore the accuracy of such a plot is totally dependent on the number of data points on the graph i.e. on the number of steps in the test. It is therefore recommended that at least four steps should be used to ensure accuracy of the results. Three steps is the absolute minimum and is usually considered as insufficient. The specific drawdown-discharge rate graph will be most accurately defined if the data points are spread out. Thus it is important that the discharge rates chosen in the step-drawdown test should cover most of the total discharge range of the well and the increments of discharge should be fairly equal. The increment in pumping rate could be a positive increment or negative increment but a positive increment is desirable and is also simpler to organize.

The length of the steps in a test can be varied to fit local conditions. The Eden and Hazel method can handle steps less than an hour long but steps are usually chosen to be one hour long for ease of timing or 100 minutes or more for ease of analysis. But a minimum step of 100 minute is recommended to allow adequate stable data to be obtained in each step. If time should allow, then three hour steps are recommended, because then there would be adequate data for a constant rate test analysis of the first step (Clark, 1977).

6.1.3 Test Procedure Used:

There were about eight wells chosen in the project area to conduct step-drawdown test (Fig. 6.1). Of these tests, four are 3-step tests and the other four tests are 2-step tests. A brief description of testing procedure of each individual wells are presented below:
Fig. 6.1: Location map showing the step testing wells.
B'Baria (Well 6): Only two steps were carried out (i.e. the well was run with two
different discharge rates) and after every step the well was allowed to make a full
recovery. During the first step the discharge rate was 0.891 cfs while the second
discharge rate was 1.34 cfs; the duration of each step was 60 minutes; and the
incremental discharge was positive. However, the 2-step test is in no way capable
of giving reliable results for well performance analysis.

Nabinagar (Well 9): is a three-step test and after each step the well was allowed
to make a full recovery. The discharge rates chosen were 1.00 cfs for the first step,
0.67 cfs for the second step and 2.00 cfs for the third step, which suggest that
neither of the conventional procedures (continuous positive increment or continuous
negative increment) was adopted. The duration of each step was only 30 minutes
which also provided insufficient time for obtaining good results.

Devidwar (Well 34): was a continuous two-step test, i.e. the discharge rate was
changed instantaneously during the second step with a positive increment. During
the first step the discharge rate was 0.535 cfs and increased to 1.07 cfs during the
second step, the duration of each step being 120 minutes.

Chandina (Well 55): is a three-step test. It is neither a continuous step test nor
a discontinuous step test, but rather a mixture of the two. During the first step, the
well was pumped with a discharge rate of 0.891 cfs and after 40 minutes (which
is the duration of pumping for every step) the well was allowed to make a full
recovery. During the second step the pumping rate was increased to 1.37 cfs and
after running for a period of 40 minutes the discharge rate was further increased to
1.87 cfs instantaneously without stopping for recovery. During these three steps the
incremental discharge was always positive.
Kotwali (Well 59): is a discontinuous 2-step test. During the first step the well was pumped with a discharge rate 0.891 cfs for a duration of 680 minutes, after that the well was allowed to make a full recovery which was then followed by pumping at the second discharge rate of 0.46 cfs for a duration of 700 minutes. The discharge rate used indicated a negative increment of discharge.

Laksam (Well 80): is a continuous three-step test (i.e. after every step the discharge rate was increased instantaneously without stopping the pumps for a recovery). During the test the discharge rates chosen for different steps were 0.535 cfs for the first step, 1.07 cfs for the second step and 1.605 cfs for the third and final step which also indicated a positive increment of the discharge rate. The duration of all the steps was kept constant to 120 minutes.

In view of the testing method necessary for an understanding of the performance and behaviour of the well, it may be seen that neither of the adapted test procedures fulfilled the requirement of an ideal step-drawdown test, nor they can be regarded as a complete test. The previous discussion of the standard procedure indicates that 3- step test is less desirable for obtaining good results but adequate, whereas 2- step test results are quite unacceptable. Therefore, only the results of the four different locations where 3- step tests were conducted are presentable and two of them (Laksam W 80 and Chandpur W 91) are better than the others on the basis of the time duration (120 minutes) allowed and the way the test discharge increments were chosen. Surprisingly, some of the 2- step tests also provided some good results. In this section, the conducted tests data were analyzed and the most important specific drawdown-discharge plots prepared.

6.2 Analysis of Step-Drawdown tests:
6.2.1 Method Used:

The primary purpose of present day step-drawdown test analysis has been extended from Jacob’s time. Then evaluation of the unknown factors B, C, and n was undertaken to determine and to separate the well loss component of drawdown from the aquifer loss of component. Now-a-days with the development of the technique by Eden and Hazel the aquifer transmissivity can also be determined. The following methods were used to calculate the above-mentioned parameters.

a) Jacob Method:

Jacob developed the following general arithmetic equation to evaluate the well loss factor C:

\[
C = \frac{(ds_i / dQ_i) - (ds_{i-1} / dQ_{i-1})}{dQ_{i-1} + dQ_i}
\]  

(6.2)

By plotting the test data as in Fig. 6.2 on a semi-logarithmic paper, the incremental drawdown can be separated which is then inserted into the above equation to obtain the value of C. The accuracy of this method depends on the efficient measurement of the incremental drawdown which is usually open to error.

b) Bruin & Hudson (1955) and Bierschenk & Wilson (1957) Method:

These authors are among the followers of the Jacob method which they developed one step further by dividing the original drawdown component equation by Q and rearranged it in the form of the equation of a straight line which takes the following form:

\[
s_i / Q = B + CQ
\]  

(6.3)

and usually describes the slope equation of a straight line with intercept. They used
the cumulative summation of discharge rate and drawdown of every step to calculate the summation of specific drawdown ($\Sigma s_i / \Sigma Q$) and produced a plot of specific-drawdown versus cumulative discharge $\Sigma Q$ (Fig. 6.6). The line of best fit is drawn which gives an intercept $B$ and a slope $C$. Since this simple plot gives both the $B$ and $C$ factors, the well loss factor can be calculated with reasonable accuracy, so the method is popular and is widely used.

c) Rorabaugh Method:

Rorabaugh’s (1953) method is one step forward and strictly speaking is most accurate graphical method available since it calculates all the parameters $B$, $C$ and $n$. In his modification of Jacob’s basic equation, he divided by $Q$ and introduced logarithms to both sides of the equation in the following manner:

\[
\begin{align*}
  s_i &= B_i Q + C Q^n \quad \text{dividing by } Q \\
  s_i / Q &= B_i + C Q^{n-1} \\
  (s_i / Q - B_i) &= C Q^{n-1} \quad \text{(rearranged)} \\
  \log (s_i / Q - B_i) &= \log C + \log C Q^{n-1} \\
  &= \log C + (n-1) \log Q
\end{align*}
\]

A log-log plot (Fig. 6.13) of $(s_i/Q - B_i)$ versus $Q$ is prepared with several trial values of $B_i$ until all the plotted points lie on a straight line and that value of $B$ is the correct value. The slope of the straight line is equal to the value $(n-1)$, from which $n$ can be determined. The corresponding value of $\log Q = 1$ cfs in the $Y$ axis is taken as the appropriate $C$ value. A lower value of $B$ would make the points concave upwards, while a higher $B$ value would produce a convex nature.
d) Eden and Hazel:

Eden and Hazel (1973) developed a graphical method of analyzing the step-drawdown test for calculating the hydraulic parameters, especially the aquifer transmissivity, based on Jacob's original equation. The simplified version of their mathematical deductions are:

\[ s_i = aQ_i + b \sum dQ_i \log (t-t_i) + CQ_i^2 \]

\[ H = \sum dQ_i \log (t - t_i) \]

Where \( H = \sum dQ_i \log (t - t_i) \)

The value of \( H \) is calculated for each step which involves lengthy and tedious computation. To overcome this computation problem a computer program has been developed to handle the calculations as well as the plotting of \( H \) vs. \( s \) (Fig. 6.17) (Holloway 1972), which produces several straight line plots, depending on the number of steps used in the step-drawdown test. The slope of these straight lines are then used to calculate the aquifer transmissivity.

6.2.2 Presentation of Analysis:

The adoption of complicated and unrealistic method in conducting the step-drawdown tests in the study area have made it impossible to analyze all the test data using all the available methods. Jacob’s method was usable with the data obtained for Devidwar, Laksam and Chandpur wells, and Bruin & Hudson’s method was found to work with all the step-drawdown test data. Rorabaugh’s method is applicable to the test data obtained from Laksam and Chandpur wells, but the results obtained for the parameters \( B, C \) and \( n \) are quite different from those obtained the by Bruin & Hudson method. The Eden & Hazel technique was applicable only with data from the Devidwar, Laksam and Chandpur Wells. A systematic description of the results are presented below.
a) Jacob method:

1) Devidwar well: The time-drawdown plot (Fig. 6.2) was used to obtain the values of 'ds' for each step and other parameters required for the calculations are tabulated below:

<table>
<thead>
<tr>
<th>Step No.</th>
<th>$\Sigma Q$ (gpm)</th>
<th>$\Sigma Q$ (cfs)</th>
<th>$dQ_1$ (cfs)</th>
<th>duration (minutes)</th>
<th>$\Sigma s_1$ (ft)</th>
<th>$\Sigma s / \Sigma Q$ (sec/ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200</td>
<td>0.535</td>
<td>0.535</td>
<td>120.0</td>
<td>20.13</td>
<td>20.13</td>
</tr>
<tr>
<td>2</td>
<td>400</td>
<td>1.070</td>
<td>0.535</td>
<td>120.0</td>
<td>11.83</td>
<td>31.96</td>
</tr>
</tbody>
</table>

The following calculations were done using the Jacob’s formula:

$$C_{21} = \frac{(ds_2 / dQ_2) - (ds_1 / dQ_1)}{dQ_2 + dQ_1} = \frac{(11.83/0.535) - (20.13/0.535)}{(0.535 + 0.535)} = 0.37$$

$$= \frac{22.11 - 37.63}{1.070} = \frac{-15.52}{1.070} = -14.5 \text{ sec/ft}^2$$

2) Laksam well:

The time drawdown plot (Fig. 6.3) was used to obtain the $ds$ value for each step and all other parameters are tabulated below:

<table>
<thead>
<tr>
<th>Step No.</th>
<th>$\Sigma Q$ (gpm)</th>
<th>$\Sigma Q$ (cfs)</th>
<th>$dQ_1$ (cfs)</th>
<th>duration (minutes)</th>
<th>$\Sigma s_1$ (ft)</th>
<th>$\Sigma s / \Sigma Q$ (sec/ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200</td>
<td>0.535</td>
<td>0.535</td>
<td>120.0</td>
<td>9.920</td>
<td>18.54</td>
</tr>
<tr>
<td>2</td>
<td>400</td>
<td>1.070</td>
<td>0.535</td>
<td>120.0</td>
<td>8.000</td>
<td>16.76</td>
</tr>
<tr>
<td>3</td>
<td>600</td>
<td>1.605</td>
<td>0.535</td>
<td>120.0</td>
<td>11.49</td>
<td>18.33</td>
</tr>
</tbody>
</table>

Two well loss factors $C_{21}$ and $C_{32}$ were obtained as follows:
Fig. 6.2: Step-drawdown test; Jacob solution for Devidwar well.
Fig. 6.3: Step-drawdown test; Jacob solution for Laksam well.
\[
C_{21} = \frac{(8.00/0.535) - (9.92/0.535)}{(0.535 + 0.535)} = -3.59 = \frac{-3.36 \text{ sec}^2/\text{ft}^5}{1.07}
\]

\[
C_{32} = \frac{(11.49/0.535) - (8.00/0.535)}{1.07} = 6.10 \text{ sec}^2/\text{ft}^5.
\]

3) Chandpur Well:

The time-drawdown plot (Fig. 6.4) provides the corrected ds value and dQ values tabulated below:

<table>
<thead>
<tr>
<th>Step No.</th>
<th>( \Sigma Q )</th>
<th>( \Sigma Q )</th>
<th>dQ</th>
<th>duration</th>
<th>ds</th>
<th>( \Sigma s_t )</th>
<th>( \Sigma s / \Sigma Q )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>gpm.</td>
<td>cfs.</td>
<td>cfs.</td>
<td>minutes</td>
<td>ft.</td>
<td>ft.</td>
<td>sec/ft²</td>
</tr>
<tr>
<td>1</td>
<td>200</td>
<td>0.535</td>
<td>0.535</td>
<td>120.0</td>
<td>8.500</td>
<td>8.500</td>
<td>15.89</td>
</tr>
<tr>
<td>2</td>
<td>400</td>
<td>1.070</td>
<td>0.535</td>
<td>120.0</td>
<td>4.500</td>
<td>12.90</td>
<td>12.06</td>
</tr>
<tr>
<td>3</td>
<td>600</td>
<td>1.605</td>
<td>0.535</td>
<td>120.0</td>
<td>5.400</td>
<td>18.30</td>
<td>11.40</td>
</tr>
</tbody>
</table>

from which the well loss factors \( C_{21} \) and \( C_{32} \) were calculated:

\[
C_{21} = \frac{(4.40 / 0.535) - (8.50 / 0.535)}{(0.535 + 0.535)} = -7.67 = \frac{-7.17 \text{ sec}^2/\text{ft}^5}{1.07}
\]

\[
C_{32} = \frac{(5.40/0.535) - (4.40/0.535)}{1.07} = 1.75 \text{ sec}^2/\text{ft}^5.
\]

b) Brunin and Hudson Method:

All the step-drawdown test data have been analyzed using this method and the results are presented below on an individual well basis.
Fig. 6.4: Step-drawdown test; Jacob solution for Chandpur well.
1) **B'Baria Well:** The necessary parameters taken from the plot (Fig. 6.5) are tabulated below:

<table>
<thead>
<tr>
<th>Step No.</th>
<th>ΣQ gpm.</th>
<th>ΣQ cfs.</th>
<th>dQ cfs.</th>
<th>duration minutes</th>
<th>ds ft.</th>
<th>Σs ft.</th>
<th>Σs / ΣQ sec/ft²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>333</td>
<td>0.891</td>
<td>0.891</td>
<td>60.00</td>
<td>11.65</td>
<td>11.65</td>
<td>13.08</td>
</tr>
<tr>
<td>2</td>
<td>500</td>
<td>1.340</td>
<td>0.449</td>
<td>60.00</td>
<td>2.880</td>
<td>14.53</td>
<td>10.84</td>
</tr>
</tbody>
</table>

The direction of slope is negative and no further use of the well data is possible.

2) **Nabinagar well:**

The specific drawdown vs. discharge plot in Figure 6.6 was drawn using data tabulated below:

<table>
<thead>
<tr>
<th>Step No.</th>
<th>ΣQ gpm.</th>
<th>ΣQ cfs.</th>
<th>dQ cfs.</th>
<th>duration minutes</th>
<th>ds ft.</th>
<th>Σs ft.</th>
<th>Σs / ΣQ sec/ft²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>374</td>
<td>1.000</td>
<td>1.000</td>
<td>30.00</td>
<td>20.00</td>
<td>20.00</td>
<td>20.00</td>
</tr>
<tr>
<td>2</td>
<td>250</td>
<td>0.670</td>
<td>-0.33</td>
<td>30.00</td>
<td>-5.84</td>
<td>14.16</td>
<td>21.13</td>
</tr>
<tr>
<td>3</td>
<td>740</td>
<td>2.000</td>
<td>1.330</td>
<td>30.00</td>
<td>30.34</td>
<td>44.50</td>
<td>22.25</td>
</tr>
</tbody>
</table>

and B and C values calculated to be

B = 19.30 sec/ft² and  C = 1.49 sec²/ft³.

When Q = 1.00 cfs then:

BQ = 19.30 x 1.00 = 19.30 ft and  CQ² = 1.49 x (1.0)² = 1.49 ft.

Calculated s = 20.79 ft compared with 20.00 ft measured.

When Q = 2.00 cfs then:

BQ = 19.30 x 2.00 = 38.60 ft and  CQ² = 1.49 x (2.0)² = 5.96 ft.

Calculated s = 44.56 ft compared with 44.5 ft measured. The differences between
Fig. 6.5: Specific drawdown vs. discharge plot for B' Baria well.
Fig. 6.6: Specific drawdown vs. discharge plot and yield - drawdown plot for Nabinagar well.
the measured and calculated drawdown at the two pumping rates are 4 and 0.13 percent, respectively.

3) **Devidwar Well:**

The specific drawdown vs. discharge plot in Figure 6.7 was drawn using previously determined data. The resulting straight line through the two data points is negative and no further use of the data can be made.

4) **Burichong Well:**

The specific drawdown vs. discharge plot in Figure 6.8 was drawn using the data tabulated below:

<table>
<thead>
<tr>
<th>Step No.</th>
<th>( \Sigma Q ) (gpm)</th>
<th>( \Sigma Q ) (cfs)</th>
<th>( dQ ) (cfs)</th>
<th>duration (minutes)</th>
<th>( ds ) (ft)</th>
<th>( \Sigma s ) (ft)</th>
<th>( \Sigma s / \Sigma Q ) (sec/ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>333</td>
<td>0.891</td>
<td>0.891</td>
<td>120.0</td>
<td>25.12</td>
<td>25.12</td>
<td>28.19</td>
</tr>
<tr>
<td>2</td>
<td>166</td>
<td>1.340</td>
<td>0.449</td>
<td>120.0</td>
<td>6.340</td>
<td>31.46</td>
<td>23.48</td>
</tr>
</tbody>
</table>

The straight line through the two data points produces a reverse alignment like that in the Devidwar well and invalidates any further use of the erroneous results.

5) **Chandina Well:** The specific drawdown vs. discharge plot of Figure 6.9 was drawn using the data tabulated below:

<table>
<thead>
<tr>
<th>Step No.</th>
<th>( \Sigma Q ) (gpm)</th>
<th>( \Sigma Q ) (cfs)</th>
<th>( dQ ) (cfs)</th>
<th>duration (minutes)</th>
<th>( ds ) (ft)</th>
<th>( \Sigma s ) (ft)</th>
<th>( \Sigma s / \Sigma Q ) (sec/ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>---</td>
<td>0.890</td>
<td>0.890</td>
<td>40.00</td>
<td>8.080</td>
<td>8.080</td>
<td>8.240</td>
</tr>
<tr>
<td>2</td>
<td>---</td>
<td>1.370</td>
<td>0.390</td>
<td>40.00</td>
<td>3.980</td>
<td>11.98</td>
<td>8.740</td>
</tr>
<tr>
<td>3</td>
<td>---</td>
<td>1.870</td>
<td>0.500</td>
<td>40.00</td>
<td>5.550</td>
<td>17.53</td>
<td>9.370</td>
</tr>
</tbody>
</table>
Fig. 6.7: Specific drawdown vs. discharge plot for Devidwar well.
Fig. 6.8: Specific drawdown vs. discharge plot for Burichong well.

Q1 = 0.89 CFS, Q2 = 1.34 CFS
Fig. 6.9: Specific drawdown vs. discharge plot and yield - drawdown plot for Chandina well.

C = 1.28 Sec² / ft³

B = 7.00 Sec / ft²

Q₁ = 0.98 CFS, Q₂ = 1.37 CFS, Q₃ = 1.87 CFS

(0.0, 7.00)

(1.60, 9.00)
The straight line drawn passes through all three data points with a correct alignment. The following B and C values were determined:

\[ B = 7.00 \text{ Sec/ft}^2 \quad \text{and} \quad C = 1.28 \text{ sec}^2/\text{ft}^3. \]

These allowed the drawdown components to be calculated as follows:

**When Q = 1.37 cfs then:**

\[ BQ = 7.00 \times 1.37 = 9.59 \text{ ft} \quad \text{and} \quad CQ^2 = 1.28 \times (1.37)^2 = 2.40 \text{ ft}. \]

Calculated \( s_t = 11.99 \text{ ft} \) compared with 11.98 ft measured.

**When Q = 1.87 cfs then:**

\[ BQ = 7.00 \times 1.87 = 13.09 \text{ ft} \quad \text{and} \quad CQ^2 = 1.28 \times (1.87)^2 = 4.48 \text{ ft}. \]

Calculated \( s_t = 17.57 \text{ ft} \) compared with 17.53 ft measured. The differences between calculated and measured drawdowns are insignificant at 0.08 and 0.23 percent.

6) **Kotwali Well:**

The specific drawdown vs. discharge plot (Fig. 6.10) was prepared using the data tabulated below:

<table>
<thead>
<tr>
<th>Step No.</th>
<th>( \Sigma Q ) gpm.</th>
<th>( \Sigma Q ) cfs.</th>
<th>( dQ ) cfs.</th>
<th>duration minutes</th>
<th>ds ft.</th>
<th>( \Sigma s_t ) ft.</th>
<th>( \Sigma s / \Sigma Q ) sec/ft²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>--- 0.891</td>
<td>0.891</td>
<td>891</td>
<td>680.0</td>
<td>21.67</td>
<td>21.67</td>
<td>24.32</td>
</tr>
<tr>
<td>2</td>
<td>--- 0.460</td>
<td>-0.451</td>
<td>451</td>
<td>700.0</td>
<td>-11.42</td>
<td>10.25</td>
<td>22.28</td>
</tr>
</tbody>
</table>

Although there are only two data points yet the straight line through these points shows normal alignment. The following B and C values were calculated:

\[ B = 20.125 \text{ sec/ft}^2 \quad \text{and} \quad C = 4.80 \text{ sec}^2/\text{ft}^3. \]

These allowed the drawdown components to be calculated as follows:
Fig. 6.10: Specific drawdown vs. discharge plot for Kotwali well.
When \( Q = 0.891 \) cfs then:

\[
BQ = 20.125 \times 0.891 = 17.93 \text{ ft} \quad \text{and} \quad CQ^2 = 4.66 \times (0.891)^2 = 3.70 \text{ ft}.
\]

Calculated \( s_i = 21.63 \) ft compared with 21.67 ft measured having a difference of 0.18 percent.

When \( Q = 0.46 \) cfs then:

\[
BQ = 20.125 \times 0.46 = 9.26 \text{ ft} \quad \text{and} \quad CQ^2 = 4.66 \times (0.46)^2 = 0.99 \text{ ft}.
\]

Calculated \( s_i = 10.25 \) ft shows no differences in comparison with the measured \( s' = 10.25 \) ft.

7) **Laksam Well:** The specific drawdown vs. discharge plot (Fig. 6.11) was prepared using previously determined data. The line of best fit through the data points represents a normal alignment. The following \( B \) and \( C \) values were determined:

\[
B = 16.80 \text{ sec/ft}^2 \quad \text{and} \quad C = 0.96 \text{ sec}^2/\text{ft}^3.
\]

These allowed the drawdown component to be calculated as follows:

When \( Q = 1.07 \) cfs then:

\[
BQ = 16.80 \times 1.07 = 17.98 \text{ ft} \quad \text{and} \quad CQ^2 = 0.96 \times (1.07)^2 = 1.10 \text{ ft}.
\]

Calculated \( s_i = 19.08 \) ft compared with \( s_i = 17.92 \) ft measured.

When \( Q = 1.605 \) cfs then:

\[
BQ = 16.80 \times 1.605 = 26.96 \text{ ft} \quad \text{and} \quad CQ^2 = 0.96 \times (1.605)^2 = 2.47 \text{ ft}.
\]

Calculated \( s_i = 29.43 \) ft compared with \( s_i = 29.41 \) ft measured. The difference between the calculated and measured drawdown at the two pumping rates are 6.5 and 0.07 percent.

8) **Chandpur Well:**

The specific drawdown vs. discharge plot (Fig. 6.12) was prepared using the previously determined data. The best fit line through the data points
Fig. 6.11: Specific drawdown vs. discharge plot for Laksam well.
Fig. 6.12: Specific drawdown vs. discharge plot and yield - drawdown plot for Chandpur well.
produces an inverted alignment. The following $B$ and $C$ values were determined:

$B = 16.50 \text{ sec/ft}^2 \quad \text{and} \quad C = 3.19 \text{ sec}^2/\text{ft}^4$.

These allowed the drawdown components to be calculated as follows:

**When $Q = 1.07$ cfs then:**

$BQ = 16.50 \times 1.07 = 17.66 \text{ ft} \quad \text{and} \quad CQ^2 = 3.19 \times (1.07)^2 = 3.65 \text{ ft}$.

Calculated $s_t = 21.31 \text{ ft}$ compared with 12.90 ft measured. The difference between the calculated and measured drawdown at the two pumping rates are 65 and 90 percent such a great difference is primarily because of negative plotting of the data points which invalidates any further use of erroneous results. Yet various parameters were analyzed because of the availability of three data points.

**When $Q = 1.605$ cfs then:**

$BQ = 16.50 \times 1.605 = 26.48 \text{ ft} \quad \text{and} \quad CQ^2 = 3.19 \times (1.605)^2 = 8.22 \text{ ft}$.

Calculated $s_t = 34.70 \text{ ft}$ compared with 18.30 ft measured. The difference between the calculated and measured drawdown at the two pumping rates are 65 and 90 percent respectively.

c) **Rorabaugh Solution:**

This method was applicable only to data from the Chandina, Chandpur, Laksam, and Nabinagar wells because while at least three steps are required to obtain reliable results, four or more steps are desirable. It was also found that in tests which combined positive and negative increments of discharge to perform the test that despite having a minimum of three steps, the Rorabaugh method was not applicable.

1) **Chandina Well:** The plot of Figure 6.13 was prepared with various trial values of $B$ (see tabulation below) until finally all the points conformed to a
Fig. 6.13: Step-drawdown test; Rorabaugh solution for Chandina well.
Step $\Sigma Q$ | $\Sigma s/\Sigma Q$ | $\Sigma s/\Sigma Q - B$ | $B=3.000$ | $B=5.000$ | $B=7.000$ | $B=8.000$
---|---|---|---|---|---|---
No. | cfs. | sec/ft$^2$ | sec/ft$^2$ | sec/ft$^2$ | sec/ft$^2$ | sec/ft$^2$
---|---|---|---|---|---|---
1 | 0.980 | 08.240 | " | 05.24 | 03.24 | 01.24 | 00.24
2 | 1.370 | 08.740 | " | 05.74 | 03.74 | 01.74 | 0.740
3 | 1.870 | 09.370 | " | 06.37 | 04.37 | 02.37 | 01.37

straight line when $B = 7.00$ sec/ft$^2$. Gratifyingly, this value coincides with the value obtained from the Bruin and Hudson method. The 'C' value, which is obtained graphically, is equivalent to $1.25$ sec$^2$/ft$^4$. The value of 'n' was calculated from the gradient using the following relationship:

$$\frac{dy}{dx} = \frac{1.26 - 0.20}{1.00 - 0.82} = 1.26.$$  

$$n = [1 + (n-1)] = 1 + 1.26 = 2.26.$$  

This method worked very well with this particular test though during the test a combination of discontinuous (during the first step) and continuous (during the second and third step) methods of changing the discharge rate was adopted. In the test a positive increment in discharge was always made after every step.

2) Chandpur well:

The data plot shown in Figure 6.14 was prepared using the various trial 'B' values tabulated below until all the points fell on a straight line when

Step $\Sigma Q$ | $\Sigma s/\Sigma Q$ | $\Sigma s/\Sigma Q - B$ | $B=8.000$ | $B=10.00$ | $B=11.03$ | $B=11.30$
---|---|---|---|---|---|---
No. | cfs. | sec/ft$^2$ | sec/ft$^2$ | sec/ft$^2$ | sec/ft$^2$ | sec/ft$^2$
---|---|---|---|---|---|---
1 | 0.535 | 15.890 | " | 7.900 | 5.900 | 4.870 | 4.670
2 | 1.070 | 12.056 | " | 4.060 | 2.060 | 1.030 | 0.756
3 | 1.605 | 11.400 | " | 3.400 | 1.400 | 0.370 | 0.100

246
Fig. 6.14: Step-drawdown test: Rorbaugh solution for Chandpur well.
However, this straight line like that obtained from the Bruin and Hudson solution shows a reverse trend which invalidates any further determinations of \( C \) and \( n \). It has been included to demonstrate that the methods should not be used mechanically, since invalid data can sometimes be apparently amenable to accepted methodology.

### 3) Laksam and Nabinagar Wells:

The Rorabaugh method was also attempted with the test data obtained for Laksam and Nabinagar (Fig. 6.15) wells since they had three steps. However, the method did not work because the plotted points never achieved a straight line distribution so that it was not possible to obtain any results. The alternative values of \( B \) used in the repeated trials are tabulated below and may be seen to have been attempted for a wide range of values. The unstable condition suggest that the wells were not properly developed for a sufficient time after the completion of the drilling. This situation was not helped by the test procedure adopted, which introduced a reduction of discharge for the second step.

**Laksam**

<table>
<thead>
<tr>
<th>Step</th>
<th>( \Sigma Q )</th>
<th>( \Sigma s/\Sigma Q )</th>
<th>( (\Sigma s/\Sigma Q - B) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>cfs.</td>
<td>sec/ft(^2)</td>
<td>sec/ft(^2)</td>
</tr>
<tr>
<td>1</td>
<td>0.535</td>
<td>18.540</td>
<td>&quot;</td>
</tr>
<tr>
<td>2</td>
<td>1.070</td>
<td>16.760</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

**Nabinagar**

<table>
<thead>
<tr>
<th>Step</th>
<th>( \Sigma Q )</th>
<th>( \Sigma s/\Sigma Q )</th>
<th>( (\Sigma s/\Sigma Q - B) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>cfs.</td>
<td>sec/ft(^2)</td>
<td>sec/ft(^2)</td>
</tr>
<tr>
<td>1</td>
<td>1.000</td>
<td>20.000</td>
<td>&quot;</td>
</tr>
<tr>
<td>2</td>
<td>0.670</td>
<td>21.103</td>
<td>&quot;</td>
</tr>
<tr>
<td>3</td>
<td>2.000</td>
<td>22.250</td>
<td>&quot;</td>
</tr>
</tbody>
</table>
Fig. 6.15: Step - drawdown test; Rorabaugh solution for (a) Laksam well, and (b) Nabinagar well.
d) Eden and Hazel Method:

Only three step-drawdown test data sets (Devidwar, Laksam and Chandpur) qualified for analysis by the Eden and Hazel method. This method requires data from a continuous step-drawdown test (i.e. test data where the discharge rate has been changed instantaneously after each step) but it does not matter whether the incremental discharge is positive or negative.

An existing Fortran-77 computer program (Appendix 6.1) was used in a modified form to suit the requirements of the data to create the sum dQ log (T - TX) vs. drawdown plot and then best fit line was drawn through the plotted points.

1) Devidwar Well: The sum dQ log (T - TX) vs drawdown plot (Fig. 6.16) was used to draw the best fit straight line through the plotted points for each step. The value of \( \tan \Theta = b \) is the gradient of the straight line which was calculated using the following equation:

\[
\frac{dy}{dx} = \frac{30.00 - 27.60}{(0.84 - 0.09) \times 10^5} = 2.86 \times 10^5.
\]

with this 'b' value 'T' is finally calculated as follows:

\[
T = \frac{2.30}{4 \pi b} = 6399.58 \text{ ft}^2/\text{d} = 590 \text{ m}^2/\text{d}.
\]

2) Laksam Well: The plot of Figure 6.17 was used to draw the best fit straight line through the plotted points for each step and 'b' and 'T' calculated as previous to give values of \( 1 \times 10^5 \) and 1700 m\(^2\)/d, respectively.

3) Chandpur Well: The plot of Figure 6.18 was prepared to draw the best fit straight line through the plotted points for calculating the transmissivity (T) value
Fig. 6.16: Step - drawdown test; Eden and Hazel solution for Devidwar well.
Fig. 6.17: Step - drawdown test; Eden and Hazel solution for Laksam well.
Fig. 6.18: Step - drawdown test; Eden and Hazel solution for Chandpur well.
of 4140 m³/d according to Eden and Hazel method.

6.2.3 Comments on the Results:

The various parameters obtained by analyzing different step-drawdown test data with the available techniques and the value of transmissivity (T) calculated for the first step (treated as a short constant discharge rate test) along with the results of constant rate test analysis for some wells for which a step-drawdown test has also been carried out, are presented in Table 6.1 for comparison.

During the calculation of aquifer loss factor (B), well loss factor (C) and the indices 'n' (for Rorabaugh solution) the drawdown data for every steps could not be corrected other than for the Devidwar, Laksam and Chandpur wells, because of unrealistic test procedure. Straight forward drawing of the time drawdown data was also not possible. Therefore, uncorrected drawdown data were used for the other wells during their analysis by the Jacob arithmetic and Bruin & Hudson graphic solutions although very little variation in results is obtained for both the corrected and uncorrected data.

Except the Chandina (well 55) and Kotwali (well 59) all other wells data shows a negative C_3,1 values obtained by Jacob arithmetic solution. It suggested an unstable well condition i.e. the well was not properly developed with adequate pumping prior to the step-drawdown test. A positive C_3,2 values were obtained for the 'third step' of the same wells and other wells indicates that much of the well development have taken place during the test itself.

The aquifer loss factor 'B_r' ranges from a maximum of 19.30 sec/ft² for Nabinagar (well 9) to a minimum of 7.0 sec/ft² for Chandina (well 55) and the well loss factor 'C' varies from a maximum of 1.49 sec²/ft⁵ for Nabinagar well to a minimum of 0.96 sec²/ft⁵ for Laksam (well 80). Considering all the values obtained from Bruin & Hudson and Rorabaugh solutions, and ignoring the negative
<table>
<thead>
<tr>
<th>Method used</th>
<th>Calculated parameters</th>
<th>B’ Baria W. No. 6</th>
<th>Nabinagar W. No. 9</th>
<th>Devidwar W. No. 34</th>
<th>Burichong W. No. 46</th>
<th>Chandina W. No. 55</th>
<th>Kotwali W. No. 59</th>
<th>Laksam W. No. 80</th>
<th>Chandpur W. No. 91</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Jacob</strong></td>
<td>( C_{2,1} (\text{sec} / \text{ft}^2) )</td>
<td>-4.97</td>
<td>-3.44</td>
<td>-14.50</td>
<td>-10.50</td>
<td>1.43</td>
<td>4.73</td>
<td>-3.36</td>
<td>-7.17</td>
</tr>
<tr>
<td></td>
<td>( C_{3,3} (\text{sec} / \text{ft}^2) )</td>
<td>-</td>
<td>5.11</td>
<td>-</td>
<td>-</td>
<td>1.01</td>
<td>-</td>
<td>6.10</td>
<td>1.75</td>
</tr>
<tr>
<td><strong>Bruin and Hudson</strong></td>
<td>( B_{1} (\text{sec} / \text{ft}^2) )</td>
<td>17.60</td>
<td>19.30</td>
<td>45.35</td>
<td>40.40</td>
<td>7.00</td>
<td>20.13</td>
<td>16.80</td>
<td>16.50</td>
</tr>
<tr>
<td></td>
<td>( B_{2} \sigma (\text{ft}) )</td>
<td>16.68 ( q = 0.891 \text{ cfs} )</td>
<td>19.30 ( q = 1.0 \text{ cfs} )</td>
<td>24.26 ( q = 0.838 \text{ cfs} )</td>
<td>35.97 ( q = 1.37 \text{ cfs} )</td>
<td>9.59 ( q = 0.891 \text{ cfs} )</td>
<td>17.93 ( q = 1.07 \text{ cfs} )</td>
<td>17.98</td>
<td>17.66</td>
</tr>
<tr>
<td></td>
<td>( C (\text{sec} / \text{ft}^5) )</td>
<td>5.0</td>
<td>1.49</td>
<td>14.51</td>
<td>12.45</td>
<td>1.28</td>
<td>4.46</td>
<td>0.96</td>
<td>3.19</td>
</tr>
<tr>
<td></td>
<td>( C_{Q} (\text{ft}) )</td>
<td>3.97 ( q = 0.891 \text{ cfs} )</td>
<td>1.49 ( q = 1.0 \text{ cfs} )</td>
<td>4.15 ( q = 0.835 \text{ cfs} )</td>
<td>9.88 ( q = 1.37 \text{ cfs} )</td>
<td>2.40 ( q = 0.891 \text{ cfs} )</td>
<td>3.40 ( q = 1.07 \text{ cfs} )</td>
<td>3.65</td>
<td>3.65</td>
</tr>
<tr>
<td></td>
<td>( B_{3} (\text{ft}) )</td>
<td>19.65</td>
<td>20.79</td>
<td>28.41</td>
<td>45.85</td>
<td>11.99</td>
<td>21.63</td>
<td>19.08</td>
<td></td>
</tr>
<tr>
<td><strong>Rorabaugh</strong></td>
<td>( B_{4} (\text{sec} / \text{ft}^2) )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>7.00</td>
<td>-</td>
<td>-</td>
<td>11.03</td>
</tr>
<tr>
<td></td>
<td>( C (\text{sec} / \text{ft}^5) )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.25</td>
<td>-</td>
<td>-</td>
<td>1.15</td>
</tr>
<tr>
<td></td>
<td>( n (\text{Index}) )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.39</td>
<td>-</td>
<td>-</td>
<td>1.11</td>
</tr>
<tr>
<td><strong>Eden &amp; Hazel</strong></td>
<td>( \tan \theta = b )</td>
<td>-</td>
<td>-</td>
<td>2.86 ( 10^{-5} )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.03 ( 10^{-5} )</td>
<td>3.82 ( 10^{-6} )</td>
</tr>
<tr>
<td></td>
<td>( \tau (m^2/d) )</td>
<td>-</td>
<td>-</td>
<td>600</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1660</td>
<td>4460</td>
</tr>
<tr>
<td><strong>Constant test analysis of first step</strong></td>
<td>( \tau (m^2/d) )</td>
<td>-</td>
<td>-</td>
<td>7.40</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>790</td>
<td>10.20</td>
</tr>
<tr>
<td><strong>Aquifer test results</strong></td>
<td>( \tau (m^2/d) )</td>
<td>890</td>
<td>400</td>
<td>450</td>
<td>12.10</td>
<td>570</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table. 6.1: Comparison of step - drawdown test results.
results, results produced by the instable wells and the results obtained by Jacob method. The 'B,' an 'C' values do not suggest any major abnormality.

The $B = 7.0 \text{ sec/ft}^2$ (both by Rorabaugh and Bruin & Hudson method) and $C = 1.25 \text{ sec}^2/\text{ft}^4$ (Rorabaugh method) and $C = 1.28 \text{ sec}^2/\text{ft}^4$ (Bruin & Hudson method) values for Chandina well shows a remarkable similarity. The index value ($n = 2.26$) obtained by the Rorabaugh method is an excellent example which support his theory that the index value should be slightly higher than 2. This index value ($n = 2.26$) also suggested that the Chandina well was properly designed and was properly developed before the test. The unstable condition of the Chandpur (well 91) on the other hand produces a great difference in $B$ value ($11.03 \text{ sec}^2/\text{ft}^4$ by Rorabaugh method and $16.5 \text{ sec/ft}^2$ by Bruin & Hudson method) and $C$ value ($1.15 \text{ sec}^2/\text{ft}^4$ by Rorabaugh method and $3.19 \text{ sec}^2/\text{ft}^4$ by Bruin & Hudson method) and a very low index value ($n = 1.20$).

The drawdown values were calculated using the obtained 'B' and 'C' values from the Bruin & Hudson method to demonstrate the differences in the field measurements. In all cases, the calculated drawdown values were found to be higher than the measured values. The variation between the measured and calculated drawdown ranges from 0.08 (Chandina well when $Q = 1.37 \text{ cfs}$) to 6.5 percent (Laksam well when $Q = 1.07 \text{ cfs}$) which is quite low and can be regarded as reasonably acceptable.

The greatest variations were seen between the transmissivity ($T$) values (Table 6.1) obtained by the constant rate test analysis of the first step and the step-drawdown test analysis of the same well using the Eden and Hazel method for the Chandpur well. In this well the transmissivity value obtained by Eden and Hazel method is three times higher than the values obtained from the constant rate test analysis. In case of the Laksam well, the transmissivity values obtained by the former method is more than twice the value obtained by the later method. A
different picture is seen for Devidwar well where the transmissivity values obtained by both methods are very close to each other. In theory, the transmissivity values should produce very little difference by the various methods. Once again the unrealistic step-drawdown test procedure and poor prior development of wells have considerable influence on these dissimilar transmissivity values.

The non-laminar flow condition is directly proportional to the increasing pumping rate. Therefore, in the case of pumping with higher discharge rates the following two conditions should be considered to ensure good results: 1) the calculated well losses at all test rates should not exceed the sum of the incremental drawdown for the early stages of the tests and 2) the calculated formation losses should not by themselves exceed the observed drawdown. A failure to consider these conditions could in some instances lead to false but superficially plausible solutions (Lennox 1966). A search for these conditions with the present analytical results (Table 6.2) reveal that the first condition is valid with all the test results except Burichong (well 46) but the second condition is valid only with half of the test results.

6.3 Well Efficiency:

There are various ways of looking at the efficiency of well performance from both a qualitative and quantitative point of view. The construction of a Yield-Depression curve is a qualitative to semi-quantitative approach. It does not quantify the information but provides valuable information with reasonable accuracy about optimum discharge that should be used for a particular well under the prevailing aquifer condition. The most commonly used quantitative approach for presenting well efficiency is to determine a numerical parameter representing well loss and called the 'Well efficiency factor'. It is a defined as \[\frac{BQ}{BQ + CQ^2}\times100\] and is usually expressed in percent. The well efficiency factor has been
<table>
<thead>
<tr>
<th>Location</th>
<th>Incremental drawdown</th>
<th>Calculated well losses</th>
<th>First condition</th>
<th>Observed drawdown</th>
<th>Formation losses</th>
<th>Second condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>B' Baria</td>
<td>11.65 + 2.85</td>
<td>3.97 + 8.98</td>
<td>Valid</td>
<td>11.65 + 14.53</td>
<td>15.68 + 23.58</td>
<td>Not valid</td>
</tr>
<tr>
<td></td>
<td>= 14.50</td>
<td>= 12.95</td>
<td></td>
<td>= 26.18</td>
<td>= 39.26</td>
<td></td>
</tr>
<tr>
<td>Nabinagar</td>
<td>20.0 - 5.84</td>
<td>1.49 + 0.87</td>
<td>Valid</td>
<td>20.0 + 44.50</td>
<td>19.30 + 38.6</td>
<td>Valid</td>
</tr>
<tr>
<td></td>
<td>= 14.16</td>
<td>= 2.36</td>
<td></td>
<td>= 64.50</td>
<td>= 57.90</td>
<td></td>
</tr>
<tr>
<td></td>
<td>= 31.96</td>
<td>= 20.76</td>
<td></td>
<td>= 52.09</td>
<td>= 72.78</td>
<td></td>
</tr>
<tr>
<td></td>
<td>= 31.46</td>
<td>= 32.24</td>
<td></td>
<td>= 56.58</td>
<td>= 90.11</td>
<td></td>
</tr>
<tr>
<td>Chandina</td>
<td>8.00 + 3.98</td>
<td>2.40 + 4.48</td>
<td>Valid</td>
<td>11.98 + 17.53</td>
<td>9.59 + 13.09</td>
<td>Valid</td>
</tr>
<tr>
<td></td>
<td>= 11.98</td>
<td>= 6.88</td>
<td></td>
<td>= 29.51</td>
<td>= 22.68</td>
<td></td>
</tr>
<tr>
<td>Kotwali</td>
<td>21.67 + 11.32</td>
<td>3.70 + 0.99</td>
<td>Valid</td>
<td>21.67 + 10.25</td>
<td>17.93 + 9.26</td>
<td>Valid</td>
</tr>
<tr>
<td></td>
<td>= 33.09</td>
<td>= 4.69</td>
<td></td>
<td>= 31.92</td>
<td>= 27.19</td>
<td></td>
</tr>
<tr>
<td>Laksam</td>
<td>9.92 + 8.00</td>
<td>1.10 + 2.47</td>
<td>Valid</td>
<td>17.92 + 29.41</td>
<td>17.98 + 26.96</td>
<td>Valid</td>
</tr>
<tr>
<td></td>
<td>= 17.92</td>
<td>= 3.57</td>
<td></td>
<td>= 47.33</td>
<td>= 44.94</td>
<td></td>
</tr>
<tr>
<td>Chandpur</td>
<td>8.50 + 4.40</td>
<td>3.65 + 8.22</td>
<td>Valid</td>
<td>12.90 + 18.30</td>
<td>17.66 + 26.48</td>
<td>Not valid</td>
</tr>
<tr>
<td></td>
<td>= 12.90</td>
<td>= 11.87</td>
<td></td>
<td>= 31.12</td>
<td>= 44.14</td>
<td></td>
</tr>
</tbody>
</table>

Table. 6.2: Verification of Lennox (1966) conditions for obtaining good results.
calculated for all the eight step test wells and the Yield-Depression curve prepared for the **Nabinagar, Chandina, Laksam and Chandpur wells** because only they have three data points. A plot with less than 3 points would be meaningless, three points being the absolute minimum though more points are desirable because the more points allow a better interpretation.

The Yield-Depression curve is plotted on arithmetic scale which usually presents graphic information on the performance of the well. The straighter the line through the plotted points, the more 'efficient' is the well over the operating range of abstraction (Jones & Rushton, 1981). Quite frequently the line becomes curved at higher pumping rates and the degree of curvature is directly related to the relative 'inefficiency' of the pumping well. Occasionally the change in curvature is most abrupt and this has been called the 'Breakaway Point' by Ineson (1959) and indicates most clearly a rapid deterioration in performance produced by higher pumping rates. The golden rule is that the usable discharge for a pumping well should always be selected well below the breakaway point.

The Yield-Drawdown curves prepared for the present study (Fig. 6.19) suggest that the different discharge rates for all the wells are well below the 'breakaway' point and all the curves suggest that the wells are quite efficient by virtue of their comparatively straight appearance. The curves for Chandina and Chandpur are more straight than the others.

The quantitative determination of 'well efficiency factor' for all the wells are presented in Table 6.3 in a systematic manner according to the position of the wells moving from north to south. It may be seen that the efficiency value decreases with an increasing 'well loss' value, but for the present test data, low 'well loss' values were calculated for all of the wells which in turn gave high efficiency values. The lowest efficiency value ($E = 75$ percent) is obtained for Chandina well with a discharge rate $Q = 1.87$ cfs that is in fact quite high value
Fig. 6.19: Yield - drawdown plot for all sites.
<table>
<thead>
<tr>
<th>Well Name</th>
<th>Efficiency</th>
<th>Aquifer loss (BQ) (ft)</th>
<th>Drawdown $s_1$ (ft)</th>
<th>E (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B’ Baria</td>
<td>$E_1$</td>
<td>15.55</td>
<td>19.48</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>$E_2$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Nabinagar</td>
<td>$E_1$</td>
<td>19.30</td>
<td>20.79</td>
<td>93</td>
</tr>
<tr>
<td></td>
<td>$E_2$</td>
<td>38.60</td>
<td>44.56</td>
<td>87</td>
</tr>
<tr>
<td>Devidwar</td>
<td>$E_1$</td>
<td>24.26</td>
<td>28.34</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>$E_2$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Burichong</td>
<td>$E_1$</td>
<td>33.41</td>
<td>41.59</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>$E_2$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Chandina</td>
<td>$E_1$</td>
<td>9.59</td>
<td>11.99</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>$E_2$</td>
<td>13.09</td>
<td>17.57</td>
<td>75</td>
</tr>
<tr>
<td>Kotwali</td>
<td>$E_1$</td>
<td>14.93</td>
<td>21.62</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>$E_2$</td>
<td>9.26</td>
<td>10.25</td>
<td>90</td>
</tr>
<tr>
<td>Laksam</td>
<td>$E_1$</td>
<td>17.98</td>
<td>19.08</td>
<td>94</td>
</tr>
<tr>
<td></td>
<td>$E_2$</td>
<td>26.96</td>
<td>29.43</td>
<td>92</td>
</tr>
<tr>
<td>Chandpur</td>
<td>$E_1$</td>
<td>17.66</td>
<td>21.31</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>$E_2$</td>
<td>26.48</td>
<td>34.70</td>
<td>76</td>
</tr>
<tr>
<td>Range</td>
<td>$E_1$</td>
<td>9.59 to 33.41</td>
<td>11.99 to 41.59</td>
<td>80 to 94</td>
</tr>
<tr>
<td></td>
<td>$E_2$</td>
<td>9.26 to 38.60</td>
<td>10.25 to 44.56</td>
<td>75 to 92</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>20.78</td>
<td>24.67</td>
<td>84.5</td>
</tr>
</tbody>
</table>

Table 6.3: Quantitative assessment of well efficiency factor.
and should be accepted as a highly efficient well and the maximum efficiency is recorded \((E = 94\ \text{percent})\) for the Laksam well with a relatively low discharge of \(Q = 0.535\ \text{cfs}\).

Therefore on the basis of the information obtained from the 'Yield-Depression' curves and the result given by the quantitative measurement of the 'Efficiency Factor' for all the test wells, it can be said that the wells are highly efficient.

### 6.4 Specific Capacity:

Specific capacity by definition is the ratio of the pumping rate to the drawdown for a particular duration of time i.e \((Q/s)\). It is another important measure of well performance and provides valuable clues about the productivity of the constructed well. Depending on the unit of discharge and drawdown it has dimensions of either \(\text{m}^3/\text{d/m}\) or \(\text{ft}^3/\text{d/ft}\) (gal/ft ). A rearrangement of the Theis non-equilibrium equation ignoring the well loss fraction establishes the following:

\[
Q/s = \frac{(4\pi T)}{2.303 \log(2.25 T/r_w^2 S)}
\]

(6.11)

relationship between the specific capacity and other hydrogeological parameters:

1) specific capacity is directly proportional to transmissivity.
2) specific capacity is inversely proportional to the logarithm of time.
3) specific capacity is inversely proportional to the square of the well radius and
4) specific capacity is inversely proportional to the logarithm of storativity.

Because of these relationships between transmissivity and specific capacity, high specific capacities usually indicate high transmissivities and vice versa. Though specific capacity is often affected by partial penetration, well loss and hydraulic boundaries, in such situations it undervalues the transmissivity estimated from specific capacity and it provides valuable information in advance about the
ground water potential of the investigated area.

To demonstrate the direct linear relationship between specific capacity and transmissivity a theoretical plot of specific capacity obtained using the ideal equation at 100 minutes with similar well radius versus the transmissivity has been constructed on a log-log paper (Fig. 6.20). Values of actual specific capacity (see Table 6.4) at 100 and 1000 minutes have also been plotted on the same figure against the transmissivity obtained by the conventional methods for all the tested wells. The solid circles and crosses shown in Figure 6.20 are the measured specific capacity values for 100 and 1000 minutes, respectively. It may be seen that the higher and lower specific capacity values corresponds to the higher and lower values of transmissivity, respectively.

The theoretical data plot (specific capacity vs. transmissivity) constructed for the confined condition serves as a line of best fit through the points drawn for actual specific capacity versus transmissivity values. The appearance of the plot produced by the actual and theoretical data also provides evidence in favour of the direct linear relationship between specific capacity and transmissivity.
Fig. 6.20: Theoretical and actual plot of specific capacity vs. transmissivity for all tests.
<table>
<thead>
<tr>
<th>Well Location</th>
<th>( r ) (well) ( (\text{ft/m}) )</th>
<th>( Q ) ( (\text{ft}^3/\text{d}) )</th>
<th>( T ) ( (\text{m}^2/\text{d}) )</th>
<th>( s ), at 100 mins. ( (\text{ft}) )</th>
<th>( (Q/s) ) ( (\text{ft}^3/\text{d}/\text{ft}) )</th>
<th>( (Q/s) ) ( (\text{m}^3/\text{d}/\text{m}) )</th>
<th>( s ), at 1000 mins. ( (\text{ft}) )</th>
<th>( (Q/s) ) ( (\text{ft}^3/\text{d}/\text{ft}) )</th>
<th>( (Q/s) ) ( (\text{m}^3/\text{d}/\text{m}) )</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>B'baria W. No. 6</td>
<td>0.33</td>
<td>76997.60</td>
<td>890.0</td>
<td>11.82</td>
<td>6514.2</td>
<td>605.2</td>
<td>13.50</td>
<td>5703.5</td>
<td>529.9</td>
<td>12.45</td>
</tr>
<tr>
<td>Nabinagar W. No. 9</td>
<td>0.25</td>
<td>86400.00</td>
<td>400.0</td>
<td>21.33</td>
<td>4050.6</td>
<td>376.3</td>
<td>24.92</td>
<td>3467.1</td>
<td>322.1</td>
<td>14.41</td>
</tr>
<tr>
<td>Devidwar W. No. 34</td>
<td>0.076</td>
<td>46224.00</td>
<td>740.0</td>
<td>19.89</td>
<td>2324.0</td>
<td>215.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Daudkandi W. No. 43</td>
<td>11</td>
<td>172785.44</td>
<td>1190.0</td>
<td>28.50</td>
<td>6062.7</td>
<td>563.2</td>
<td>29.42</td>
<td>5873.1</td>
<td>545.6</td>
<td>3.13</td>
</tr>
<tr>
<td>Burichong W. No. 46</td>
<td>11</td>
<td>76962.28</td>
<td>450.0</td>
<td>24.10</td>
<td>3193.5</td>
<td>296.7</td>
<td>25.75</td>
<td>2988.8</td>
<td>277.6</td>
<td>6.42</td>
</tr>
<tr>
<td>Chandina W. No. 55</td>
<td>11</td>
<td>84662.0</td>
<td>1210.0</td>
<td>8.46</td>
<td>10007.3</td>
<td>929.7</td>
<td>9.17</td>
<td>9232.5</td>
<td>857.7</td>
<td>7.74</td>
</tr>
<tr>
<td>Kotwali W. No. 59</td>
<td>11</td>
<td>76982.40</td>
<td>570.0</td>
<td>20.21</td>
<td>3809.1</td>
<td>353.9</td>
<td>21.75</td>
<td>3539.4</td>
<td>328.8</td>
<td>7.08</td>
</tr>
<tr>
<td>Barura W. No. 69</td>
<td>11</td>
<td>1280.0</td>
<td>12.42</td>
<td>6198.3</td>
<td>575.8</td>
<td>13.04</td>
<td>5903.6</td>
<td>548.9</td>
<td>4.68</td>
<td></td>
</tr>
<tr>
<td>Laksam W. No. 80</td>
<td>11</td>
<td>46224.00</td>
<td>790.0</td>
<td>9.91</td>
<td>4664.4</td>
<td>433.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Haziganj W. No. 82</td>
<td>11</td>
<td>180273.60</td>
<td>1490.0</td>
<td>25.83</td>
<td>6979.2</td>
<td>648.4</td>
<td>27.11</td>
<td>6635.0</td>
<td>616.4</td>
<td>4.93</td>
</tr>
<tr>
<td>Chandpur W. No. 91</td>
<td>11</td>
<td>46224.00</td>
<td>1020.0</td>
<td>8.64</td>
<td>5350.0</td>
<td>497.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Chaudogram W. No. 101</td>
<td>11</td>
<td>86604.64</td>
<td>390.0</td>
<td>23.79</td>
<td>3640.4</td>
<td>338.2</td>
<td>29.17</td>
<td>2968.9</td>
<td>275.8</td>
<td>18.44</td>
</tr>
<tr>
<td>Feni W. No. 117</td>
<td>11</td>
<td>1615.68</td>
<td>1000.0</td>
<td>25.66</td>
<td>6296.0</td>
<td>584.9</td>
<td>28.11</td>
<td>5747.2</td>
<td>533.9</td>
<td>8.72</td>
</tr>
<tr>
<td>Senbagh W. No. 130</td>
<td>0.33</td>
<td>86604.64</td>
<td>770.0</td>
<td>22.95</td>
<td>3773.6</td>
<td>350.6</td>
<td>24.09</td>
<td>3596.5</td>
<td>334.1</td>
<td>4.69</td>
</tr>
</tbody>
</table>

Table 6.4: Specific capacity data at 100 minutes and 1000 minutes for all the pumping wells.
7.1 Collation of Existing Chemical Analytical Data.

7.2 Field Collection of Ground Water Samples.

7.3 Chemical Analysis of Ground Water Samples.

7.4 Quality of Analytical Data.

7.5 Graphical Hydrochemical Interpretation.
   7.5.1 Distribution Maps.
      a) Introduction.
      b) TDS Distribution Map.
      c) Sodium/Σ Cation Ratios.

   7.5.2 Stiff Pattern Diagram.

   7.5.3 Trilinear Diagram.

   7.5.4 Chemistry Along Flow Lines.

   7.5.5 Expanded Durov Classification.

7.6 Application of PHREEQE Hydrochemical Model.
   7.6.1 Introduction.

   7.6.2 PHREEQE Model.

7.7 Ground Water Quality.
   7.7.1 Drinking Water Quality.

   7.7.2 Irrigation Water Quality.
7.1 Collation of existing ground water samples:

The first series of chemical analysis of ground water samples was carried out by the UNDP for selected wells in the northern part of the study area (greater Comilla district). During the four-year period (March, 1976 to June, 1979) UNDP analyzed water samples from 20 wells. Its aim was to repeat the analysis of ground water samples from the same location several times in order to identify any major changes in the quality of the ground water.

The national organization for water management and development in Bangladesh (BWDB) started its systematic analysis of ground water for selected locations in October, 1979. The sample locations are mainly situated in major metropolitan city areas and in important small towns. 18 BWDB wells are relevant to the present project for which they have carried out routine chemical analysis on ground water samples. For some of the wells, the analyses were done in 1979 and for others the analyses were carried out in 1990 with some of the wells being sampled on both occasions.

The Bangladesh Agricultural Development Corporation (BADC) has also analyzed ground water samples from 23 of their irrigation wells scattered all over the study area. Since their aim was to examine the concentration of certain ions, they carried out only partial analysis. Because of the lack of information on the other major constituents these analytical results were excluded from any further interpretation.

Although UNDP and BWDB have undertaken their independent analysis on ground water samples from 20 and 18 different locations, respectively; in reality they have covered 33 locations because 5 locations were duplicated.
7.2 Field collection of ground water samples:

After a careful evaluation of the distribution of the UNDP and BWDB sampling locations it became evident that the southern part of the project area had a serious shortage of ground water quality information. It had complete chemical analyses for only four locations (wells 99, 122, 141 and 144) (Fig. 7.1) which are quite inadequate for the interpretation and evaluation of the hydrochemical behaviour of the ground water in the southern part.

To overcome this inadequacy a field visit was made by the author during February and March, 1988 to collect ground water samples from pre-selected locations. A total of 16 samples were collected from 15 locations most of them being from the southern part. Two water samples were collected from two different depths of well 136. Standard procedures used by the UNDP and BWDB were followed during the collection of water samples. The manner of preserving the samples varies from constituent to constituent to obtain better analytical results. Therefore to ensure better results the water samples were preserved in three ways:

1: The samples were filtered using no. 5 filter paper having a pore size of 2.5 micron and then acidified with concentrated HCl having a ratio of 1 ml HCl in 100 ml of sample. This type of preservation is needed for Mn, Fe and SiO₂.

2: Samples needing only to be filtered for good analytical results of Ca, Mg, (TDS).

3: To avoid any alteration in NO₃ and PO₄ concentrations during the period between collection and analysis, after filtering HgCl₂ is added at a recommended ratio of 1ml HgCl₂ (solution strength 2 percent) in 1 litre of sample (pers. comm. Dr. McArthur).

Although normally it is recommended that pH, EC, CO₃ and HCO₃ should be analyzed in the field because of inadequate facilities only pH was
FIG. 7-1: MAP SHOWING THE QUALITY WELL LOCATIONS
measured in the field. All the samples were stored in air tight plastic bottles.

7.3 Chemical analysis of ground water samples:

The samples were brought to U.K. from the field and analyzed at the geochemical laboratory in the department. Analyses of TDS, pH, SiO₂, Ca, Mg, Na, K, Fe, Mn, CO₃, HCO₃, SO₄, Cl, NO₃, PO₄, F, EC were done to make a complete analysis. The analysis was made by the author assisted when necessary by the laboratory technician Mr. A. T. Osborn. Spectrophotometric, titrimetric, turbidimetric, ion selective electrodes and simple drying methods were selected to cover the whole range of analysis. Standard procedures similar to those described in the ASTM Methods Manual (1978) were followed fairly closely for all these methods in order to obtain as high an accuracy as possible for the analytical results.

The following is a list of the constituents along with the method used to analyse them:

Atomic Absorption Spectrophotometry: for Mg, Mn and Fe.

Titrimetry: for Ca, Cl, CO₃ and HCO₃.

Turbidimetry: for SO₄.

Conductivity meter: for EC.

Flame Photometry: for Na and K.

Ion selective electrode: for F.

Spectrophotometric analysis by U.V. visible photometry: for SiO₂, NO₃ and PO₄.

Total dissolved solids (TDS) concentration was measured as residue on evaporation at 80° C.

Eventually complete chemical analyses of 48 ground water samples were considered for the present hydrochemical interpretation (Fig. 7.1). These are the maximum number of analytical results of ground water samples available.
data are summarized in Table 7.1 and the **ionic-balance and comparison of TDS** are presented in Table 7.1(a).

### 7.4 Quality of analytical data:

It is mentioned in Section 7.1 that the majority of the ground water samples were analyzed by various local and international organizations at different times during the preparation of hydrogeological reports. Although all these reports are published yet the quality of these chemical data were checked again. The criteria of **ionic-balance and comparison of TDS** (TDS obtained by residue on evaporation and the calculated TDS), were adopted in order to check the validity of the analytical data so that most erroneous data can be identified and excluded from any further geochemical interpretation.

The following empirical formula was used to calculate the ionic-balance (Table 7.1(a)) as percentage differences:

\[
\frac{((\Sigma \text{cation} - \Sigma \text{anion})/(\Sigma \text{cation} + \Sigma \text{anion})) \times 100.}
\]

Excellent ionic-balance (error $\leq \pm 5$ percent) is obtained for 25 samples which constitute about 41 percent of all the samples. Acceptable ionic-balance (error $\leq \pm 10$ percent) is obtained for another 22 samples (constitute about 36.1 percent). Together they constitute about 77.1 percent. The hydrochemical data of 10 samples (16.4 percent) (W18(b), W20, W27, W32(a), W75(b), W88(a), W89(a), W95, W122(b) and W141) provided very high percentage differences (error between $\pm 10$ to $\pm 15$ percent) but in another 4 samples (6.5 percent) (W13(a), W13(b), W51(b) and W54) the percentage differences (error $> \pm 15$ percent) obtained were unacceptably high. These suggests that any interpretation of geochemical properties based on these data, particularly the later wells, could be potentially erroneous and misleading.
<table>
<thead>
<tr>
<th>Well No.</th>
<th>Location</th>
<th>Date</th>
<th>Depth (ft)</th>
<th>Analysis by</th>
<th>pH</th>
<th>SiO₂ mg/L</th>
<th>Ca mg/L</th>
<th>Mg mg/L</th>
<th>Na mg/L</th>
<th>K mg/L</th>
<th>Fe mg/L</th>
<th>Mn mg/L</th>
<th>CO₃ mg/L</th>
<th>HCO₃ mg/L</th>
<th>SO₄ mg/L</th>
<th>Cl mg/L</th>
<th>NO₃ mg/L</th>
<th>PO₄ mg/L</th>
<th>F mg/L</th>
<th>EC mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Nasimagar, Khandra</td>
<td>15.4.87</td>
<td>N/A</td>
<td>Author</td>
<td>7.50</td>
<td>55.8</td>
<td>17.7</td>
<td>10.5</td>
<td>20.0</td>
<td>26.0</td>
<td>1.80</td>
<td>0.25</td>
<td>Nil</td>
<td>124.4</td>
<td>25.8</td>
<td>1.00</td>
<td>0.72</td>
<td>0.11</td>
<td>440</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Nasimagar, Kunda</td>
<td>5.6.79</td>
<td>150</td>
<td>UNDP</td>
<td>10.00</td>
<td>35.5</td>
<td>26.0</td>
<td>20.0</td>
<td>105.4</td>
<td>N/A</td>
<td>2.10</td>
<td>N/A</td>
<td>46.0</td>
<td>155.0</td>
<td>9.0</td>
<td>98.0</td>
<td>10.0</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Kalikachha, Sarail</td>
<td>14.3.77</td>
<td>302</td>
<td>UNDP</td>
<td>8.35</td>
<td>30.0</td>
<td>6.00</td>
<td>29.2</td>
<td>18.70</td>
<td>N/A</td>
<td>0.65</td>
<td>N/A</td>
<td>6.0</td>
<td>109.8</td>
<td>2.5</td>
<td>34.0</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Jalalpur, B'Baria</td>
<td>11.2.78</td>
<td>306</td>
<td>UNDP</td>
<td>7.50</td>
<td>30.0</td>
<td>12.5</td>
<td>6.70</td>
<td>207.6</td>
<td>N/A</td>
<td>5.00</td>
<td>N/A</td>
<td>Nil</td>
<td>157.0</td>
<td>25.1</td>
<td>217.0</td>
<td>Trace</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Railway station, Akhaura</td>
<td>23.10.79</td>
<td>106</td>
<td>GWC</td>
<td>7.50</td>
<td>43.0</td>
<td>12.5</td>
<td>3.40</td>
<td>56.20</td>
<td>N/A</td>
<td>4.60</td>
<td>N/A</td>
<td>Nil</td>
<td>98.0</td>
<td>11.0</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Railway station, Akhaura</td>
<td>13.10.80</td>
<td>78</td>
<td>GWC</td>
<td>7.50</td>
<td>29.0</td>
<td>11.5</td>
<td>4.90</td>
<td>44.00</td>
<td>N/A</td>
<td>9.00</td>
<td>N/A</td>
<td>Nil</td>
<td>96.0</td>
<td>12.5</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Akhaura town, Akhaura</td>
<td>28.3.77</td>
<td>106</td>
<td>UNDP</td>
<td>9.00</td>
<td>37.0</td>
<td>11.5</td>
<td>7.60</td>
<td>30.7</td>
<td>N/A</td>
<td>6.50</td>
<td>N/A</td>
<td>4.0</td>
<td>99.0</td>
<td>7.9</td>
<td>19.5</td>
<td>20.5</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Nabinagar town, Nabinagar</td>
<td>30.1.78</td>
<td>146</td>
<td>UNDP</td>
<td>7.00</td>
<td>31.8</td>
<td>9.50</td>
<td>18.3</td>
<td>73.2</td>
<td>N/A</td>
<td>3.40</td>
<td>N/A</td>
<td>Nil</td>
<td>212.0</td>
<td>22.5</td>
<td>11.0</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Nabinagar town, Nabinagar</td>
<td>18.4.79</td>
<td>146</td>
<td>UNDP</td>
<td>8.50</td>
<td>31.3</td>
<td>23.5</td>
<td>20.1</td>
<td>58.9</td>
<td>N/A</td>
<td>0.50</td>
<td>N/A</td>
<td>6.0</td>
<td>106.0</td>
<td>86.0</td>
<td>2.00</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Banchharampur, Muradnagar</td>
<td>6.11.77</td>
<td>282</td>
<td>UNDP</td>
<td>8.00</td>
<td>26.2</td>
<td>48.5</td>
<td>17.1</td>
<td>37.6</td>
<td>N/A</td>
<td>8.00</td>
<td>N/A</td>
<td>32.0</td>
<td>176.0</td>
<td>23.0</td>
<td>2.50</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Kasha town, Kasha</td>
<td>9.5.80</td>
<td>90</td>
<td>GWC</td>
<td>7.00</td>
<td>23.8</td>
<td>68.0</td>
<td>43.0</td>
<td>83.4</td>
<td>N/A</td>
<td>1.30</td>
<td>N/A</td>
<td>Nil</td>
<td>292.0</td>
<td>46.1</td>
<td>64.0</td>
<td>Nil</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Muradnagar, Bhangra</td>
<td>15.4.87</td>
<td>250</td>
<td>Author</td>
<td>8.50</td>
<td>36.0</td>
<td>22.1</td>
<td>15.2</td>
<td>91.0</td>
<td>60.5</td>
<td>0.80</td>
<td>0.04</td>
<td>Nil</td>
<td>292.1</td>
<td>13.6</td>
<td>71.0</td>
<td>2.6</td>
<td>9.26</td>
<td>0.24</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Homna town, Homna</td>
<td>16.11.77</td>
<td>302</td>
<td>UNDP</td>
<td>8.50</td>
<td>20.8</td>
<td>23.0</td>
<td>8.20</td>
<td>32.5</td>
<td>N/A</td>
<td>2.7</td>
<td>N/A</td>
<td>Nil</td>
<td>135.0</td>
<td>12.0</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Muradnagar town, Mudnagar</td>
<td>24.11.77</td>
<td>352</td>
<td>UNDP</td>
<td>N/A</td>
<td>29.0</td>
<td>23.0</td>
<td>48.2</td>
<td>114.8</td>
<td>N/A</td>
<td>Nil</td>
<td>N/A</td>
<td>Nil</td>
<td>415.0</td>
<td>47.5</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Muradnagar town, Muradnagar</td>
<td>4.11.80</td>
<td>138</td>
<td>GWC</td>
<td>8.50</td>
<td>25.3</td>
<td>27.5</td>
<td>2.40</td>
<td>87.40</td>
<td>N/A</td>
<td>4.3</td>
<td>Nil</td>
<td>Nil</td>
<td>220.0</td>
<td>33.0</td>
<td>50.0</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Chhota Alampur, Devidwar</td>
<td>29.3.80</td>
<td>402</td>
<td>GWC</td>
<td>7.5</td>
<td>41.5</td>
<td>56.5</td>
<td>3.00</td>
<td>148.5</td>
<td>N/A</td>
<td>4.1</td>
<td>0.10</td>
<td>N/A</td>
<td>180.0</td>
<td>11.0</td>
<td>198.8</td>
<td>Nil</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Brahmanpara, Shabababad</td>
<td>15.14.87</td>
<td>268</td>
<td>Author</td>
<td>?</td>
<td>57.4</td>
<td>11.1</td>
<td>5.60</td>
<td>65.50</td>
<td>16.8</td>
<td>0.50</td>
<td>0.20</td>
<td>Nil</td>
<td>222.0</td>
<td>13.2</td>
<td>16.0</td>
<td>46.1</td>
<td>2.98</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Daudkandi, town</td>
<td>6.3.76</td>
<td>106</td>
<td>UNDP</td>
<td>8.1</td>
<td>32.0</td>
<td>54.0</td>
<td>31.0</td>
<td>48.0</td>
<td>N/A</td>
<td>0.05</td>
<td>N/A</td>
<td>Nil</td>
<td>334.0</td>
<td>52.0</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Daudkandi, town</td>
<td>26.2.78</td>
<td>106</td>
<td>UNDP</td>
<td>8.6</td>
<td>21.0</td>
<td>55.0</td>
<td>34.8</td>
<td>57.3</td>
<td>N/A</td>
<td>0.20</td>
<td>N/A</td>
<td>37.8</td>
<td>320.0</td>
<td>88.5</td>
<td>2.0</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Daudkandi, Daudkandi</td>
<td>12.1.79</td>
<td>342</td>
<td>UNDP</td>
<td>8.0</td>
<td>25.3</td>
<td>25.5</td>
<td>11.3</td>
<td>80.1</td>
<td>N/A</td>
<td>4.5</td>
<td>Nil</td>
<td>180.0</td>
<td>67.5</td>
<td>10.0</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Chandina, Chandina</td>
<td>11.5.80</td>
<td>70</td>
<td>GWC</td>
<td>6.5</td>
<td>27.2</td>
<td>54.0</td>
<td>39.7</td>
<td>66.9</td>
<td>N/A</td>
<td>9.6</td>
<td>Nil</td>
<td>Nil</td>
<td>79.0</td>
<td>238.0</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Comilla town, Kotwali</td>
<td>19.3.76</td>
<td>106</td>
<td>UNDP</td>
<td>7.9</td>
<td>41.0</td>
<td>13.0</td>
<td>8.00</td>
<td>27.0</td>
<td>N/A</td>
<td>1.00</td>
<td>N/A</td>
<td>Nil</td>
<td>144.0</td>
<td>5.00</td>
<td>2.00</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7.1: Results of chemical analysis of ground water in the Comilla-Noakhali region (1976 - 1987).
| Well No. | Location                  | Date       | Depth (ft) | Analysis pH | SiO₂ | Ca mg/L | Mg mg/L | Na mg/L | K mg/L | Fe mg/L | Mn mg/L | CO₃ mg/L | HCO₃ mg/L | SO₄ mg/L | Cl mg/L | NO₃ mg/L | PO₄ mg/L | P mg/L | EC mg/L |
|---------|---------------------------|------------|------------|-------------|------|---------|---------|---------|--------|---------|---------|---------|---------|---------|---------|---------|-------|--------|
| 51(b)   | Cornilla town, Kotwal    | 28.1.78    | 106        | UNDP 8.0    | 35.5 | 15.0   | 7.60   | 45.8    | N/A    | 1.30    | N/A     | Nil     | 120.0   | N/A     | 8.0     | N/A     | N/A | N/A |
| 54      | Cornilla (Saktola), Cornilla | 28.3.79    | 106        | UNDP 9.0    | 31.8 | 12.5   | 10.7   | 43.7    | N/A    | 9.5     | N/A     | Nil     | 134.0   | N/A     | 11.0    | Trace   | N/A | N/A |
| 56(a)   | Cornilla Town, Kotwal    | 5.5.80     | 106        | GWC 7.9     | 15.0 | 10.4   | 5.3    | 43.7    | N/A    | 7.24    | N/A     | Nil     | 136.6   | N/A     | 7.00    | 0.04    | N/A | N/A |
| 56(b)   | Cornilla Town, Kotwal    | 6.10.80    | 106        | GWC 6.5     | 35.0 | 13.5   | 7.30   | 63.4    | N/A    | 1.90    | N/A     | Nil     | 145.0   | 10.0    | 37.5    | Trace   | N/A | N/A |
| 60      | Cornolla Town, Kotwal    | 28.11.80   | 320        | GWC 8.0     | 54.0 | 16.0   | 7.30   | 60.0    | N/A    | Nil     | N/A     | Nil     | 122.0   | 5.00    | 39.0    | 8.00    | N/A | N/A |
| 70      | Uttar Silmuri, Barura    | 15.4.87    | 120        | Author 8.6  | 25.9 | 27.8   | 32.9   | 21.9    | 80.0   | 2.80    | 0.29    | Nil     | 283.5   | 30.0    | 24.0    | 16.1   | 1.19 | 0.19 |
| 73      | Kachua Bazar, Kachua     | 9.4.77     | 302        | UNDP 8.7    | 41.0 | 24.0   | 47.1   | 37.0    | N/A    | 0.24    | N/A     | 24.0    | 246.4   | 15.0    | 48.4    | N/A     | N/A | N/A |
| 75(a)   | Matlab Bazar, Matlab     | 20.5.78    | 390        | UNDP 8.3    | 21.5 | 62.5   | 18.6   | 33.8    | N/A    | 2.5     | N/A     | Nil     | N/A     | 15.5    | 3.5     | N/A     | N/A | N/A |
| 75(b)   | Matlab Bazar, Matlab     | 10.11.80   | 302        | GWC 8.7     | 23.0 | 21.5   | 43.6   | 50.2    | N/A    | N/A     | N/A     | Nil     | 201.0   | N/A     | 60.5    | 3.00    | N/A | N/A |
| 79      | Chaudagram, Kalikapur    | 15.4.87    | 362        | Author N/A  | 64.9 | 16.6   | 4.10   | 16.4    | 22.4   | 1.7     | 0.22    | Trace   | 132.7   | 21.8    | 0.80    | 12.0   | 0.90 | 0.15 |
| 85      | Chandpur, Ashikari       | 30.12.79   | 340        | GWC 7.0     | 34.8 | 28.5   | 18.0   | 88.2    | N/A    | 7.30    | N/A     | Nil     | 128.0   | N/A     | 170.5   | Nil     | N/A | N/A |
| 87(a)   | Railway station, Laksam  | 21.10.79   | 74         | GWC 9.0     | 23.0 | 11.0   | 22.6   | 60.2    | N/A    | 3.00    | N/A     | Nil     | 202.0   | N/A     | 34.0    | Trace   | N/A | N/A |
| 87(b)   | Railway station, Laksam  | 6.10.80    | 74         | GWC 9.5     | 23.0 | 13.5   | 21.4   | 44.2    | N/A    | 0.30    | N/A     | Nil     | 203.0   | N/A     | 9.50    | 7.0    | N/A | N/A |
| 88(a)   | Haziganj town, Haziganj  | 11.2.77    | 350        | UNDP 9.0    | 29.5 | 23.5   | 12.8   | 14.4    | N/A    | 0.4     | N/A     | 8.0     | 104.0   | 17.0    | 5.0     | 3.0    | N/A | N/A |
| 88(b)   | Haziganj town, Haziganj  | 15.4.79    | 350        | UNDP 10.0   | 32.3 | 7.50   | 10.4   | 46.0    | N/A    | 0.20    | N/A     | 28.0    | 140.0   | N/A     | 27.5    | 12.0   | N/A | N/A |
| 89(a)   | Laksam town, Laksam     | 18.2.77    | 74         | UNDP N/A    | 20.9 | 20.0   | 14.0   | 15.3    | N/A    | 2.10    | N/A     | Nil     | 115.0   | N/A     | 8.5     | 1.50    | N/A | N/A |
| 89(b)   | Laksam town, Laksam     | 27.1.79    | 74         | UNDP 7.0    | 19.0 | 12.5   | 19.8   | 39.5    | N/A    | Trace   | N/A     | Nil     | 187.0   | N/A     | 10.0    | 1.00    | N/A | N/A |
| 93(a)   | Sholaghfar, Chaudpur     | 29.1.78    | 750        | UNDP 8.0    | 32.2 | 44.0   | 17.4   | 89.7    | N/A    | 3.9     | N/A     | Trace   | 152.0   | N/A     | 130.0   | Trace   | N/A | N/A |
| 93(b)   | Sholaghfar, Chaudpur     | 14.4.79    | 750        | UNDP 9.5    | 22.0 | 61.5   | 41.5   | 92.4    | N/A    | 3.90    | N/A     | 18.0    | 430.0   | 12.1    | 76.0    | 12.0   | N/A | N/A |
| 95      | Shahrusti, Nawara        | 9.4.79     | 391        | UNDP N/A    | 37.3 | 24.0   | 10.7   | 94.4    | N/A    | 3.8     | N/A     | 10.0    | 146.0   | N/A     | 79.0    | Nil     | N/A | N/A |
| 96      | Daulatganj, Nangalkot   | 28.4.77    | 302        | UNDP 8.45   | 53.0 | 22.4   | 39.4   | 120.0   | N/A    | 0.26    | N/A     | 12.0    | 310.0   | 12.5    | 100.0   | 8.0    | N/A | N/A |
| 99      | Parshuram, Kolapara     | 27.11.79   | 230        | GWC 9.5     | 32.8 | 20.5   | 6.70   | 47.70   | N/A    | 2.5     | N/A     | Nil     | 105.0   | 6.0     | 58.5    | 4.0    | N/A | N/A |
| 106     | Faridganj town, BWDB     | 15.4.87    | 600        | Author 8.0  | 55.6 | 28.5   | 17.1   | 33.5    | 48.9   | 0.40    | 0.04    | Nil     | 258.6   | 12.6    | 6.0     | 14.3   | 0.97 | 0.12 |

Table 7.1: (continued)
<table>
<thead>
<tr>
<th>Well No.</th>
<th>Location</th>
<th>Date</th>
<th>Depth (ft)</th>
<th>Analysis pH</th>
<th>SiO₂ (mg/L)</th>
<th>Ca (mg/L)</th>
<th>Mg (mg/L)</th>
<th>Na (mg/L)</th>
<th>K (mg/L)</th>
<th>Fe (mg/L)</th>
<th>Mn (mg/L)</th>
<th>CO₃ (mg/L)</th>
<th>HCO₃ (mg/L)</th>
<th>SO₄ (mg/L)</th>
<th>Cl (mg/L)</th>
<th>NO₃ (mg/L)</th>
<th>PO₄ (mg/L)</th>
<th>F (mg/L)</th>
<th>EC (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>107</td>
<td>Mohamaya, Haimchar</td>
<td>12.5.79</td>
<td>350</td>
<td>UNDP 10.0</td>
<td>34.0</td>
<td>37.0</td>
<td>51.2</td>
<td>153.2</td>
<td>N/A</td>
<td>7.8</td>
<td>N/A</td>
<td>N/A</td>
<td>100.0</td>
<td>N/A</td>
<td>317.0</td>
<td>0.2</td>
<td>N/A</td>
<td>N/A</td>
<td>850</td>
</tr>
<tr>
<td>112</td>
<td>Romapur, Chathkhill</td>
<td>15.4.87</td>
<td>N/A</td>
<td>Author N/A</td>
<td>31.8</td>
<td>21.7</td>
<td>30.9</td>
<td>45.5</td>
<td>92.6</td>
<td>0.30</td>
<td>0.22</td>
<td>Nil</td>
<td>301.3</td>
<td>14.0</td>
<td>29.0</td>
<td>48.8</td>
<td>2.73</td>
<td>0.17</td>
<td>540</td>
</tr>
<tr>
<td>113</td>
<td>Haimchar, Chandpur</td>
<td>27.11.79</td>
<td>270</td>
<td>GWC N/A</td>
<td>23.8</td>
<td>22.5</td>
<td>43.6</td>
<td>39.9</td>
<td>N/A</td>
<td>2.20</td>
<td>N/A</td>
<td>Nil</td>
<td>240.0</td>
<td>10.0</td>
<td>54.0</td>
<td>0.50</td>
<td>0.97</td>
<td>0.13</td>
<td>540</td>
</tr>
<tr>
<td>114</td>
<td>Ramganj town, Ramganj</td>
<td>16.4.87</td>
<td>700</td>
<td>Author N/A</td>
<td>74.1</td>
<td>34.2</td>
<td>19.5</td>
<td>21.0</td>
<td>54.0</td>
<td>0.71</td>
<td>0.07</td>
<td>Nil</td>
<td>200.8</td>
<td>11.4</td>
<td>49.0</td>
<td>18.2</td>
<td>0.97</td>
<td>0.13</td>
<td>540</td>
</tr>
<tr>
<td>120</td>
<td>Sonaikuri, Laksam</td>
<td>16.4.87</td>
<td>120</td>
<td>Author N/A</td>
<td>28.1</td>
<td>16.6</td>
<td>35.0</td>
<td>400.0</td>
<td>21.0</td>
<td>0.50</td>
<td>0.11</td>
<td>Nil</td>
<td>294.0</td>
<td>16.4</td>
<td>562.0</td>
<td>28.4</td>
<td>1.69</td>
<td>0.53</td>
<td>1920</td>
</tr>
<tr>
<td>122(a)</td>
<td>Feni town, Feni</td>
<td>10.10.74</td>
<td>44</td>
<td>GWC 7.5</td>
<td>29.0</td>
<td>20.5</td>
<td>21.4</td>
<td>4.60</td>
<td>N/A</td>
<td>3.00</td>
<td>N/A</td>
<td>N/A</td>
<td>201.0</td>
<td>N/A</td>
<td>12.0</td>
<td>Nil</td>
<td>N/A</td>
<td>N/A</td>
<td>850</td>
</tr>
<tr>
<td>122(b)</td>
<td>Feni town, Feni</td>
<td>6.5.80</td>
<td>44</td>
<td>GWC 8.0</td>
<td>35.0</td>
<td>23.2</td>
<td>25.3</td>
<td>9.30</td>
<td>N/A</td>
<td>7.4</td>
<td>0.5</td>
<td>Nil</td>
<td>217.2</td>
<td>35.0</td>
<td>14.0</td>
<td>0.10</td>
<td>N/A</td>
<td>N/A</td>
<td>850</td>
</tr>
<tr>
<td>123</td>
<td>Chhagamal, Jaypur</td>
<td>16.4.87</td>
<td>N/A</td>
<td>Author N/A</td>
<td>19.9</td>
<td>9.6</td>
<td>3.60</td>
<td>13.7</td>
<td>33.9</td>
<td>7.6</td>
<td>0.79</td>
<td>Nil</td>
<td>59.0</td>
<td>15.6</td>
<td>13.0</td>
<td>27.9</td>
<td>0.87</td>
<td>&lt;0.1</td>
<td>205</td>
</tr>
<tr>
<td>128</td>
<td>Senbagh health complex, Senbagh</td>
<td>16.4.87</td>
<td>2600</td>
<td>Author N/A</td>
<td>40.9</td>
<td>38.7</td>
<td>21.7</td>
<td>128.0</td>
<td>24.5</td>
<td>0.30</td>
<td>0.06</td>
<td>Nil</td>
<td>205.5</td>
<td>15.0</td>
<td>133.0</td>
<td>42.5</td>
<td>1.15</td>
<td>0.20</td>
<td>854</td>
</tr>
<tr>
<td>131</td>
<td>Laksmipur town, DHIE well</td>
<td>16.4.87</td>
<td>N/A</td>
<td>Author N/A</td>
<td>38.8</td>
<td>53.6</td>
<td>32.7</td>
<td>95.0</td>
<td>15.0</td>
<td>0.60</td>
<td>0.08</td>
<td>Nil</td>
<td>194.0</td>
<td>12.8</td>
<td>218.0</td>
<td>32.6</td>
<td>1.26</td>
<td>0.11</td>
<td>977</td>
</tr>
<tr>
<td>136(a)</td>
<td>BADC well, Majdey</td>
<td>16.4.87</td>
<td>52</td>
<td>Author N/A</td>
<td>29.3</td>
<td>54.2</td>
<td>118.8</td>
<td>1366.0</td>
<td>38.5</td>
<td>0.20</td>
<td>0.34</td>
<td>Nil</td>
<td>758.4</td>
<td>23.2</td>
<td>2150.0</td>
<td>50.1</td>
<td>5.10</td>
<td>0.23</td>
<td>5800</td>
</tr>
<tr>
<td>136(b)</td>
<td>PWD well, Majdey</td>
<td>16.5.87</td>
<td>&gt;1200</td>
<td>Author N/A</td>
<td>62.6</td>
<td>18.2</td>
<td>18.8</td>
<td>146.0</td>
<td>28.0</td>
<td>0.30</td>
<td>0.18</td>
<td>Nil</td>
<td>398.5</td>
<td>17.0</td>
<td>63.2</td>
<td>51.9</td>
<td>13.2</td>
<td>0.28</td>
<td>720</td>
</tr>
<tr>
<td>139</td>
<td>Saudagarhat, Sonagazi</td>
<td>16.4.87</td>
<td>800</td>
<td>Author N/A</td>
<td>36.2</td>
<td>19.0</td>
<td>10.5</td>
<td>39.0</td>
<td>41.6</td>
<td>0.50</td>
<td>0.05</td>
<td>Nil</td>
<td>237.2</td>
<td>13.2</td>
<td>3.00</td>
<td>33.5</td>
<td>1.48</td>
<td>0.15</td>
<td>465</td>
</tr>
<tr>
<td>141</td>
<td>Companiganj, Char kakra</td>
<td>5.7.79</td>
<td>800</td>
<td>GWC 9.0</td>
<td>28.0</td>
<td>21.5</td>
<td>54.0</td>
<td>46.2</td>
<td>N/A</td>
<td>1.3</td>
<td>N/A</td>
<td>36.0</td>
<td>303.0</td>
<td>N/A</td>
<td>16.0</td>
<td>Nil</td>
<td>N/A</td>
<td>N/A</td>
<td>850</td>
</tr>
<tr>
<td>144(a)</td>
<td>Noakhali town, Sonapur</td>
<td>20.10.79</td>
<td>36</td>
<td>GWC 9.0</td>
<td>28.0</td>
<td>17.0</td>
<td>25.0</td>
<td>179.0</td>
<td>N/A</td>
<td>1.90</td>
<td>N/A</td>
<td>Nil</td>
<td>474.0</td>
<td>N/A</td>
<td>71.5</td>
<td>5.0</td>
<td>N/A</td>
<td>N/A</td>
<td>850</td>
</tr>
<tr>
<td>144(b)</td>
<td>Noakhali town, Sonapur</td>
<td>4.11.80</td>
<td>28</td>
<td>GWC 8.5</td>
<td>17.0</td>
<td>13.0</td>
<td>15.3</td>
<td>198.1</td>
<td>N/A</td>
<td>0.80</td>
<td>N/A</td>
<td>Nil</td>
<td>532.0</td>
<td>N/A</td>
<td>44.0</td>
<td>3.0</td>
<td>N/A</td>
<td>N/A</td>
<td>850</td>
</tr>
</tbody>
</table>

Table 7.1: (continued)
<table>
<thead>
<tr>
<th>Sample No.</th>
<th>( \Sigma \text{Cation} ) (meq/l)</th>
<th>( \Sigma \text{Anion} ) (meq/l)</th>
<th>Percent (diff.)</th>
<th>TDS (residue)</th>
<th>TDS (calc.)</th>
<th>Percent (diff.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.282</td>
<td>3.214</td>
<td>+1.05</td>
<td>277</td>
<td>267</td>
<td>+1.8</td>
</tr>
<tr>
<td>2</td>
<td>7.526</td>
<td>6.408</td>
<td>+8.02</td>
<td>404</td>
<td>417</td>
<td>-1.5</td>
</tr>
<tr>
<td>4</td>
<td>3.533</td>
<td>2.910</td>
<td>+9.67</td>
<td>297</td>
<td>191</td>
<td>+21.7</td>
</tr>
<tr>
<td>6</td>
<td>3.159</td>
<td>3.172</td>
<td>-0.21</td>
<td>269</td>
<td>247</td>
<td>+4.5</td>
</tr>
<tr>
<td>9</td>
<td>10.205</td>
<td>9.216</td>
<td>+5.09</td>
<td>632</td>
<td>590</td>
<td>+3.4</td>
</tr>
<tr>
<td>13(a)</td>
<td>3.346</td>
<td>1.917</td>
<td>+27.15</td>
<td>144</td>
<td>187</td>
<td>-13.0</td>
</tr>
<tr>
<td>13(b)</td>
<td>2.891</td>
<td>1.927</td>
<td>+20.0</td>
<td>136</td>
<td>166</td>
<td>-9.9</td>
</tr>
<tr>
<td>15</td>
<td>2.534</td>
<td>2.735</td>
<td>-3.78</td>
<td>110</td>
<td>201</td>
<td>-29.3</td>
</tr>
<tr>
<td>18(a)</td>
<td>5.164</td>
<td>4.287</td>
<td>+9.27</td>
<td>281</td>
<td>283</td>
<td>-0.3</td>
</tr>
<tr>
<td>18(b)</td>
<td>5.387</td>
<td>4.294</td>
<td>+11.29</td>
<td>298</td>
<td>287</td>
<td>+1.9</td>
</tr>
<tr>
<td>20</td>
<td>5.461</td>
<td>4.100</td>
<td>+14.23</td>
<td>287</td>
<td>275</td>
<td>+2.1</td>
</tr>
<tr>
<td>22</td>
<td>7.375</td>
<td>7.552</td>
<td>-1.19</td>
<td>416</td>
<td>444</td>
<td>-3.3</td>
</tr>
<tr>
<td>23</td>
<td>7.860</td>
<td>7.117</td>
<td>+4.96</td>
<td>501</td>
<td>476</td>
<td>+2.6</td>
</tr>
<tr>
<td>27</td>
<td>3.235</td>
<td>2.552</td>
<td>+11.80</td>
<td>183</td>
<td>175</td>
<td>+2.2</td>
</tr>
<tr>
<td>32(a)</td>
<td>10.104</td>
<td>8.145</td>
<td>+10.73</td>
<td>457</td>
<td>470</td>
<td>-1.4</td>
</tr>
<tr>
<td>32(b)</td>
<td>5.370</td>
<td>5.343</td>
<td>+0.25</td>
<td>238</td>
<td>348</td>
<td>-18.8</td>
</tr>
<tr>
<td>34</td>
<td>9.539</td>
<td>8.787</td>
<td>+4.10</td>
<td>652</td>
<td>561</td>
<td>+7.5</td>
</tr>
<tr>
<td>35</td>
<td>4.294</td>
<td>5.109</td>
<td>+8.67</td>
<td>361</td>
<td>355</td>
<td>+0.8</td>
</tr>
<tr>
<td>39(a)</td>
<td>7.333</td>
<td>6.943</td>
<td>+2.73</td>
<td>437</td>
<td>392</td>
<td>+5.4</td>
</tr>
<tr>
<td>39(b)</td>
<td>8.098</td>
<td>8.396</td>
<td>-1.81</td>
<td>650</td>
<td>446</td>
<td>+18.6</td>
</tr>
<tr>
<td>43</td>
<td>5.686</td>
<td>5.016</td>
<td>+6.26</td>
<td>277</td>
<td>322</td>
<td>-7.5</td>
</tr>
<tr>
<td>50</td>
<td>8.868</td>
<td>8.023</td>
<td>+5.00</td>
<td>435</td>
<td>482</td>
<td>-5.0</td>
</tr>
<tr>
<td>51(a)</td>
<td>2.480</td>
<td>2.534</td>
<td>-1.07</td>
<td>174</td>
<td>177</td>
<td>-0.8</td>
</tr>
</tbody>
</table>

Table 7.1(a): Summary of ionic-balance and comparison of TDS.
<table>
<thead>
<tr>
<th>Sample No.</th>
<th>ΣCation (meq/l)</th>
<th>ΣAnion (meq/l)</th>
<th>Percent (diff.)</th>
<th>TDS (residue)</th>
<th>TDS (calc.)</th>
<th>Percent (diff.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>51(b)</td>
<td>3.366</td>
<td>2.194</td>
<td>+21.08</td>
<td>115</td>
<td>181</td>
<td>-22.3</td>
</tr>
<tr>
<td>54</td>
<td>3.561</td>
<td>2.508</td>
<td>+17.35</td>
<td>151</td>
<td>199</td>
<td>-13.7</td>
</tr>
<tr>
<td>56(a)</td>
<td>2.854</td>
<td>2.437</td>
<td>+7.88</td>
<td>136</td>
<td>165</td>
<td>-9.6</td>
</tr>
<tr>
<td>56(b)</td>
<td>4.032</td>
<td>3.643</td>
<td>+5.07</td>
<td>170</td>
<td>247</td>
<td>-18.5</td>
</tr>
<tr>
<td>60</td>
<td>4.008</td>
<td>3.333</td>
<td>+9.19</td>
<td>200</td>
<td>258</td>
<td>-12.6</td>
</tr>
<tr>
<td>70</td>
<td>7.092</td>
<td>6.209</td>
<td>+6.64</td>
<td>373</td>
<td>413</td>
<td>-5.1</td>
</tr>
<tr>
<td>73</td>
<td>6.679</td>
<td>5.718</td>
<td>+7.75</td>
<td>402</td>
<td>357</td>
<td>+5.9</td>
</tr>
<tr>
<td>75(a)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75(b)</td>
<td>6.840</td>
<td>5.051</td>
<td>+15.04</td>
<td>351</td>
<td>311</td>
<td>+6.0</td>
</tr>
<tr>
<td>79</td>
<td>2.452</td>
<td>2.845</td>
<td>-7.42</td>
<td>259</td>
<td>228</td>
<td>+6.4</td>
</tr>
<tr>
<td>85</td>
<td>6.738</td>
<td>6.907</td>
<td>-1.24</td>
<td>442</td>
<td>418</td>
<td>+2.8</td>
</tr>
<tr>
<td>87(a)</td>
<td>5.025</td>
<td>4.270</td>
<td>+8.12</td>
<td>179</td>
<td>264</td>
<td>-19.2</td>
</tr>
<tr>
<td>87(b)</td>
<td>4.355</td>
<td>3.710</td>
<td>+8.00</td>
<td>204</td>
<td>230</td>
<td>-6.0</td>
</tr>
<tr>
<td>88(a)</td>
<td>2.851</td>
<td>2.247</td>
<td>+11.84</td>
<td>175</td>
<td>171</td>
<td>+1.2</td>
</tr>
<tr>
<td>88(b)</td>
<td>3.230</td>
<td>3.724</td>
<td>-7.10</td>
<td>519</td>
<td>244</td>
<td>+36.0</td>
</tr>
<tr>
<td>89(a)</td>
<td>2.815</td>
<td>2.149</td>
<td>+13.41</td>
<td>157</td>
<td>140</td>
<td>+5.8</td>
</tr>
<tr>
<td>89(b)</td>
<td>3.970</td>
<td>3.365</td>
<td>+8.25</td>
<td>180</td>
<td>202</td>
<td>-5.8</td>
</tr>
<tr>
<td>93(a)</td>
<td>7.529</td>
<td>6.158</td>
<td>+10.01</td>
<td>428</td>
<td>401</td>
<td>+3.2</td>
</tr>
<tr>
<td>93(b)</td>
<td>10.500</td>
<td>9.935</td>
<td>+2.78</td>
<td>553</td>
<td>555</td>
<td>-0.2</td>
</tr>
<tr>
<td>95</td>
<td>6.184</td>
<td>4.786</td>
<td>+12.74</td>
<td>312</td>
<td>337</td>
<td>-3.9</td>
</tr>
<tr>
<td>96</td>
<td>9.576</td>
<td>8.490</td>
<td>+6.01</td>
<td>641</td>
<td>525</td>
<td>+9.9</td>
</tr>
<tr>
<td>99</td>
<td>3.649</td>
<td>3.561</td>
<td>+1.22</td>
<td>169</td>
<td>241</td>
<td>-17.6</td>
</tr>
<tr>
<td>106</td>
<td>5.624</td>
<td>4.903</td>
<td>+6.85</td>
<td>338</td>
<td>357</td>
<td>-2.7</td>
</tr>
</tbody>
</table>

Table. 7.1(a): (continued)
<table>
<thead>
<tr>
<th>Sample No.</th>
<th>ΣCation (meq/l)</th>
<th>ΣAnion (meq/l)</th>
<th>Percent (diff.)</th>
<th>TDS (residue)</th>
<th>TDS (calc.)</th>
<th>Percent (diff.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>107</td>
<td>12.719</td>
<td>10.583</td>
<td>+9.17</td>
<td>776</td>
<td>660</td>
<td>+8.1</td>
</tr>
<tr>
<td>112</td>
<td>7.973</td>
<td>6.836</td>
<td>+7.68</td>
<td>499</td>
<td>468</td>
<td>+3.2</td>
</tr>
<tr>
<td>113</td>
<td>6.442</td>
<td>5.675</td>
<td>+6.33</td>
<td>313</td>
<td>326</td>
<td>-2.0</td>
</tr>
<tr>
<td>114</td>
<td>5.605</td>
<td>5.205</td>
<td>+3.70</td>
<td>396</td>
<td>384</td>
<td>+1.5</td>
</tr>
<tr>
<td>120</td>
<td>21.643</td>
<td>21.480</td>
<td>+0.38</td>
<td>1180</td>
<td>1226</td>
<td>-3.5</td>
</tr>
<tr>
<td>122(a)</td>
<td>2.983</td>
<td>3.635</td>
<td>-9.85</td>
<td>198</td>
<td>198</td>
<td>-0.1</td>
</tr>
<tr>
<td>122(b)</td>
<td>3.642</td>
<td>4.687</td>
<td>-12.55</td>
<td>220</td>
<td>266</td>
<td>-9.5</td>
</tr>
<tr>
<td>123</td>
<td>2.239</td>
<td>2.108</td>
<td>+3.01</td>
<td>155</td>
<td>176</td>
<td>-6.3</td>
</tr>
<tr>
<td>128</td>
<td>9.910</td>
<td>8.117</td>
<td>+9.95</td>
<td>572</td>
<td>558</td>
<td>+1.2</td>
</tr>
<tr>
<td>131</td>
<td>9.879</td>
<td>10.120</td>
<td>-1.21</td>
<td>652</td>
<td>598</td>
<td>+4.3</td>
</tr>
<tr>
<td>136(a)</td>
<td>72.887</td>
<td>74.355</td>
<td>-0.99</td>
<td>3964</td>
<td>4213</td>
<td>-3.0</td>
</tr>
<tr>
<td>136(b)</td>
<td>9.521</td>
<td>9.507</td>
<td>+0.07</td>
<td>584</td>
<td>629</td>
<td>-3.7</td>
</tr>
<tr>
<td>139</td>
<td>4.573</td>
<td>4.789</td>
<td>-2.31</td>
<td>331</td>
<td>317</td>
<td>+2.2</td>
</tr>
<tr>
<td>141</td>
<td>7.521</td>
<td>6.011</td>
<td>+11.16</td>
<td>315</td>
<td>364</td>
<td>-7.2</td>
</tr>
<tr>
<td>144(a)</td>
<td>10.691</td>
<td>9.869</td>
<td>+3.99</td>
<td>517</td>
<td>574</td>
<td>-5.2</td>
</tr>
<tr>
<td>144(b)</td>
<td>10.524</td>
<td>10.014</td>
<td>+2.48</td>
<td>562</td>
<td>566</td>
<td>-0.4</td>
</tr>
</tbody>
</table>

Table 7.1(a): (continued)
The comparison of TDS (Table 7.1(a)), on the other hand, produced a slightly different view contradicting with some of the ionic-balance interpretation. The percentage differences were also calculated by using the same empirical formula used for ionic-balance computation but this time the cations and anions were replaced by the TDS obtained by residue on evaporation and calculated TDS, respectively. Therefore the empirical formula took the following form:

\[ \frac{(\text{TDS}_{\text{cal}} - \text{TDS}_{\text{res}})}{(\text{TDS}_{\text{cal}} + \text{TDS}_{\text{res}})} \times 100. \]

Excellent TDS balance (error ≤ ± 5 percent) was obtained for 31 samples (50.8 percent). Reasonably acceptable TDS balance (error ≤ ± 10 percent) is obtained for another 18 samples (29.5 percent). Both category jointly make up about 80.3 percent of all the samples. The analytical data in 3 samples (4.9 percent) (W13(a), W54 and W60) produced high percentage differences (error ≤ ± 15 percent) but the differences (error > ± 15 percent) were objectionally high in another 9 samples (14.8 percent) (W4, W15, W32(b), W39(b), W51(b), W56(b), W87(a), W88(b) and W99). But it is interesting to note that the ionic-balance criteria suggested good quality condition of the analytical data for most of these samples (W4, W15, W32(b), W39(b), W51(b), W56(b), W60, W87(a), W88(b), and W99). Both the ionic-balance and the TDS comparison unanimously suggested that the analytical data of 3 wells (W13(a), W51(b) and W54) are potentially erroneous and are most likely to provide misleading interpretation of geochemical interpretation.

Usually the analysis of Ca, Mg, Na and K from the cationic part and HCO₃, SO₄, Na and K from the anionic part makes an analysis complete but unfortunately most of the previous analyses do not include the determination of K and SO₄ so that strictly speaking those analysis can not be regarded as complete. Interestingly it is found that the percentage of error (17.7 percent excess - ve and 82.3 percent excess + ve) in the ionic balance is fairly low (less or around 10
percent) in most of the samples (Table 7.1(a)). Therefore, it can be assumed that the amount of potassium and sulphate present in the ground water is fairly low. The availability of potassium and sulphate concentration might have been helpful to improve the percentage error obtained in the specified wells.

The ground water samples which were analyzed at UCL are considered to be more accurate complete chemical analysis and the percentage of error in the ionic balance is fairly low. Out of 16 samples, excellent ionic balance (error $\leq \pm 5$ percent) is obtained for 10 samples (62.5 percent) and the ionic balance is within acceptable range (error $\leq \pm 10$ percent) for the remaining 6 samples (37.5 percent). The comparison of TDS (between the value obtained by residue on evaporation and the calculated TDS) also produced smaller differences between them. Excellent TDS comparison (error $\leq \pm 5$ percent) is obtained for 13 samples (81.3 percent) and the percentage difference is $\leq \pm 6.4$ percent for the remaining 3 samples.

7.5 Graphical Interpretation:

7.5.1 Distribution Maps:

a) Introduction: A distribution map provides useful preliminary information about the hydro-chemical behaviour of a system with some indication of prevailing water quality trends. Very often, therefore, it is used as a guide for identifying the most appropriate methods for further interpretation of ground water chemistry, the active processes particularly, ion-exchange, dissolution and redox potential and the mixing behaviour while it also provides some indication about water types. For the present work the TDS and the sodium/Σcation ratio distribution have been prepared for the above purposes. Figure 7.2 shows the aereal distribution of TDS in the study area, and is used to assess potability and ground water quality. Figure
7.3 shows Na/Σ Cation ratios and is used as an index of ion-exchange, on the assumption that other processes might affect this ratio. The hydrochemical ratio map have long been favoured by French workers and can provide useful information concerning such features as ion exchange and the onset of brackish water influence (Lloyd and Heathcote, 1985).

b) TDS distribution map: The TDS map (Fig. 7.2) is contoured at 100 mg/L intervals. It shows the distribution of TDS within the project area for all the available samples. The eastern margin shows the minimum TDS concentration which increases along flow lines (Fig. 4.5). Though the distribution map does not closely accord with the ground water flow lines because of the substantial increase in TDS concentration at wells 34 (in Devidwar) and 120 (in Sonaimuri) which dominate over most of the region and greatly upsets the general distribution pattern yet the increase of TDS concentration coincides with the increasing distance along the down gradient direction. At well 120, the TDS concentration is >1100 mg/L which is unusually high in comparison with the rest of the ground water. It should however be noted that a TDS with such a concentration is well below the EEC safety limit (EEC standard 1975) and can be classified as a low TDS category. Apart from this, the general distribution of soluble solids is very low, and two reasons can be offered to explain this low TDS condition. Firstly, the ground water receives abundant fresh water recharge primarily by vertical deep percolation of infiltrated water (see Section 8.2.2.a) as well as by means of horizontal flow from precipitation originating at the outcrops located to the east of the area of study every year which dilutes the existing concentration of the relatively older ground water. Secondly, the ground water does not travel long enough through the aquifer to pick up enough soluble material from the aquifer matrix to markedly increase its
concentration. Further study of Tritium and $^4$C data are required to support this contention.

A smooth TDS distribution can only be prepared by ignoring TDS measurements of some of the wells where the values are considered to be anomalously high or low. Figure 7.2(a) depicts a much better regional distribution by ignoring wells 22, 23, 27, 34, 43, 96, 106, 113, 114 and 120. In this map the increase of TDS is very well defined following the major direction of flow, which is towards west, south-west and north-west.

c) Na/$\Sigma$ Cation ratios:

The ratio index values obtained from the distribution map of the ratio of sodium/$\Sigma$cations (Fig. 7.3) indicate that considerable amount of ion exchange has occurred in combination with other processes responsible for the modification of calcium and sodium ions concentration as they become predominantly affected by the ion-exchange phenomena. A contour interval value of 0.2 was used to construct the ratio map and the contoured area between 0.6 index value and the largest obtained value has been shaded to locate the area where a significant amount of ion-exchange has taken place. Four major and one minor isolated ion-exchange areas have been identified. Both the northern-most and the southern-most ion-exchanged areas demonstrate that the increasing amount of ion-exchange activities is coincident with the increasing flow distance. But the centrally located ion-exchanged areas demonstrates that the ion-exchange activities increase towards the centre of each block from all directions.

Optimum exchange condition occurs in sands with significant clay content where the permeability is still sufficiently high for the water to be developed as a resource (Lloyd and Heathcote, 1985). Even though these aquifer in
Fig. 7.2(a): Modified contour map of total dissolved solids (TDS) in mg/L.
FIG. 7.3: HYDROCHEMICAL RATIO DISTRIBUTION OF SODIUM TO TOTAL CATIONS.

LEGENDS
- INTERNATIONAL BOUNDARY CHANNELS
- PRIMARY SECONDARY WELL LOCATION

Contour interval .2

SUPPLEMENTARY QUALITY STATIONS
- UNDP QUALITY STATIONS
- GWC QUALITY STATIONS
- BADC QUALITY STATIONS
- UNDP + GWC QUALITY STATIONS
- UNDP + BADC QUALITY + PIEZO WELLS
- UNDP QUALITY + PIEZO WELLS
- GWC QUALITY + PIEZO WELLS
- BADC QUALITY + PUMP TEST WELLS
- GWC QUALITY + AUTO PIEZO WELLS
- BADC + GWC QUALITY + PIEZO WELLS
- UNDP QUALITY + RT-PIEZO WELLS

BAY OF BENGAL
most cases appear to be composed of dominantly sandy and gravelly particles, up to 15% by weight of clay/silt materials are associated with the aquifer materials (see Section 2.5). It was mentioned previously that major part of the ground water recharge takes place by direct infiltration of rain water which is solely intergranular flow in these unconsolidated deposits. As these fresh recharge water passes through the sequence some ion-exchange activity takes place which increases significantly when the recharge water comes in contact with connate water and saline water. The connate water was trapped during the deposition of sediments and the quantity of saline water is increasing by the sea water intrusion from the Bay of Bengal. Further investigation is required to provide confirmation and better understanding.

7.5.2 Pattern Diagram:

Hydrogeological facies variation across the study area are presented in Figure 7.4 as Stiff patterns for each well plotted on a grid map of the area. The following comments can be made about the pattern diagram distribution:

1) With the exception of wells 9, 34, 50, 85, 107, 120, 131 and 136, the Anion group is dominated by the HCO₃ ions. But this domination is superseded in the south by an increasing amount of chloride, which usually behaves conservatively in solution.

2) The analytical results clearly demonstrate that the ground water is dominated by sodium but the influence of calcium, magnesium and potassium ions are also observed in the following instances: a) in wells 20, 39, 72 and 75 where a calcium domination is observed; b) magnesium is important in wells 4, 70, 73, 113 and 141 and c) a limited domination of potassium ion is observed in wells 106, 112 and 114.
3) The useful measure of total ionic content in terms of the pattern indicates that the width increases along the flow direction in comparison with its source which is the north-easterly located ground water divide (Fig. 7.11), although it is some time better presented by the TDS plot which is also true for the present TDS distribution.

4) The ground water towards the outcrop appears to have been an essentially NaHCO$_3$ type in nature but as it moves towards the west, south-west and south hydrochemical evolution modifies the ground water into a mixed NaHCO$_3$/Cl type because of ion-exchange and mixing with connate water.

7.5.3 Trilinear Diagram:

The chemical composition of the samples has been plotted (in %meq/l) on a trilinear diagram (Fig. 7.5) drawn by the use of fortran 77 program (Appendix. 7.1) devised by the IGS (1978). Occasionally this plot is useful to summarise the important chemical processes (mentioned in Section 7.5.1.a) and to visualise the prevailing water type(s) that may have developed as a consequence of the operation of those processes. Both the Piper-Hill (1944) (Appendix. 7.2.1) and Back (1966) (Appendix. 7.2.2) classifications failed to elucidate processes or to give a useful interpretation of data but they indicated that the water does not belong to any particular group rather there are many water types.

7.5.4 Chemistry along flow lines:

A number of flow lines were selected to demonstrate the pattern of hydrochemical change. A maximum of four flow lines were selected from Figure 4.5 and the ground water sampling locations falling along or close to each of the flow lines (Fig. 7.6) were treated individually. The major ionic content of the
Fig. 7.5: Piper diagram showing the hydrochemical distribution of ground water samples in terms of major ion percentages. Size of symbol is proportional to TDS (mg/L).
Fig. 7.6: Map showing the selected flow lines from Figure 4.5.
ground water samples falling along a particular flow line were plotted in separate trilinear diagrams as Figure 7.7 in which the flow directions are indicated by arrowheads. The total ionic concentration of each sample is expressed in terms of the size of the plotted points; the larger the size the higher is the concentration of the dissolve ions. The general rule about the ionic concentration under normal simple flow conditions is that the amount of total dissolved solids increases with increasing flow line distances. Because of the complex flow pattern this rule has not been maintained in any of the flow lines. The natural flow lines are distorted by over pumping so also the active processes. The reverse ion-exchange process may be explained by flow line 2 and 3 where both the wells 18 and 50 indicate endpoint waters and a progressive increase of unstable ions (Ca and Mg) are observed at the expense of stable ions (Na and K). The wells 23, 35 and 51 along flow line 2 can be regarded as a group so also the wells 54 and 60 along flow line 3. The sequential direction of flow in flow line 1 looks rather unlikely as a chemical evolution. The plot of wells 89, 106 and 112 can best be described as a group rather than a chemical evolution. It is not possible to resolve such fine structure in chemical processes with inadequate data. Although dissolution is not pronounced in sand dominated aquifer but occasionally it may be significant. The dominance of calcium in wells 20, 22, 39 and 75 and magnesium in wells 4, 70, 73, 113 and 141 is indicative of limited chemical dissolution of associated calcitic and dolomitic materials. Major part of the present ground water originates from the direct recharge of rain water, a solution which is oxygen rich. The inter-actions between the recharge water and the reducing aquifer matrix are responsible for redox phenomena observed in many aquifers (Lloyd and Heathcote, 1985), therefore certain amount of reduction is more likely. A detailed discussion is prevented by the absence of redox potential ($E_t$) and other measurements.
Fig. 7.7: Variation in ground water chemistry (arrow represent sequential directions of flow)
7.5.5 Expanded Durov diagram:

The original Durov (1948) diagram has significantly been expanded in two different stages firstly by Burdon & Mozloum (1958) and secondly by Lloyd and Heathcote (1985), into nine convenient fields to provide a better classification and understanding of the hydrochemical groupings of ground water types and some of the processes that changes ground water composition. A detailed description of the modification and the significance of each of the fields is available elsewhere (Lloyd and Heathcote, 1985). For the present sets of hydro-chemical data, a clearer explanation of the types of water and the active chemical processes has been provided by the expanded Durov diagram.

The plotted points in the expanded Durov diagram (Fig. 7.8) fall into two fields suggesting the existence of two different types of ground water. More than 77 percent (38 data points) of the waters are confined in the second and third fields with a majority lying in the third field. Those lying in second field show the dominance of Mg and HCO₃ but at the same time Ca and Na are also an important part of their concentration suggestive of partial ion-exchange accomplishment. On the other hand, those falling in the third field exclusively, show the dominance of Na and HCO₃ which normally indicates a strong ion-exchange accomplishment. Therefore the water in the second and third fields would normally be classified as ion-exchanged waters (Durov, 1948; and Lloyd and Heathcote, 1985). The second major group of water samples plotted in the ninth field indicating the dominance of Na and Cl ions. Waters having such features are usually regarded as end point waters which often suggests the existence of older waters in the aquifer. Only two water samples plotted in the eighth field suggesting Cl ion dominance and no dominant cations which is a positive indication that the water may have experienced reverse ion-exchange processes from Na-Cl waters.
Fig. 7.8: Classification of ground water types using the expanded Durov diagram: I, Ion exchange waters; II, Old brackish water with some reverse ion exchange.
Waters in both the eighth and ninth fields jointly can be classified as Old Brackish Water where some reverse ion-exchange processes have taken place.

The map (Fig. 7.9) of the two different types of water identified from the expanded Durov trilinear plot (Fig. 7.8) strengthens the idea that the scatter distribution of the brackish water within the major ion-exchange waters neither represents any distinct pattern nor does it indicate any link with brackish waters. Therefore, it may be concluded that the saline water entrapped in the southern region at shallow depth is because of sea water intrusion from the Bay of Bengal. However, this does not wholly explain the isolated locations of saline ground waters in the northern and central parts is jointly because of connate brackish water trapped since deposition with some possible segregation of Na, K and Cl ions by ion-exchange processes.

7.6 Application of PHREEQE Hydrochemical Model:

7.6.1 Introduction:

The assessment of the ground water equilibrium state with respect to soluble solids as a result of the continued action of chemical processes is made in terms of saturation indices (SI). To perform such calculation PHREEQE the hydrochemical model has been used and the model does this particular task by calculating the distribution of species in the water. The saturation index (SI) of a water is defined by the expression:

\[ SI = \log \left( \frac{\text{IAP}}{K} \right) \]

where,

\( \text{IAP} \) = ion activity product and

\( K \) = equilibrium constant.

A water is in equilibrium with a mineral when the Saturation Index is zero. When this index is negative, the water is under-saturated and mineral dissolution may occur. When the Saturation Index is positive the water is super-saturated and
Fig. 7.9: Map showing the distribution of two water types.
mineral precipitation may occur.

7.6.2 PHREEQE Model:

a) Data base for species calculation:

A thermodynamic data base (See Plummer, 1985 for a detailed description) is required to run the model. The major part of the data base is compiled by the authors of the model and must be appended by the users analytical data to complete the data base. In the model data base the ionic concentration is supplied in units of mg/L. The various ions (both cation and anion) are recognized by the model through a predefined identifying number as for example, 4 for calcium, 5 for magnesium, 14 for chloride and so on. In the model, the ions are treated as elements and in doing so the anions are treated as their major elemental content. For example $\text{SO}_4^-$ is considered in terms of its elemental sulphur. During simulation every element under-goes a series of reactions as intermediate stages on its way to attain final equilibrium. These reactionary products at every stage are individually termed as species in the PHREEQE model. All the species associated with a particular element is grouped together as the member of a particular system.

b) Description of model results:

It would be wholly unnecessary to attach the lists of results for all the 48 water samples for which species calculation have been completed. Therefore a summary of the model-calculated results for a particular water sample (W 144) are presented in Table 7.2.

The upper part of the table represents the various elemental ions which were read and calculated by the model. Under the heading 'description of solution' the model summarizes certain important calculated geochemical
SPECIATION AND CALCULATION FOR WELL 144 SONAPUR NOAKHALI TOWN

-------TOTAL MOLALITIES OF ELEMENTS--------

<table>
<thead>
<tr>
<th>ELEMENTS</th>
<th>MOLALITY</th>
<th>LOG MOLALITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca</td>
<td>3.246131D-04</td>
<td>-3.4886</td>
</tr>
<tr>
<td>Mg</td>
<td>6.300083D-04</td>
<td>-3.2007</td>
</tr>
<tr>
<td>Na</td>
<td>8.623821D-03</td>
<td>-2.0643</td>
</tr>
<tr>
<td>Fe</td>
<td>1.433641D-05</td>
<td>-4.8436</td>
</tr>
<tr>
<td>Cl</td>
<td>1.242082D-03</td>
<td>-2.9058</td>
</tr>
<tr>
<td>C</td>
<td>8.728349D-03</td>
<td>-2.0591</td>
</tr>
<tr>
<td>N</td>
<td>4.842232D-05</td>
<td>-4.3150</td>
</tr>
</tbody>
</table>

------- DESCRIPTION OF SOLUTION -------

pH = 9.5000
PE = 0.0000
ACTIVITY H₂O = 0.9997
IONIC STRENGTH = 0.0123
TEMPERATURE = 27.0000
TOTAL ALKALINITY = 1.0764D-02
ITERATIONS = 9

------LOOK MIN IAP------

<table>
<thead>
<tr>
<th>PHASE</th>
<th>LOG IAP</th>
<th>LOG KT</th>
<th>LOG IAP/KT (S.I.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CALCITE</td>
<td>-6.9992</td>
<td>-8.4881</td>
<td>1.4889</td>
</tr>
<tr>
<td>DOLOMITE</td>
<td>-13.6368</td>
<td>-17.0605</td>
<td>3.4237</td>
</tr>
<tr>
<td>SIDERITE</td>
<td>-11.3574</td>
<td>-10.5760</td>
<td>-0.7814</td>
</tr>
</tbody>
</table>

Table 7.2: A modified form of the PHREEQE model calculated results output for well 144.
parameters. In the final stage, the program determine the Saturation Indices (SI) of those minerals (phase) for which sufficient chemical data were available to allow their calculation.

c) State of saturation Indices:

The saturation indices (SI) of certain important minerals such as gypsum, calcite and dolomite are summarized in Table 7.3 to provide information on the saturation states. It should be mentioned that any interpretation on the basis of saturation is only meaningful for sparingly dissolved mineral. Therefore to demonstrate any possible relationship only calcite, dolomite and siderite saturation indices were used to construct the X-Y plots.

Calcite versus Dolomite SI Plot:

A plot of calcite SI versus dolomite SI (Fig. 7.10) is effectively linear, passing through the points of mutual equilibrium and shows 73 percent of the water to be over-saturated with respect to both minerals. The linearity of the plot suggests the following points: 1) the degree of saturation of the water with respect to the minerals tends to increase with the increasing distance of the water from the outcrops with some exceptions (see Figure 7.9 and 7.10). Some of the wells in Figure 7.10 have been numbered to illustrate this trend; 2) the increasing depth of water also clearly demonstrates an increase in degree of saturation with even fewer exceptions; 3) 28.6 percent of the strong ion-exchanged water (where Na/Σcation ratios > 0.6) shows under-saturation while 29.6 percent of the other ion-exchanged water (where Na/Σcation ratios < 0.6) suggest under-saturation, and 4) 50 percent of the old brackish water (wells 9,18, 34, 50 and 85) suggests under-saturation conditions; therefore no recognisable trend is visible from the ion-
<table>
<thead>
<tr>
<th>WELL</th>
<th>SATURATION INDEX (S.I.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GYSUM</td>
</tr>
<tr>
<td>1</td>
<td>-2.601</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>-3.526</td>
</tr>
<tr>
<td>6</td>
<td>-2.782</td>
</tr>
<tr>
<td>9</td>
<td>-2.898</td>
</tr>
<tr>
<td>13</td>
<td>-</td>
</tr>
<tr>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>18</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>-</td>
</tr>
<tr>
<td>22</td>
<td>-1.923</td>
</tr>
<tr>
<td>23</td>
<td>-3.070</td>
</tr>
<tr>
<td>27</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>-</td>
</tr>
<tr>
<td>34</td>
<td>-</td>
</tr>
<tr>
<td>35</td>
<td>-3.271</td>
</tr>
<tr>
<td>39</td>
<td>-5.409</td>
</tr>
<tr>
<td>43</td>
<td>-</td>
</tr>
<tr>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td>51</td>
<td>-</td>
</tr>
<tr>
<td>54</td>
<td>-</td>
</tr>
<tr>
<td>56</td>
<td>-</td>
</tr>
<tr>
<td>60</td>
<td>-</td>
</tr>
<tr>
<td>70</td>
<td>-2.614</td>
</tr>
<tr>
<td>73</td>
<td>-3.335</td>
</tr>
<tr>
<td>75</td>
<td></td>
</tr>
<tr>
<td>79</td>
<td>-2.692</td>
</tr>
<tr>
<td>85</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 7.3: Summary of saturation indices of certain mineral matrix.
<table>
<thead>
<tr>
<th>WELL</th>
<th>SATURATION INDEX (S.I.)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GYPSUM</td>
<td>CALCITE</td>
<td>DOLOMITE</td>
</tr>
<tr>
<td>87</td>
<td>-</td>
<td>0.859</td>
<td>3.358</td>
</tr>
<tr>
<td>88</td>
<td>-</td>
<td>1.246</td>
<td>3.006</td>
</tr>
<tr>
<td>89</td>
<td>-</td>
<td>-1.076</td>
<td>-1.643</td>
</tr>
<tr>
<td>93</td>
<td>-2.948</td>
<td>2.262</td>
<td>4.765</td>
</tr>
<tr>
<td>95</td>
<td>-</td>
<td>1.678</td>
<td>3.372</td>
</tr>
<tr>
<td>96</td>
<td>-3.664</td>
<td>0.549</td>
<td>1.653</td>
</tr>
<tr>
<td>99</td>
<td>-</td>
<td>1.263</td>
<td>2.356</td>
</tr>
<tr>
<td>106</td>
<td>-2.748</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>107</td>
<td>-</td>
<td>1.591</td>
<td>3.647</td>
</tr>
<tr>
<td>112</td>
<td>-2.942</td>
<td>0.798</td>
<td>2.044</td>
</tr>
<tr>
<td>113</td>
<td>-</td>
<td>1.194</td>
<td>2.998</td>
</tr>
<tr>
<td>114</td>
<td>-2.817</td>
<td>1.304</td>
<td>2.675</td>
</tr>
<tr>
<td>120</td>
<td>-3.170</td>
<td>0.999</td>
<td>0.237</td>
</tr>
<tr>
<td>122</td>
<td>-2.455</td>
<td>0.263</td>
<td>0.869</td>
</tr>
<tr>
<td>123</td>
<td>-3.048</td>
<td>-0.640</td>
<td>-1.430</td>
</tr>
<tr>
<td>128</td>
<td>-2.926</td>
<td>1.868</td>
<td>3.834</td>
</tr>
<tr>
<td>131</td>
<td>-2.723</td>
<td>0.937</td>
<td>1.954</td>
</tr>
<tr>
<td>136</td>
<td>-3.406</td>
<td>1.668</td>
<td>3.702</td>
</tr>
<tr>
<td>139</td>
<td>-2.916</td>
<td>0.189</td>
<td>0.403</td>
</tr>
<tr>
<td>141</td>
<td>-</td>
<td>1.578</td>
<td>3.893</td>
</tr>
<tr>
<td>144</td>
<td>-</td>
<td>1.489</td>
<td>3.424</td>
</tr>
</tbody>
</table>

Table: 7.3: continued.
Fig. 7.10: Plot showing the linear relationship between Calcite and Dolomite S.I. value.
exchange point of view and saturation interpretation in terms of old brackish water.

Calcite versus Siderite SI plot:

The calcite against siderite plot (Fig. 7.11), on the other-hand, demonstrates a wide variability on the SI value reflected by their plotting position. All the SI points are randomly scattered in all four quadrants and is probably meaningless.

7. Ground water quality:

The major part of the ground water withdrawn in urban areas is used as a potable supply whereas the major part of the rural ground water is used for both irrigation and drinking water purposes, with a little also being used for industrial purposes. Depending on the type of industry, the required quality of the usable water also varies remarkably. Therefore the following discussion will be limited to drinking and irrigation aspects of water quality.

7.1 Drinking water quality:

The potability of a ground water is entirely dependent on the concentration of soluble solids. Some soluble materials are more injurious than others; a minute increase of some soluble materials is more harmful than a large increase of another soluble material. To maintain the quality of ground water, international agencies such as WHO (World Health Organization), EEC (European Economic Community) and USEPA (U.S. Environmental Protection Agency) have recommended certain standard limits for most of the dissolved materials. The obtained maximum and minimum concentrations for the measured ions are compared with the three different major international standards in Table 7.4 primarily to
Fig. 7.11: Plot showing the random distribution of Calcite and Siderite S.I. value.
### Table 7.4: Comparative tabulation of potable water quality in terms of various ions with selected international standards.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAC (mg/L)</td>
<td>MRC (mg/L)</td>
<td>MAC (mg/L)</td>
<td>MRC (mg/L)</td>
</tr>
<tr>
<td>TDS</td>
<td>1000</td>
<td>-</td>
<td>1500</td>
<td>-</td>
</tr>
<tr>
<td>pH</td>
<td>6.5-8.5</td>
<td>65-85</td>
<td>6.0</td>
<td>65-85</td>
</tr>
<tr>
<td>SiO₂</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ca</td>
<td>100-300</td>
<td>-</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>Mg</td>
<td>-</td>
<td>-</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td>Na</td>
<td>200</td>
<td>-</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>K</td>
<td>-</td>
<td>-</td>
<td>12</td>
<td>-</td>
</tr>
<tr>
<td>Fe</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>-</td>
</tr>
<tr>
<td>Mn</td>
<td>0.1</td>
<td>0.05</td>
<td>0.05</td>
<td>-</td>
</tr>
<tr>
<td>CO₃</td>
<td>-</td>
<td>-</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>HCO₃</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SO₄</td>
<td>400</td>
<td>250</td>
<td>250</td>
<td>5</td>
</tr>
<tr>
<td>Cl</td>
<td>250</td>
<td>250</td>
<td>200</td>
<td>-</td>
</tr>
<tr>
<td>NO₃</td>
<td>44</td>
<td>10 (GL)</td>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td>P0₄</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>F</td>
<td>1.5</td>
<td>2.0</td>
<td>1.4-2.4</td>
<td>-</td>
</tr>
<tr>
<td>Ec</td>
<td>-</td>
<td>-</td>
<td>1250</td>
<td>1686</td>
</tr>
</tbody>
</table>

MAC = Maximum admissible concentration  GL = Guide level
MRC = Minimum required concentration

Table. 7.4: Comparative tabulation of potable water quality in terms of various ions with selected international standards.
indicate the range of differences and hence to visualise the status of the quality aspect of the ground water being examined. On many occasions the standards for several ions are not available. The reason for this is that for some of the ions it is unimportant to set a standard and in other cases, especially for USEPA, it was not possible to obtain the standard criteria. To assess the potable quality of the present ground water, a comparative study of more important major ionic concentrations is presented below with the EEC standard concentration.

**TDS (total dissolved solids):** the maximum admissible concentration (MAC) is 1500 mg/L and this limit is mainly set to retain original natural taste. The measured TDS concentration in the study area is well below the recommended limit, except at well 136 where at a depth of 52 ft (> 15 m) the water has a TDS concentration of 3964 mg/L. The same well when it withdraws water from a depth of >1200 ft (>365 m) provides a TDS concentration of 474 mg/L. This enormous TDS rise at shallow depth is because of the very high concentration of Na and Cl ions supplied by the sea water intrusion. The high TDS at shallow depth is not representative for the main aquifer.

**pH:** The MAC and minimum required concentration (MRC) levels for hydrogen ion concentrations are 9.5 and 6.0, respectively. A pH of 10.0 is recorded in a number of wells which is above the MAC limit. The majority of the remaining wells recorded a pH of 8.0 and above, indicating that the solution is increasingly basic.

**Silica (SiO₂):** The range of concentration of silica most commonly observed in natural water is from 1 to 30 mg/L. The maximum (74.1 mg/L) and minimum
(15.0 mg/L) silica contents from the study area indicate that they are on the very high side.

Major ions: The analytical list (Table 7.1) suggests that in most cases the calcium, magnesium, sodium, iron, sulphate, chloride and nitrate levels are well below the EEC recommended safety limits except for the following ions: calcium concentrations were found to be a little lower than the MRC limit in wells 18 and 123; magnesium concentrations less than the MRC level was noted in wells 13, 15, 22, 32, 34, 79 and 123; sodium concentrations exceeded the MAC limit in wells 2, 9, 32, 34, 39, 86, 107, 120, 127, 136 and 144; iron concentrations exceeded the MAC limit in most of the wells; and chloride levels in excess of the MAC limit are reported in wells 9, 50, 107, 120 and 136. The analytical results also revealed that where-ever an analysis of potassium and manganese is available, the MAC level has been exceeded in the case of potassium for all wells and except for wells 23, 106 and 139 the manganese level is also much higher than the MAC.

Minor ions: Of the two minor ions analyzed (Table 7.1), the fluoride level is much lower than the lower range of the MAC limit in all the analyses and phosphate concentrations in excess of the MAC limit was noted in wells 23, 35, 112 and 136.

7.2 Irrigation Water Quality:

The ground water resource is most extensively used for irrigation purposes during the dry period (November - March). Therefore a study of the most common relevant chemical factors for irrigation water suitability has been carried out on the basis of field and laboratory measurements and calculations. The calculated indices are sodium absorption ratio (SAR) = \[ \text{SAR} = \frac{\text{Na}}{\left(\frac{\text{Ca} + \text{Mg}}{2}\right)^{1/2}} \]
(Richard, 1954), residual sodium carbonate (RSC) = \((\text{CO}_3 + \text{HCO}_3^-) - (\text{Ca} + \text{Mg})\) (Eaton, 1950) and magnesium hazard (MH) = \([\frac{\text{Mg}}{\text{Ca} + \text{Mg}}] \times 100\) (Szabolcs and Darab, 1964). All these indices were calculated in meq/l unit.

All these indices provide a good practical guide to water suitability in terms of major ions. However, the irrigation water quality is usually represented in terms of total salt content which is normally measured as EC in irrigation uses. The U.S. Department of Agriculture has devised a better classification for irrigation water based on a combination of parameters. In their classification (Fig. 7.12) they have considered the SAR in combination with EC which has proved very convenient and is widely used in assessing irrigation water quality.

The actual plot (Fig. 7.12) of the calculated SAR value and the measured EC values (EC values were measured only for those water samples analyzed at UCL) suggest that with the exception of wells 112, 120, 128 and 131 all the water belongs to a Low to Medium Salinity Hazard. Low sodium water as described by Wilcox (1955) can be used for irrigation on almost all soils with little danger of the development of harmful levels of exchangeable sodium. Quoting from the U.S. salinity report (1954) "low salinity water can be used for irrigation with most crops on most soils with little likelihood that a salinity problem will develop". Some leaching is required but this occurs under normal irrigation practices except in soils of extremely low permeability. Medium salinity water can be used if a moderate amount of leaching occurs. Plants with moderate salt tolerance can be grown in most instances without special practices for salinity control.

**Low Sodium and High Salinity -->** hazard condition is shown in wells 112, 128 and 131.

**High Sodium and High Salinity -->** hazard condition is present only in well 120.
Fig. 7.12: Plot showing the range of combined sodium and salinity hazard for classification of irrigation water quality.
Of these the only well 131 is located on the south-western border along the Meghna estuary indicating a high salinity condition which is primarily due to salinity intrusion along the coastal belt (mentioned previously in Section 7.4.3) and not surprising being close to the Bay of Bengal. The other wells (112, 128 and 120) having higher hazards indicate isolated representation rather than part of a pattern or trend. On the basis of the above explanation of the different categories of hazards, it may be concluded that most of the waters are suitable for most crops. Nevertheless, selective cropping patterns would be more appropriate in areas having high sodium and high salinity hazard.

The bicarbonate hazard (measured in terms of residual sodium carbonate (RSC) and the magnesium hazard (MH) (empirical formula devised by Eaton (1950)) along with the sodium absorption ratio (SAR) are summarized in Table 7.5 which compares the agreement between different types of hazards. The result of this comparison in some cases are conflicting in nature and to elaborate this situation the status of different hazards in a couple of wells can be examined. When the SAR index of well 36 indicates a 'Low Hazard' and the MH indicates a 'Harmless' condition then the RSC provides a 'not suitable' condition. Again the 'not suitable' RSC and 'Harmful' MH of well 144 is contradicted a by Low SAR hazard. For the present sets of data, 'Low Hazard' and 'Suitable' conditions for most of the wells are indicated by the SAR and RSC indices respectively rather than the MH hazard. Perhaps these problems reflect the poor quality of some of the analytical data. It is mentioned in Section 7.4 that better ionic-balance (error $\leq \pm 10$ percent) is obtained for 77.1 percent of the water samples therefore the conflicting nature hazard condition due to bad or inaccurate data should be fairly low.
<table>
<thead>
<tr>
<th>WELL NO.</th>
<th>SAR HAZARD</th>
<th>SAR HAZARD</th>
<th>RSC HAZARD</th>
<th>RSC HAZARD</th>
<th>MH HAZARD</th>
<th>MH HAZARD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.931</td>
<td>LOW 0.206</td>
<td>SUITABLE 49</td>
<td>HARMLESS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>3.028</td>
<td>LOW 1.290</td>
<td>HARMFULL</td>
<td>71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.937</td>
<td>-0.820</td>
<td>HARMFULL</td>
<td>88</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.973</td>
<td>0.706</td>
<td>HARMLESS</td>
<td>31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>11.782</td>
<td>MEDIUM 1.400</td>
<td>MARGINAL 46</td>
<td>HARMLESS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>2.739</td>
<td>LOW 0.600</td>
<td>SUITABLE 41</td>
<td>HARMFULL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>1.724</td>
<td>-0.084</td>
<td>HARMFULL</td>
<td>52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>2.137</td>
<td>-1.030</td>
<td>HARMLESS</td>
<td>59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>1.183</td>
<td>-0.415</td>
<td>HARMLESS</td>
<td>36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>2.461</td>
<td>1.043</td>
<td>HARMLESS</td>
<td>09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>3.650</td>
<td>2.440</td>
<td>MARGINAL 53</td>
<td>HARMFULL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>1.482</td>
<td>0.392</td>
<td>SUITABLE 36</td>
<td>HARMLESS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>3.124</td>
<td>1.700</td>
<td>MARGINAL 77</td>
<td>HARMFULL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>6.984</td>
<td>-1.100</td>
<td>HARMFUL</td>
<td>68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>4.001</td>
<td>2.627</td>
<td>NOT SUITABLE</td>
<td>45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>4.088</td>
<td>0.263</td>
<td>SUITABLE 51</td>
<td>HARMFULL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>43</td>
<td>3.321</td>
<td>0.751</td>
<td>HARMLESS</td>
<td>42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>1.686</td>
<td>-4.662</td>
<td>HARMFULL</td>
<td>54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>51</td>
<td>2.404</td>
<td>0.595</td>
<td>HARMLESS</td>
<td>45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>54</td>
<td>2.373</td>
<td>0.694</td>
<td>HARMFUL</td>
<td>58</td>
<td></td>
<td></td>
</tr>
<tr>
<td>56</td>
<td>3.456</td>
<td>1.104</td>
<td>HARMLESS</td>
<td>47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>3.122</td>
<td>0.603</td>
<td>HARMLESS</td>
<td>42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>0.666</td>
<td>0.558</td>
<td>HARMFULL</td>
<td>66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>73</td>
<td>1.011</td>
<td>-2.292</td>
<td>HARMFULL</td>
<td>76</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>1.431</td>
<td>-1.361</td>
<td>HARMLESS</td>
<td>74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>79</td>
<td>0.934</td>
<td>1.011</td>
<td>HARMLESS</td>
<td>28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>85</td>
<td>3.178</td>
<td>-0.803</td>
<td>HARMLESS</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>87</td>
<td>1.744</td>
<td>0.896</td>
<td>HARMFULL</td>
<td>72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>88</td>
<td>11.748</td>
<td>MEDIUM 2.445</td>
<td>MARGINAL 69</td>
<td>HARMFULL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>89</td>
<td>1.619</td>
<td>0.815</td>
<td>SUITABLE 72</td>
<td>HARMLESS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>93</td>
<td>2.233</td>
<td>0.868</td>
<td>HARMLESS</td>
<td>52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>95</td>
<td>4.028</td>
<td>0.480</td>
<td>HARMLESS</td>
<td>42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>96</td>
<td>3.537</td>
<td>-1.963</td>
<td>HARMFULL</td>
<td>74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>99</td>
<td>2.339</td>
<td>0.148</td>
<td>HARMLESS</td>
<td>35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>106</td>
<td>1.298</td>
<td>1.403</td>
<td>MARGINAL 49</td>
<td>HARMFULL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>107</td>
<td>3.830</td>
<td>-2.415</td>
<td>SUITABLE 69</td>
<td>HARMFULL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>112</td>
<td>1.470</td>
<td>1.318</td>
<td>MARGINAL 70</td>
<td>HARMFULL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>113</td>
<td>1.132</td>
<td>-0.738</td>
<td>SUITABLE 76</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>114</td>
<td>0.709</td>
<td>-0.017</td>
<td>HARMLESS</td>
<td>48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>12.784</td>
<td>MEDIUM 1.117</td>
<td>HARMFULL 77</td>
<td>HARMFULL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>122</td>
<td>0.318</td>
<td>0.327</td>
<td>HARMFUL</td>
<td>64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>123</td>
<td>0.957</td>
<td>0.193</td>
<td>HARMLESS</td>
<td>38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>128</td>
<td>4.085</td>
<td>-0.348</td>
<td>HARMFULL</td>
<td>48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>131</td>
<td>2.523</td>
<td>-2.161</td>
<td>HARMLESS</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>136</td>
<td>5.734</td>
<td>4.082</td>
<td>NOT SUITABLE</td>
<td>65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>139</td>
<td>1.782</td>
<td>2.079</td>
<td>MARGINAL 47</td>
<td>HARMLESS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>141</td>
<td>1.210</td>
<td>0.048</td>
<td>SUITABLE 30</td>
<td>HARMFULL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>144</td>
<td>8.826</td>
<td>6.818</td>
<td>NOT SUITABLE</td>
<td>65</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table: 7.5: Comparative study of the irrigation water quality in terms of various types of hazards.
CHAPTER 8 GROUND WATER RESOURCES

8.1 Introduction.

8.2 Assessment of Resources.

8.2.1 Introduction.

8.2.2 Ground Water Replenishment (Inputs).

a) Infiltration from Precipitation.

b) Irrigation Return Flow.

c) Influent Seepage of Surface Flow.

d) Influent Seepage of Sewage Water.

e) Leakage from Contiguous Strata.

f) Subsurface Inflow through Aquifer Boundaries.

8.2.3 Ground Water Discharge (Outputs).

a) Evapotranspiration.

b) Effluent Flow to Rivers, Canals and other Water Bodies.

c) Leakage into Contiguous Strata.

d) Subsurface Outflow through Aquifer Boundaries.

e) Artificial Withdrawal by Pumping.

8.2.4 Ground Water Budget.

8.3 Ground Water Management.

8.3.1 Introduction.

8.3.2 Development Status of Resources.

8.3.3 Perennial Yield.

8.3.4 Ground Water in Storage.
8.1 Introduction:

Ground water resources have long been neglected in Bangladesh despite their easy availability since surface water was considered as the only viable resource. The continued inadequacy of global potable water to meet the growing demand has now largely changed the traditional concept to include the non-potable part of ground water as resources regardless of how they became non-potable. The scarcity of potable water has also helped to change the attitude towards water as a whole recognising that although ground water is the only resource that is naturally renewable, it is not of unlimited quantity. The attention directed towards water resources during the last couple of decades has established the fact that nonpotable waters are just as much part of the hydrologic cycle as potable water and cannot be ignored in any ground water resources assessment.

The assessment of resources is almost entirely dependent on the correct identification of those active components of the hydrologic cycle which make significant contribution to water balance computations both from potable and nonpotable sources. Using the results of ground water balance computations, Jones (1972) defined four different states of ground water resources development, and the state of development in turn determining the importance of the degree of management practice. The same approach will be used to assess the state of ground water development in Bangladesh and to recognise the status of the management practice that may be required for the present ground water regime in the relevant subsequent sections.

8.2 Assessment of resources:

8.2.1 Introduction:

In most ground water development programmes one of the most important aspects of resources evaluation is to estimate how much ground
water is available from a ground water regime. An accurate quantitative assessment of the resources is not easy to make simply because so many parameters are involved and direct measurement of these parameters is often difficult. As a result, assessment of resources is done therefore in the form of the water balance.

The success in making a reasonably acceptable water balance depends on the proper identification and authentic calculation of the various component parts of the hydrologic cycle that control both the natural and artificial flows of ground water into and out of the basin. The various components that regulate the flow into the basin are collectively called 'recharge' components whereas the various ways by which the ground water basin loses water are collectively called 'discharge' components. In any water balance computation, the recharge and discharge components are related by the following expression:

Recharge = Discharge + Change in permanent ground water storage.

The following are the most important components of recharge:

- Infiltration from precipitation
- Irrigation return flow
- Influent seepage of surface waters
- Influent seepage of sewage waters
- Leakage from contiguous strata
- Subsurface inflow across aquifer boundaries.

The principal components of discharge most commonly include:

- Evapotranspiration
- Effluent flow to rivers, canals and other water bodies
- Subsurface outflow across aquifer boundaries
- Artificial withdrawal by pumping
- Leakage into contiguous strata.
Most of these components are governed by nature and very little can be
done to affect their inherent course of action but some of them, particularly
irrigation return flow and artificial withdrawal, can be controlled almost entirely to
ensure their best possible utilization.

8.2.2  Ground Water Replenishment (Inputs):

a) Infiltration from precipitation:

There is no straight-forward direct and accurate method to determine
the effective infiltration \( I_e \) component of rainfall for a large catchment. As a result,
an indirect approach in the form of water balance computation (method described
in Section 8.2.3.a. evapotranspiration) has become the normal practice to separate
the various component of distribution for the basin rainfall over a known period.
In this computation the amount of rainfall in excess of actual evapotranspiration
\( (A_{E_t}) \) and surface runoff \( (SR) \) is considered to be the amount of rainfall that is
transformed into effective infiltration \( (I_e) \).

In section 8.2.3.a. the Agnew (1982) model separates the Drainage
component \( (1718.05 \text{ mm}) \) which is in effect equivalent to the amount of effective
infiltration \( (I_e) \). The Grindley (1969,1970) model, on the other hand, combines both
the surface runoff and the effective infiltration in the form of Water Surplus
\( (2178.31 \text{ mm}) \). Therefore in this section the aim is to separate the surface runoff
\( (SR) \) from the water surplus \( (WS) \). The total amount of surface runoff of a large
catchment can be calculated with reasonable accuracy by analyzing and separating
the river discharge hydrograph into its major components i.e. into direct runoff and
base-flow. On the basis of the hydrograph analysis in Section 8.2.2.b (Effluent flow
to rivers etc) the different relevant components are summarized below and expressed
in cumec-days/annum.
<table>
<thead>
<tr>
<th>Rivers</th>
<th>Total flow</th>
<th>Base flow</th>
<th>Direct run-off</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern rivers</td>
<td>83274</td>
<td>55726</td>
<td>27547</td>
</tr>
<tr>
<td>Southern rivers</td>
<td>21527</td>
<td>8040</td>
<td>13487</td>
</tr>
<tr>
<td>Total</td>
<td>104802</td>
<td>63767</td>
<td>41034</td>
</tr>
</tbody>
</table>

Total surface (direct) runoff for the entire region is 41034 cumec-days/annum

\[= 41034 \times 60 \times 60 \times 24 = 3545337600 \text{ m}^3/\text{annum}\]

\[= 346.80 \text{ mm/annum} \quad (\text{area} = 10223 \text{ sq. km}).\]

Effective Infiltration (I_e) = WS - SR.

\[= 2178.31 - 346.80 = 1831.51 \text{ mm/annum}.\]

This amount of effective infiltration compares quite well with the amount of drainage (1718.05 mm/year) obtained by Agnew model (about 6% difference) in spite of its limitations that applies to the soil condition and surface runoff occurrences. Therefore it should not be unrealistic to consider the average I_e (1775 mm/annum) value to compute the ground water balance.

b) Irrigation return flow:

Practically speaking it is almost impossible to provide the exact amount of irrigation water that the producible crops require for healthy growth. Since some percentage of irrigation water will always be lost by both evapotranspiration and deeper subsurface infiltration/percolation, the usual practice is to provide an irrigation in excess of crop water requirements. This inevitable loss of water is called Irrigation loss and the part of irrigation loss that returns via the vadose zone to saturated zone is called the Irrigation Return Flow.

Irrigation is provided to the crops in the study area during the dry period (November-April) when the rainfall is insignificant or absent. Throughout
this period soil moisture deficits (SMD) occur (Grindley Model, Table 8.2); moreover, most of the time final soil moisture (FSM) remains at its wilting point (Agnew Model, Table 8.4). As a result of the cumulative effects the actual evapotranspiration rate drops considerably and the major part of irrigation water in excess of crop water requirements attempts to turn into irrigation return flow to reduce the soil moisture deficit (SMD). Any water in excess of field capacity infiltrates down to the saturated zone to make a positive contribution and increase the amount of effective infiltration (I).

It must be mentioned that irrigation is not entirely sustained by the use of ground water. A significant amount of irrigation (about 25%) is supplied from easily accessible surface water sources obtained from both running water (rivers) and bodies of standing water (beals, haors & ponds etc). In the absence of any reliable records it is thought that about 80 percent of the ground water withdrawal is used for irrigation purposes and the remaining 20 percent is used for both municipal and industrial purposes. Because the surface water is easily available no record has ever been kept of how much surface water irrigation has been applied to the crops. Therefore it is assumed here that both the surface water and ground water irrigation is equivalent to the total ground water withdrawal (2.13 x 10^9 m³/year) to prepare a rough estimate of the part of irrigation return flow that becomes part of effective infiltration (I).

The varieties of rice (Table 8.3) produced during dry period require occasional flooding of the rice paddy lands, particularly during the early stage of crop growth. This practice allows significant amounts of water to return to the subsurface. Since there are no measurements available of how much irrigation water is lost by transpiration or turned into return flow, it was assumed that some 25 percent of the total irrigation (2 x 10^9 m³/year) is transformed into irrigation loss which amounts to 5 x 10^8 m³/year and 50 percent of this amount
(2.5 x 10⁸ m³/year) reaches the saturated zone to become a part of effective infiltration (Iₑ). The remaining half of the irrigation loss is treated as true loss in the form of evapotranspiration and subsurface contribution to reduction of the soil moisture deficit. The evapotranspiration loss become an integral part of the total evapotranspiration loss worked out for the whole catchment (Section 8.2.3.a.).

c) **Influ ent seepage of surface waters:**

During the monsoon season, surface water levels rise very quickly due to the enormous amount of rain along with the increased flow of rivers originating outside the study area. The existing river channels and other forms of water storage can not accommodate this huge rapid inflow which overflows into the surrounding low-lying areas causing floods. During this period, huge amounts of surface water are available to infiltrate into different subsurface zones. Significant amounts of surface water are seasonally added to ground water storage every year until the aquifer rejects any further recharge when a major part of the surface water surplus is wasted into the sea.

The surface water contribution to any ground water basin is usually assessed by measuring the discharge of all the major rivers that control the surface water hydrology of the basin, at two convenient points, one upstream of and the other downstream of the area. The upstream measurement allows determination how much water is entering, while the downstream measurement quantifies how much water is leaving the basin. After allowing for evaporation, any reduction in flow at the downstream point is indicative of influent seepage. The difference between the incoming and outgoing flow is the amount of surface water that has gone into ground water storage.

Out of seven perennial rivers (Section 1.8), excluding the two bounding major rivers, discharge measurements for two points are available only for
the Gumti river. The upstream discharge measuring point is at Comilla Town (BWDB station 110) and the downstream discharge measuring point is at Jibanpur (BWDB station 114). The total amounts of flow at these two stations for the year 1979-80 (Figs. 8.1 and 8.2) and 1980-81 (Figs. 8.3 and 8.4) suggest that the amount of influent seepage to ground water during those two years was \((19612-18328) = 1284\) and \((23196-22137) = 1059\) cumec-days/annum respectively with an average of 1170 cumec-days/annum.

In the absence of basic discharge measurements for the other six rivers which are flowing inside the basin area, some generalizations have been made to estimate the influent seepage based on the following assumption. Firstly, to large extent these rivers are of similar type and their discharge capacities are not remarkably different because of relatively smaller width, cross-section and areal extension. Secondly, minimal soil variation and less textural variation of the materials making up the unsaturated zone give rise to similar infiltration characteristics. Finally, ground water flow net analysis (Section 4.4.3) suggests that the permeability does not change abruptly given the remarkably uniform hydraulic gradient. All these factors allow generalizations to be made regarding the similar range of influent seepage for the seven internal rivers. The total amount of influent seepage is estimated to be about:

\[ 1170 \times (60 \times 60 \times 24) \times 7 = 707616000 \text{ m}^3/\text{year}. \]

Because of high magnitudinal variations these generalizations would not be appropriate for the Meghna river, nor for the lesser Feni river from where significant amounts of inflow do take place. The above estimate thus excludes the amount of influent seepage that occurs from both these bounding rivers. The estimate, therefore, will be considerably less than the actual amount.
Fig. 8.1. Hydrograph showing the baseflow and surface run-off component.
Fig. 8.2. Hydrograph showing the baseflow and surface run-off component.
UPSTREAM DISCHARGE AT COMILLA STATION
RIVER GUMTI DAILY FLOW, CUMECS, 1980-1981
TOTAL ANNUAL FLOW CUMECS-DAYS: 23196.2461
BASEFLOW, CUMECS-DAYS: 14697.3125
BASEFLOW INDEX: 0.6336

Fig. 8.3. Hydrograph showing the baseflow and surface run-off component.
Fig. 8.4. Hydrograph showing the baseflow and surface run-off component.
d) Influent seepage of Sewage/Municipal waste water:

The generation of collected sewage/municipal waste water is minimal in the rural areas because modern sewage network facilities are not available on a sufficient scale to increase the production of sewage waste water. Because of the favourable weather conditions and the availability of surface water for most of the year the major water-related personal uses like swimming and bathing is largely done by the inhabitants in rivers, canals and ponds thereby producing no waste water. Very little waste water is also produced as a result of cooking and other household uses, and certainly none large enough to produce any significant seepage.

On the other hand, water supply and sewage/waste water collection are in operation on a limited scale in Comilla and Noakhali town areas and produce some sewage/municipal waste water. This could well result in a small amount of influent seepage which should be regarded as negligible.

e) Leakage from contiguous strata:

It was explained in the hydrogeology section (Figs. 3.1 and 3.2) that the separation of the main aquifer from aquifer 2 in some areas is not well defined because of the absence of the clay aquitard. When this is the case the main aquifer maintains hydraulic continuity via those locations so that under favourable circumstances some leakage from below might be expected. This amount is likely to be small because of the slight differences in hydraulic gradient, though at the moment there is no idea about the quantity.

The analysis of the pumping test data (Chapter 5), on the other hand, have clearly demonstrated that leaky confined conditions prevail over much of the aquifer and indicates that some leakage definitely takes place from the overlying aquiclude. The analysis of the pumping test data for almost all the leaky
confined condition produced a fairly high to very high leakage factor (the higher the leakage factor the lower is the amount of leakage) indicating that though leakage is occurring through the aquiclude the amount of leakage is small in comparison with the other components of recharge and has been ignored.

f) Subsurface inflow across aquifer boundaries:

Subsurface inflow takes place across the aquifer boundaries of every hydrogeological regime from the area of higher potential head to the lower potential heads, whatever small amount that may be. In the quantitative assessment of this particular component of ground water replenishment, the flow-net plays a most important role for two basic reasons. Firstly, two of the more important parameters are obtained from the flow-net. Secondly, it is from the flow-net that the peripheral extension of the aquifer boundary through which both Inflow and Outflow occurs is identified and separated. The two parameters obtained from flow-net are the hydraulic gradient \( i = \frac{dh}{dl} \) and the length of the equipotential line which effectively represent the actual length of the inflow and outflow zones \( (L) \). The third parameter is the transmissivity \( (T) \) obtained from the analysis of the pumping test data. These three parameters are used in the most convenient form of Darcy's Law \( (Q = TxixL) \) to make the assessment.

The greater the complexity of the flow pattern the more difficult it is to make the estimate which also reduces the degree of accuracy. Since the present flow pattern is very complicated, some degree of inaccuracy in the estimate is unavoidable. Following a standard procedure the zones of inflow have been separated from the zones of outflow (Fig. 8.5). Five different inflow zones or sections have been recognized from the flow-net constructed for the wet period (August, 1985) and six different inflow zones or sections have been identified from the flow-net map constructed for the dry period (March 1985).
Fig. 8.5. Map showing the subsurface peripheral inflow and outflow zones.
The conventional way of estimating the amount of inflow through the particular zone of the aquifer boundary is obtained by multiplying the actual physical length of the equipotential line that covers the maximum length of the peripheral boundary zone by the average transmissivity prevailing in that part of the area and further multiplied by the hydraulic gradient obtained by using the disposition of the adjacent pair of contours. The total inflow of the basin is obtained by totalling the amount of inflow estimated for all the zones or sections (Table 8.1). Since the total inflow for the entire basin is obtained for two different periods (one wet and the other dry) therefore the average of the two is accepted as the ultimate total inflow (2.3 x 10^7 m³/year).

8.2.3 Ground water discharge:

a) Evapotranspiration:

By definition, evapotranspiration is the process which accounts for the combined water losses by the processes of evaporation and transpiration. The calculation of water loss from an open water condition or from a desert condition is quite straightforward and is roughly equivalent to the evaporation loss. But in an area (like the present one) where there is extensive vegetation, which is under active cultivation and is controlled by the monsoonal climatic pattern, the total amount of water loss is significantly influenced by the process of transpiration and must be taken into consideration when calculating the true amount of water loss. The mechanism of transpiration is well understood but difficult to quantify or present in mathematical terms. Some degree of accuracy is attainable for a very small area on an experimental basis by the use of lysimeters but that method is impractical for a large catchment area. When this is the case, calculation of evapotranspiration tends to adopt the meteorological approach that takes into account climatological factors as well as important vegetation/crop properties. This is a
<table>
<thead>
<tr>
<th>TYPE</th>
<th>PERIOD</th>
<th>ZONES</th>
<th>ZONE WISE FLOW (cumec/year)</th>
<th>TOTAL INFLOW (cumec/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUBSURFACE</td>
<td>WET PERIOD</td>
<td>ZONE-1</td>
<td>$4.3 \times 10^6$</td>
<td>$2.6 \times 10^7$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZONE-2</td>
<td>$4.8 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZONE-3</td>
<td>$3.6 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZONE-4</td>
<td>$3.6 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZONE-5</td>
<td>$4.9 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DRY PERIOD</td>
<td>ZONE-1</td>
<td>$3.1 \times 10^6$</td>
<td>$1.9 \times 10^7$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZONE-2</td>
<td>$1.5 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZONE-3</td>
<td>$2.1 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZONE-4</td>
<td>$1.5 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZONE-5</td>
<td>$4.8 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZONE-6</td>
<td>$5.9 \times 10^6$</td>
<td></td>
</tr>
<tr>
<td>AVERAGE TOTAL INFLOW</td>
<td></td>
<td></td>
<td></td>
<td>$2.3 \times 10^7$</td>
</tr>
</tbody>
</table>

Table 8.1. Subsurface Inflow of ground water along various Zones across the boundary.
much simpler operation and fairly accurate, bearing in mind that water loss from a catchment does not always proceed at the same rate since it is dependent on the availability of water, degree and type of vegetation along with the climatic factors.

The value of the actual evapotranspiration over a catchment is more often obtained by first calculating the potential rate of evapotranspiration (PE), assuming an unrestricted availability of water and then modifying the answer by taking into consideration the other factors. Several methods are available to calculate the different components of rainfall using the water balance approach. Some methods are more suitable for particular areas than others depending on the geographical location and climatic condition but largely on the availability of the data that dictates the use of certain methods. For the present example, considering all the facts and figures, a calculation of (AE) based on climatological factors as well as crop properties was found to be more appropriate by the use of the Grindley (1969) and Agnew (1982) water balance approaches.

For both approaches the key data are average monthly rainfall and evaporation measurements recorded from standard rain gauges and widely used U.S. class-A pan, respectively, for the year 1985-86. It is an established fact that pan evaporation readings over-estimate the actual amount of water loss even though a maximum possible ideal condition is maintained during the pan construction and subsequent maintenance of the pan. To overcome this problem an adjustment factor called the pan co-efficient has been introduced to correct the evaporation losses. The pan co-efficient depends on several factors (a detailed description is available in 'Crop water requirements', FAO, 1977) but the most important ones are relative humidity, wind speed and pan setting environment (i.e. whether placed in a dry bare soil or at the centre of a vegetated area) as well as the distance of the green crops. Updated values of pan coefficient (FAO, 1977) for several variable conditions have been critically examined to select that most appropriate for the present catchment.
under the prevailing conditions. In short, the determining factors for selecting pan co-efficient are: 1) the pans are constructed within grassland or short vegetation cover; 2) the distances to green vegetation are between 10 and 100 metres from the pan; 3) during the post-monsoon and the winter season, humidity levels remain in the medium category level, but during the pre-monsoon and the monsoon season the humidity level remains in the high category level of the Dorenbos & Pruitt (FAO, 1977) classification chart for humidity to be used to determine the pan co-efficient ($K_{pc}$).

Grindley (1969) water balance model:

This model allows calculation of the soil moisture budget on a monthly basis for various types of vegetation classified according to their root constants (the amount of soil moisture that can be extracted from a soil without difficulty by a particular type of vegetation). Typical root constants have been experimentally worked out for certain vegetation in the U.K. (Shaw, 1982) e.g- permanent grassland 75 mm, potato 100 mm and woodlands 200 mm. After personal discussions with Dr. Clive Agnew of the Department of Geography, UCL, it was decided that the root constants for different kinds of rice and grass in the study area would not be much different from those of British permanent grass and similarly the root constant for woodlands should not be very different from the root constant of woodlands in U.K. About 75 percent of the land area is covered by rice paddy/grass vegetation, some 10 percent of the area is covered by woodlands and the remaining 15 percent can be considered as riparian. A minor amount of other vegetables and crops which are also cultivated in the area has been ignored because in comparison with rice the percentage of land they cover is insignificant. The use of the root constant is most crucial when the soil moisture deficit (SMD) is higher than the root constant and in this situation the AE, will be much lower than the
PE\textsubscript{r} (i.e. December, January and February for croplands and February to April for woodlands).

In Table 8.2, the second column is the average monthly rainfall (P), the third column is the average monthly direct pan evaporation (E\textsubscript{p}) measurement, the fourth column pan co-efficient (K\textsubscript{pan}), the fifth column represents the corrected pan evaporation (E\textsubscript{cor}), which is equivalent to the PE\textsubscript{r} obtained by multiplying the pan evaporation with the corresponding pan co-efficient, the sixth column represents the rainfall in excess of the PE\textsubscript{r}, the seventh column represents the potential soil moisture deficit (PSMD) when there is no excess rainfall (November to April), the eighth and ninth columns summarise the actual soil moisture deficit (ASMD) and the actual evapotranspiration (AE\textsubscript{r}), respectively, for rice paddy crop/grass land, the tenth and eleventh columns give the ASMD and AE\textsubscript{r}, respectively, for the woodland part of the area, the twelfth and thirteenth columns summarise the ASMD and AE\textsubscript{r}, respectively, for the entire catchment area using the following relationship of the proportional representation:

\[
\text{ASMD} = 0.75 \text{ASMD}_{75} + 0.1 \text{ASMD}_{200}
\]

with the riparian areas remaining at field capacity and

\[
\text{AE}_r = 0.15 \text{PE}_r + 0.75 \text{AE}_r_{75} + 0.1 \text{AE}_r_{200}.
\]

Finally, the fourteenth column documents the amount of water surplus (effective infiltration + surface run-off). During the months of July through October there is no soil moisture deficit since there is enough water around during this time of rainfall in excess of PE\textsubscript{r}; this is the true amount of water surplus. From November through April, soil moisture deficits occur which increase with time because the amount of rainfall is less than the PE\textsubscript{r}; accordingly there is no water surplus. In May, the amount of rainfall in excess of PE\textsubscript{r} is +532.65 mm but there is a soil moisture deficit from the previous month of about 118.40 mm. Therefore during May the true amount of water surplus is 414.25 mm (532.65 - 118.40). During
<table>
<thead>
<tr>
<th>PERIOD 1985-86</th>
<th>P (mm)</th>
<th>E₀ (mm)</th>
<th>Kₚₐν</th>
<th>Eₐ = P - E₀ (mm)</th>
<th>P - Pₑ (mm)</th>
<th>PSMD</th>
<th>CROPLAND / GRASS</th>
<th>WOODLANDS</th>
<th>CATCHMENT</th>
<th>WATER SURPLUS (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JUL</td>
<td>565.97</td>
<td>78.00</td>
<td>0.80</td>
<td>62.40</td>
<td>503.57</td>
<td>0.0</td>
<td>0.0</td>
<td>62.40</td>
<td>0.0</td>
<td>62.40</td>
</tr>
<tr>
<td>AUG</td>
<td>464.29</td>
<td>80.52</td>
<td>0.80</td>
<td>64.42</td>
<td>399.87</td>
<td>0.0</td>
<td>0.0</td>
<td>64.42</td>
<td>0.0</td>
<td>64.42</td>
</tr>
<tr>
<td>SEP</td>
<td>362.30</td>
<td>80.01</td>
<td>0.80</td>
<td>64.01</td>
<td>298.29</td>
<td>0.0</td>
<td>0.0</td>
<td>64.01</td>
<td>0.0</td>
<td>64.01</td>
</tr>
<tr>
<td>OCT</td>
<td>129.98</td>
<td>94.00</td>
<td>0.75</td>
<td>70.50</td>
<td>59.48</td>
<td>0.0</td>
<td>0.0</td>
<td>70.50</td>
<td>0.0</td>
<td>70.50</td>
</tr>
<tr>
<td>NOV</td>
<td>0.0</td>
<td>96.50</td>
<td>0.70</td>
<td>67.55</td>
<td>67.55</td>
<td>67.55</td>
<td>67.55</td>
<td>67.55</td>
<td>67.55</td>
<td>67.55</td>
</tr>
<tr>
<td>DEC</td>
<td>4.89</td>
<td>76.50</td>
<td>0.80</td>
<td>61.20</td>
<td>123.86</td>
<td>108.33</td>
<td>45.67</td>
<td>123.86</td>
<td>61.20</td>
<td>93.63</td>
</tr>
<tr>
<td>JAN</td>
<td>1.29</td>
<td>74.93</td>
<td>0.80</td>
<td>59.94</td>
<td>122.51</td>
<td>113.89</td>
<td>6.85</td>
<td>122.51</td>
<td>59.94</td>
<td>103.67</td>
</tr>
<tr>
<td>FEB</td>
<td>14.95</td>
<td>81.79</td>
<td>0.80</td>
<td>65.43</td>
<td>232.99</td>
<td>119.44</td>
<td>20.50</td>
<td>216.66</td>
<td>49.10</td>
<td>111.22</td>
</tr>
<tr>
<td>MAR</td>
<td>76.97</td>
<td>101.10</td>
<td>0.75</td>
<td>76.83</td>
<td>231.85</td>
<td>118.83</td>
<td>75.83</td>
<td>215.52</td>
<td>75.83</td>
<td>110.67</td>
</tr>
<tr>
<td>APR</td>
<td>77.80</td>
<td>117.35</td>
<td>0.75</td>
<td>88.01</td>
<td>242.06</td>
<td>129.04</td>
<td>88.01</td>
<td>216.20</td>
<td>78.48</td>
<td>118.40</td>
</tr>
<tr>
<td>MAY</td>
<td>601.46</td>
<td>98.30</td>
<td>0.70</td>
<td>68.81</td>
<td>532.65</td>
<td>0.0</td>
<td>0.0</td>
<td>68.81</td>
<td>0.0</td>
<td>68.81</td>
</tr>
<tr>
<td>JUN</td>
<td>570.93</td>
<td>85.10</td>
<td>0.80</td>
<td>68.08</td>
<td>502.85</td>
<td>0.0</td>
<td>0.0</td>
<td>68.08</td>
<td>0.0</td>
<td>68.08</td>
</tr>
<tr>
<td>TOTAL</td>
<td>2870.83</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>605.14</td>
</tr>
</tbody>
</table>

Table 8.2. Separation of various soil moisture components using the Grindley (1969) model.
June, enough water is available with no SMD; at the same time, $PE_t = AE_t$, therefore the rainfall minus $PE_t$ is the true amount of water surplus. The water balance:

$$P = AE_t + \text{water surplus} + dS$$

$$dS = AE_t + \text{water surplus} - P$$

$$dS = 728.43 + 2178.31 - 2870.83$$

$$dS = +35.91 \text{ mm.}$$

In theory, if the water balance can be carried out with sufficient accuracy, then the amount of water surplus plus the $AE_t$ should be equal to the amount of rainfall if there is no significant changes in storage. In this example, 35.91 mm of water is found as a positive change of storage. Several reasons could account for this, firstly, the assumed root constants could have some influence, secondly, the percentage of total land thought to have covered by a particular kind of vegetation is based on sensible guesses which could definitely have some influence of the result and thirdly, the other minor vegetation types which were ignored during this calculation also may have some influence on the result.

**Agnew (1982) water balance model:**

It was mentioned previously that the present study area is under active cultivation for rice. Therefore, the quantification of evapotranspiration loss in terms of rice crop production under optimum soil water and fertility conditions is another appropriate method. In this water balance model in addition to rainfall (P) and evaporation ($E_{\text{evap}}$), one other important parameter that is required is the crop co-efficient ($K_{\text{crop}}$) of the reference crop which is rice in this instances. The crop coefficient varies from one crop to another and for a particular crop the selection of the coefficient requires consideration of several important factors (see Dorenbos and Pruitt, 1977). These include primarily crop characteristics, time of
planting/sowing, stage of crop development and the general climatic conditions, particularly humidity and wind speed. Other factors that also affect the value of the crop co-efficient include rate of crop development, length of growing season and frequency of rain or irrigation. Since rice is an important crop, special attention has been given for the correct measurement of \( K_{\text{crop}} \). Dorenbos and Pruitt (1977) have tabulated the up-to-date \( K_{\text{crop}} \) for rice considering every possible factor that may have direct or indirect influence on the crop for different parts of the world.

The year-round cultivation in the present study area allows the production of three varieties of rice (Table. 8.3), therefore special consideration was given to the planting/sowing, growing and harvesting time for each of the varieties along with the prevailing wind speed and humidity to select the appropriate \( K_{\text{crop}} \). As a result, three different sets of crop co-efficient values were obtained for three different varieties of rice but to perform the water balance computation average \( K_{\text{crop}} \) values were used.

The various steps of the water balance computation (Table. 8.4) are presented here with brief descriptions. In the table, columns 1, 2 (average monthly rainfall), 3 (corrected pan evaporation) and 4 (average crop co-efficient) are self explanatory. The PE in column 5 is calculated by multiplying the \( E_{\text{corr}} \) by the corresponding \( K_{\text{crop}} \). The available water (AW) in column 6 is worked out by adding the current month’s rainfall (P) to the previous month’s final soil moisture (FSM). Drainage (D) in column 7 is the available soil moisture (ASM) in excess of field capacity (FC) and that is the amount of water that goes into the sub-surface and turns into effective infiltration (Ie). When the available water is greater than field capacity (which is the case during the months of July, August, September and October) then the initial soil moisture (column 8) of the soil is its field capacity (FC) and that is the maximum quantity the soil can hold as its initial soil moisture (ISM). When the ISM is less than the FC then the ISM is obtained by subtracting...
<table>
<thead>
<tr>
<th>PERIOD 1985-86</th>
<th>MAR</th>
<th>APR</th>
<th>MAY</th>
<th>JUN</th>
<th>JUL</th>
<th>AUG</th>
<th>SEP</th>
<th>OCT</th>
<th>NOV</th>
<th>DEC</th>
<th>JAN</th>
<th>FEB</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AVERAGE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{crop}$</td>
<td>1.15</td>
<td>1.15</td>
<td>1.05</td>
<td>1.05</td>
<td>1.07</td>
<td>1.07</td>
<td>1.03</td>
<td>1.05</td>
<td>1.05</td>
<td>1.00</td>
<td>1.10</td>
<td>1.25</td>
</tr>
<tr>
<td><strong>BORO/IRRI</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.10</td>
<td>1.10</td>
<td>1.25</td>
</tr>
<tr>
<td>$K_{crop}$</td>
<td>1.25</td>
<td>1.25</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.05</td>
<td>1.05</td>
<td>0.95</td>
</tr>
<tr>
<td><strong>AMAN</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{crop}$</td>
<td>1.10</td>
<td>1.10</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>0.95</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>AUS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_{crop}$</td>
<td>1.10</td>
<td>1.10</td>
<td>1.10</td>
<td>1.05</td>
<td>1.05</td>
<td>1.05</td>
<td>0.95</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 8.3. Estimated crop coefficient ($K_{crop}$) for various kinds of rice in Comilla-Noakhali region.
<table>
<thead>
<tr>
<th>PERIOD</th>
<th>P (mm)</th>
<th>E_corrected (mm)</th>
<th>K_crop</th>
<th>PE_t (mm)</th>
<th>AW (mm)</th>
<th>DRAINAGE (mm)</th>
<th>ISM (mm)</th>
<th>AE_t (mm)</th>
<th>FSM (mm)</th>
<th>MD (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JUL</td>
<td>565.97</td>
<td>62.40</td>
<td>1.07</td>
<td>66.77</td>
<td>565.97</td>
<td>125.97</td>
<td>440.0</td>
<td>66.77</td>
<td>373.23</td>
<td>0.0</td>
</tr>
<tr>
<td>AUG</td>
<td>464.29</td>
<td>64.42</td>
<td>1.07</td>
<td>68.93</td>
<td>837.52</td>
<td>397.52</td>
<td>440.0</td>
<td>68.93</td>
<td>371.07</td>
<td>0.0</td>
</tr>
<tr>
<td>SEP</td>
<td>362.30</td>
<td>64.01</td>
<td>1.03</td>
<td>65.93</td>
<td>733.37</td>
<td>293.37</td>
<td>440.0</td>
<td>65.93</td>
<td>374.07</td>
<td>0.0</td>
</tr>
<tr>
<td>OCT</td>
<td>129.98</td>
<td>70.50</td>
<td>1.05</td>
<td>74.03</td>
<td>504.05</td>
<td>64.05</td>
<td>440.0</td>
<td>74.03</td>
<td>365.97</td>
<td>0.0</td>
</tr>
<tr>
<td>NOV</td>
<td>0.0</td>
<td>67.55</td>
<td>1.05</td>
<td>70.93</td>
<td>365.97</td>
<td>0.0</td>
<td>365.97</td>
<td>70.93</td>
<td>295.04</td>
<td>0.0</td>
</tr>
<tr>
<td>DEC</td>
<td>4.89</td>
<td>61.20</td>
<td>1.00</td>
<td>61.20</td>
<td>299.93</td>
<td>0.0</td>
<td>299.93</td>
<td>61.20</td>
<td>238.73</td>
<td>0.0</td>
</tr>
<tr>
<td>JAN</td>
<td>1.29</td>
<td>59.94</td>
<td>1.10</td>
<td>65.93</td>
<td>240.02</td>
<td>0.0</td>
<td>240.02</td>
<td>63.02</td>
<td>177.00</td>
<td>2.91</td>
</tr>
<tr>
<td>FEB</td>
<td>14.95</td>
<td>65.43</td>
<td>1.25</td>
<td>81.79</td>
<td>191.95</td>
<td>0.0</td>
<td>191.95</td>
<td>14.95</td>
<td>177.00</td>
<td>66.84</td>
</tr>
<tr>
<td>MAR</td>
<td>76.97</td>
<td>75.83</td>
<td>1.15</td>
<td>87.20</td>
<td>253.97</td>
<td>0.0</td>
<td>253.97</td>
<td>76.97</td>
<td>177.00</td>
<td>10.23</td>
</tr>
<tr>
<td>APR</td>
<td>77.80</td>
<td>88.01</td>
<td>1.15</td>
<td>101.21</td>
<td>254.80</td>
<td>0.0</td>
<td>254.80</td>
<td>77.80</td>
<td>177.00</td>
<td>23.41</td>
</tr>
<tr>
<td>MAY</td>
<td>601.46</td>
<td>68.81</td>
<td>1.05</td>
<td>72.25</td>
<td>778.46</td>
<td>338.46</td>
<td>440.00</td>
<td>72.25</td>
<td>367.75</td>
<td>0.0</td>
</tr>
<tr>
<td>JUN</td>
<td>570.93</td>
<td>68.08</td>
<td>1.05</td>
<td>71.48</td>
<td>938.68</td>
<td>498.68</td>
<td>440.00</td>
<td>71.48</td>
<td>368.52</td>
<td>0.0</td>
</tr>
<tr>
<td>TOTAL</td>
<td>2870.83</td>
<td>887.65</td>
<td>1.718.05</td>
<td>784.26</td>
<td>103.39</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 8.4. Separation of various soil moisture components using the Agnew (1982) model.
the amount of drainage (D) from the available water (AW). When there is not much water available to bring the ISM to its field capacity (FC) (which is the case during the months of November, December, January, February, March and April) then the total amount of ISM slowly decreases until it drops down to the wilting point (WP) and in theory soil moisture can not drop below WP. Since there is very little water available in excess of WP, therefore the plants will also have very little water to transpire. As a result $AE_t$ in column 9 would be much lower than the potential rate. At this stage $AE_t = (ISM-WP)$ when $(ISM-PE_t) < WP$ (January, February, March and April), otherwise in all other circumstances $AE_t = PE_t$ (May, June, July, August, September and October) even if the ISM < FC (November and December). Final soil moisture (FSM) in column 10 is the amount of ISM in excess of $AE_t$ but since FSM can not fall below the WP, therefore minimum FSM = WP (January, February, March and April). When $PE_t = AE_t$ there is no soil moisture deficit (column 11) but when $AE_t < PE_t$ then the SMD is the difference between $PE_t$ and $AE_t$ (January, February, March and April). The field capacity of 440 mm and the wilting point of 177 mm for the present area were obtained from the study conducted by Rohman (1986) of Soil Resources Development Institute (SRDI), Dhaka, Bangladesh. The resultant water balance is:

$$P = D(I_c) + SR + AE_t + dS$$

$$2870.83 = 1718.05 + 0 + 784.26 + dS$$

$$dS = -368.52 \text{ mm.}$$

**Drawbacks:**

This method was developed by Clive Agnew (1982) to compute the water balance for a semi-arid part of West Africa and is particularly applicable where the soil condition is dominantly sandy and where surface water run-off is negligible. Therefore, strictly speaking, this method is not entirely
appropriate for the present conditions where the soil is predominantly loamy in
texture and at the same time considerable amount of surface run-off takes place.
The method is not acceptable for computation on a daily or even weekly basis but
a monthly basis calculation can be accepted with caution because it averages out
most of the extreme conditions if it is not characterized by a very high flood.

Comments:

The separation of different components of rainfall by the
Grindley model (1969, 1970) is widely used for all climatic conditions with
reasonable accuracy yet it depends on essential parameters which are crucial to
obtain a satisfactory result. The Agnew model (1982), on the other hand, though
applicable for certain climatic and soil conditions, can be used to obtain sensible
results for most conditions on a broader scale with certain reservations. It is a good
method for comparative study but can be quite useful when most of the available
methods can not be used.

b) Effluent flow to rivers, canals and other water bodies:

Apart from the major perennial rivers and canals, the study
area also has quite a large number of ponds, beals and haors (large depressed
basins where shallow water remains during most of the year in a stagnant
condition). Regardless of flow conditions, the water bodies which sustain water all
the year round or for most of the year receive a continuous supply of ground water,
especially during the dry season (winter season). The quantity of river/canal flow
that is derived from ground water resources is called the base flow, which can be
quantified by analyzing the river discharge hydrograph. Several analytical and
numerical techniques are available to separate the ground water component of
stream flow. For the present case, the method developed by the Institute of
Hydrology (1978), which has been written in the form of a fortran 77 program (Appendix. 8.1 and 8.2), has been adapted to analyze the hydrograph for separating base flow.

Other than the Gumti river, the discharge measurement at a single point was available for only the Muhuri river. The Muhuri river discharge measurement is available for the year 1980-81 (Fig. 8.6) and 1982-83 (Fig. 8.7) measured at Parshuram station (BWDB station 212). The hydrograph analysis for Gumti river (Figs. 8.1 to 8.4) shows that on an average about 67 percent (or BFI = 0.6683) of the flow originates from ground water discharge which amounts to about 14000 cumec-days/annum. On the other hand, the ground water component of the Muhuri river discharge flow constitutes about 38 percent (or BFI = 0.3756) which is one-third of the total flow indicating that the Muhuri river is less dependent on base flow in comparison with the Gumti river. The average quantity of base flow calculated during this two year period is about 2700 cumec-days/annum.

Unfortunately, river discharge measurements are not available for the other rivers to accurately measure the base-flow component. In such a situation, the assumptions made in Section 8.2.2.c to estimate the influent seepage can be used along with the textural property of the aquifer to estimate the total base-flow. The aquifer material that constitutes the northern part is made up of relatively coarser material and via these materials the northerly located Titas, Gumti, Buri and Dakatia rivers maintain continuity with the aquifers. Therefore it may be sensible to assume that these rivers have a similar range of base-flow. The aquifer material, on the other hand, in the southern part is dominated by finer sandy sediments (Section 3.3.2) through which it maintains continuity with the overlying Noakhali canal, Little Feni and Muhuri rivers. In the southern part therefore similar range of base-flow may also be imagined for these rivers. The
Fig. 8.6. Hydrograph showing the baseflow and surface run-off component.
Fig. 8.7. Hydrograph showing the baseflow and surface run-off component.
estimated base-flow for the northern rivers (Titās, Buri, Gumti and Dakatia rivers) on the basis of the foregoing assumptions is about 14000 \( \times 4 = 56000 \) cumec-days/annum, considering the Gumti river base flow as the ideal. The base-flow for the southern rivers (Noakhali canal, Little Feni and Muhuri river) is about 2700 \( \times 3 = 8100 \) cumec-days/annum, considering the Muhuri river base-flow as the ideal. It follows the total base-flow of all the rivers in the entire region is about 56000 + 8100 = 64100 cumec-days/annum, which does not take into account the base-flow loss caused by the two bounding rivers, the Meghna and the Feni. It is true that a significant amount of base-flow of the Meghna river is derived from the presently studied main aquifer system but the major part of its base-flow comes from the aquifer system of the eastern, northern and north-eastern parts of the country. Similarly, the major part of the base-flow of the Feni river is derived from the aquifer system of the further south-eastern hilly region. The influent seepage of these two rivers have not been taken into account, therefore the exclusion of the effluent seepage of the two rivers should in fact cancel each other rather than upsetting the results.

c) Leakage into contiguous strata:

As a consequence of the relationship between the aquifers described in Section 8.2.2.e there could be some leakage into the contiguous strata from the main aquifer under favourable circumstances. If so the quantity should be small because under normal conditions, the ground water in the second aquifer remains under greater pressure than atmospheric therefore there will always be a tendency for the water to move upwards. The movement depends on the potentiometric head conditions in both aquifers. When the heads are equal then the flow of ground water will depend on the relative density of the two waters. At present, it is not possible to make any comment on which way the flow occurs and

how much water is flowing from one aquifer to the other.

d) Subsurface outflow across aquifer boundaries:

Applying the same procedure which was applied to identify the different peripheral aquifer boundary zones of subsurface inflow, five different outflow zones or sections for the wet period flow-net map and six different outflow zones or sections for the dry period flow-net map have been identified (Fig. 8.5). The Darcy formula was used to assess the quantity of outflow through each of the identified zones. The total volume of outflow \(2.1 \times 10^7\) from the entire basin has been determined taking the average of the total outflows (Table 8.5).

e) Artificial withdrawal by pumping:

It has been shown previously that ground water is used both for drinking and for irrigation purposes. The most extensive use is made for the irrigation of croplands since the area has a high proportion of excellent cropland. In this section the quantitative assessment of the total withdrawal of ground water by pumping has been estimated on the assumption that the ground water is only used for drinking and irrigation purposes and ignoring industrial and other minor uses.

Until December, 1984 there were about 1921 deep tube wells (DTW) and 4589 shallow tube wells (STW) on record, of which a significant number are either out of order or are permanently abandoned (pers. comm. Pitman, G.T.K.). There were also a significant number of purpose built shallow hand tube wells before the installation of deep tube wells which were previously used for drinking water purposes. But with the rapidly increasing number of power driven shallow and deep tube wells their installation has virtually ceased a long time ago
<table>
<thead>
<tr>
<th>TYPE</th>
<th>PERIOD</th>
<th>ZONES</th>
<th>ZONE WISE FLOW</th>
<th>TOTAL OUTFLOW (GumeC/Year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUBSURFACE</td>
<td>WET PERIOD</td>
<td>ZONE-1</td>
<td>1.5 x 10^6</td>
<td>2.1 x 10^7</td>
</tr>
<tr>
<td>OUTFLOW</td>
<td></td>
<td>ZONE-2</td>
<td>3.7 x 10^6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZONE-3</td>
<td>7.3 x 10^6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZONE-4</td>
<td>3.7 x 10^6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZONE-5</td>
<td>5.2 x 10^6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DRY PERIOD</td>
<td>ZONE-1</td>
<td>2.4 x 10^6</td>
<td>2.1 x 10^7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZONE-2</td>
<td>4.4 x 10^6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZONE-3</td>
<td>3.4 x 10^6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZONE-4</td>
<td>3.3 x 10^6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZONE-5</td>
<td>4.3 x 10^6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZONE-6</td>
<td>3.7 x 10^6</td>
<td></td>
</tr>
<tr>
<td>AVERAGE</td>
<td>TOTAL OUTFLOW</td>
<td>2.1 x 10^7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table. 8.5. Subsurface Outflow of ground water along various Zones across the boundary.
and most of the existing ones are already out of service. Therefore their influence on ground water withdrawal has altogether been ignored. To make sure that the amounts of ground water being withdrawn are not underestimated, a conservative approach has been adopted by assuming that at the time of calculation all wells (DTW and STW) are in working condition and are able to withdraw ground water when it is required. The wells are in constant use for irrigation during the dry period, the late part of the post-monsoon period and the early part of the pre-monsoon period (December until May). On average during this period the wells are in operation about eight hours a day, which also automatically fulfils the drinking water requirement. During the remainder of the year (June until November), when ground water irrigation is not required, the wells are only in short time use to meet drinking water requirements. On average during this time of the year the wells are run about an hour a day. The statistics of the ground water withdrawals are summarized in the following table:

<table>
<thead>
<tr>
<th>Duration</th>
<th>Well Type</th>
<th>Irrigation period (hrs)</th>
<th>Other period (hrs)</th>
<th>Gross Total hours</th>
<th>Gross Total days</th>
<th>annual Withdrawal (m³/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total run (DTW)</td>
<td>1456</td>
<td>183</td>
<td>3278</td>
<td>136.58</td>
<td>1.31 x 10⁹</td>
<td></td>
</tr>
<tr>
<td>Total run (STW)</td>
<td>1456</td>
<td>183</td>
<td></td>
<td></td>
<td>0.81 x 10⁹</td>
<td></td>
</tr>
</tbody>
</table>

A deep tube well has a capacity of 58 l/s (5000 m³/d) and a shallow tube well, on the other hand, has a capacity of 15 l/s (1300 m³/d). Therefore on the basis of the foregoing assumptions and available information, the total annual withdrawal from both the DTW and STW is about 2 x 10⁹ m³/d.
8.2.4 Ground water Budget:

A ground water budget is the quantitative assessment of the total incoming water, total outgoing water and the changes of the ground water storage of a ground water basin over a specified period of time. Under normal conditions when all the components are known, the volume of inputs (I) should be equal to the volume of output (O) with the addition or subtraction of the changes in storage, when expressed in mathematical terms it takes the following form:

\[ I = O + dS \]

where

- \( I \) = Inputs
- \( O \) = outputs
- \( dS \) = Changes in storage.

A ground water balance is very much like the surface water balance and requires a proper identification the different components of recharge as well as discharge because some of the components are more important than others. This largely depends on the climate, regional hydrogeology and the amount of ground water used for various purposes. The present ground water regime is under the direct control of tropical humid monsoonal climatic conditions accompanied by periodic flooding and is under active cultivation.

Among the recharge elements, the rainfall replenishment is found to be the largest source of recharge, followed by influent surface water seepage, then followed by irrigation return flow and finally followed by subsurface inflow across aquifer boundaries. The contribution towards recharge from leakage from contiguous strata and influent sewage flow was found to be very small and insignificant. Evapotranspiration, on the other hand, is identified as the largest form of discharge, followed by effluent flow to rivers, canals ponds etc, then followed by artificial withdrawal, and finally followed by subsurface outflow across aquifer boundaries. An out flow in the form of leakage into contiguous strata is estimated to be of negligible amount.
The estimation of effective infiltration (Ie) was carried out in two different ways. The first method adapted the Grindley (1969,1970) and Agnew (1982) form of water balance approach while the second method considered the volumetric changes obtained from ground water fluctuation contour map (Fig. 4.5 and Table 4.2). The results obtained by these two methods are grossly different and show a three-fold variation, though in theory they should be reasonably close to one another. The resulting ground water balance is therefore presented in two different budgets. The first budget (Table 8.6) includes the (Ie) value obtained from the Grindley (1970) and Agnew (1982) method which suggests a huge surplus of ground water recharge in comparison with discharge. The second budget (Table 8.7) consider the Ie value obtained from the volumetric changes of ground water presented a huge shortage in ground water recharge suggesting an excessive ground water mining condition, which is not the actual case.

An examination of the change in ground water level record is presented in the following table:

<table>
<thead>
<tr>
<th>Location</th>
<th>Incremental changes between successive years (mm)</th>
<th>overall incremental changes (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W 4</td>
<td>+138.68 -213.36 +640.08 +096.01 -640.08 +021.33</td>
<td></td>
</tr>
<tr>
<td>W 58</td>
<td>+154.69 -106.68 +512.06 -181.36 -245.36 +133.35</td>
<td></td>
</tr>
<tr>
<td>W 142</td>
<td>+064.01 +032.01 +053.34 +096.01 -042.67 +202.69</td>
<td></td>
</tr>
</tbody>
</table>

It shows that there was a general decline of ground water level during the 1985-86 water year by comparison with the previous 1984-85 water year (Fig. 4.1) and this lowering has been recorded in all three observation wells (W4, W58 and W142). But an inspection of the incremental changes of the ground water level for
<table>
<thead>
<tr>
<th>Recharge Components</th>
<th>(m$^3$/Year)</th>
<th>Discharge Components</th>
<th>(m$^3$/Year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Infiltration ($I_e$)</td>
<td>1.81 x 10$^8$</td>
<td>Actual Evapotranspiration ($A_{eb}$)</td>
<td>7.73 x 10$^8$</td>
</tr>
<tr>
<td>Irrigation Return Flow</td>
<td>2.66 x 10$^8$</td>
<td>Effluent Flow to Rivers etc.</td>
<td>5.51 x 10$^8$</td>
</tr>
<tr>
<td>Influent Seepage from Rivers etc.</td>
<td>7.08 x 10$^8$</td>
<td>Subsurface Outflow through Aquifer Boundaries</td>
<td>2.1 x 10$^7$</td>
</tr>
<tr>
<td>Subsurface Inflow through Aquifer Boundaries</td>
<td>2.3 x 10$^7$</td>
<td>Artificial Withdrawal</td>
<td>2.13 x 10$^8$</td>
</tr>
<tr>
<td>Total Recharge</td>
<td>1.9 x 10$^10$</td>
<td>Total Discharge</td>
<td>1.5 x 10$^10$</td>
</tr>
<tr>
<td>Recharge Excess</td>
<td>4.0 x 10$^9$</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 8.6. First ground water budget using the $I_e$ value calculated by the Grindley (1969) and Agnew (1982) model.
<table>
<thead>
<tr>
<th>RECHARGE COMPONENTS</th>
<th>ESTIMATED VOLUME (m³/YEAR)</th>
<th>DISCHARGE COMPONENTS</th>
<th>ESTIMATED VOLUME (m³/YEAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFFECTIVE INFILTRATION (Iₑ)</td>
<td>5.71 x 10⁹</td>
<td>ACTUAL EVAPOTRANSPIRATION (AEₑ)</td>
<td>7.73 x 10⁹</td>
</tr>
<tr>
<td>IRRIGATION RETURN FLOW</td>
<td>2.66 x 10⁸</td>
<td>EFFLUENT FLOW TO RIVERS etc.</td>
<td>5.51 x 10⁹</td>
</tr>
<tr>
<td>INFLENT SEEPAGE FROM RIVERS etc.</td>
<td>7.08 x 10⁸</td>
<td>SUBSURFACE OUTFLOW THROUGH AQUIFER BOUNDARIES</td>
<td>2.10 x 10⁷</td>
</tr>
<tr>
<td>SUBSURFACE INFLOW THROUGH AQUIFER BOUNDARIES</td>
<td>2.30 x 10⁷</td>
<td>ARTIFICIAL WITHDRAWAL</td>
<td>2.13 x 10⁹</td>
</tr>
<tr>
<td>TOTAL RECHARGE</td>
<td>6.7 x 10⁹</td>
<td>TOTAL DISCHARGE</td>
<td>1.5 x 10⁹</td>
</tr>
<tr>
<td>RECHARGE DEFICIT</td>
<td>8.3 x 10⁹</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table. 8.7. Second ground water budget using the Iₑ value calculated from the ground water fluctuation contour map.
all the three observation wells during the last five years provides a different picture. With the exception of 1985-86 water year, W142 shows a continuing rise in water level therefore the incremental change is always positive. W4 and W58 represent alternative positive and negative incremental changes. When the incremental change in ground water level during the last five years is added together in the above table the overall incremental change is found to be positive which implies that no permanent lowering of ground water level has taken place. The general depletion of ground water level in the preceding year was fully recovered by the following rainfall. It also suggests that ground water withdrawal is less than the available recharge, indicating no use of permanent ground water storage, which implies that no changes in permanent ground water storage have taken place during the last five years.

8.3 Ground water management:

8.3.1 Introduction:

The success of a ground water development project and the obtaining of long term benefit from it, require that skilful management should be put into practice as soon as possible. The management technique is a lot easier to effect efficiently if the water balance of the region is known or can be estimated to a reasonable degree of accuracy. During a youthful state of development management practice is unappreciated though desirable. Effective management practice becomes increasingly necessary when the mature state of ground water development prevails in a ground water regime. The management practice become absolutely essential during Old age and Rejuvenation states of development to rescue the resources from any further damage. During these stages a great deal of manipulation of resources may be required and the special circumstances when conjunctive use of surface water and ground water requires critical assessment of
both permanent and temporary storage and perennial yield. Only sophisticated management equipped with technological innovation can determine whether a mining yield should be put into practice because mining of ground water is prone to produce so many undesirable effects.

8.3.2 Development state of resources:

It was shown in Section 8.2.4 that the estimation of $(I_a)$ by two different methods gave a wide variability in the results (Tables 8.6 and 8.7). Therefore two different water budgets have been prepared to demonstrate the differences in the final results. In the first, the natural inflow is found to be much higher than the combined natural and artificial outflow. The second water budget, on the other hand, demonstrates that the natural inflow is much lower than the joint natural and artificial outflow.

Using the criteria of Jones (1972), the state of development of ground water has been assessed. The first water balance computation demonstrates that the resource is at a Youthful state of development but the second water balance results suggest that the resources has passed into an Old age state of development. It can be argued that the arrival of Old age state should be indicated by the response of other parameters such as continuous decline of water table, severe deficit of moisture both in the soil and unsaturated zone which should cause destruction of shallow rooted crops/vegetation. But none of these undesirable conditions are seems to be prevailing in the study area in general, therefore, it is unlikely that the Old age state of development has been reached.

8.3.3 Perennial yield:

The modern concept of optimum ground water yield is expressed in terms of perennial yield which have shadowed the traditional safe yield concept
because the optimum yield does not depend on the recharge alone. The perennial yield of a ground water basin defines the rate at which water can be withdrawn perennially under specified condition of operation without producing an adverse result such as progressive depletion of the water resources, land subsidence, degradation of ground water quality, excessive pumping cost and interference with the prior water rights.

The maximum quantity of water that can be extracted from an underground reservoir depends on the perennial yield. In general, the basin recharge criterion governs perennial yield because exceeding this factor is normally responsible for inducing other undesired results. Possibly for the present ground water regime, the factors likely to produce undesired results are not present indicated by the following facts: 1) no long term decline of ground water level is visible; 2) no significant changes of ground water storage have taken place; and 3) the youthful state of development of resources prevails. The quantitative determination of perennial yield therefore has been carried out considering the recharge as the limiting factor. At this point perennial yield is defined in terms of a rate at which ground water can be withdrawn from a basin over a representative time period without producing significant changes in ground water storage and the perennial yield is estimated from the water balance computation. The volume of total recharge in excess of natural discharge is equivalent to perennial yield in this case. On the basis of the first water balance computation (Table 8.6) the amount of perennial yield is about 5.7 x 10⁹ (= 1.9 x 10¹⁰ - 1.33 x 10¹⁰) m³/year. The total volume of present artificial withdrawal is about 37 percent of the estimated perennial yield.

A consideration of the second water balance computation (Table 8.7) shows that the available perennial yield is much lower than the natural discharge. Under this sort of prevailing condition a natural discharge of 6.6 x 10⁹
m³/year plus the total artificial withdrawal of 2.13 x 10⁹ m³/year, gives a total of
8.73 x 10⁹ m³/year from permanent storage in the form of mining yield.

8.3.4 Ground water in storage:

The volume of ground water in storage is determined by multiplying the average saturated thickness of the aquifer by the area over which the aquifer is areally extended and further multiplied by the specific yield i.e:

Ground water in storage = b x A x S,

where
b = thickness of the aquifer in case of a confined aquifer or the saturated thickness of the aquifer in case of an unconfined aquifer;
A = area of the ground water basin; and
S = specific yield.

Since the nature of the present aquifer under study ranges from leaky confined to confined therefore the saturated thickness of the aquifer would be the total average thickness of the aquifer. The thickness of the aquifer (Section 3.3.3) ranges from <100 ft (>30 m) to >445 ft (>135 m) with an average thickness of about 250 ft (about 75 m). In the absence of any direct measurement a specific yield value of 20 percent has been considered acceptable on the basis of lithology and various published results (specific yield selection is justified in Section 4.5). Therefore, the volume of ground water in storage for the present basin area which is about 10,223 sq. km. is:

75 m x (10,223 x 1000000 m²) x 0.20
= 1.53345 x 10¹¹ = 1.5 x 10¹¹ cubic metres of ground water.
CHAPTER 9 CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions.

9.2 Recommendations.
9.1 Conclusions:

On the basis of the analysis of various geological and hydrogeological components the following conclusions can be drawn about the ground water resources and the aquifer materials:

1) In the central part of the geosynclinal basin fresh ground water occurs at a depth of more than 2296 ft (700 m) beneath the present study area. Within this depth, six major well-defined potential aquifers containing fresh water have been identified. The present detailed evaluation of ground water potential is limited to the main aquifer (no.1) which in many places maintains a hydraulic continuity with aquifer no. 2 where the separating clay aquitard is either missing or negligibly thin.

2) The main aquifer is almost entirely covered by a clay/silt layer of variable thickness that ranges from <10 ft (<3 m) around the Lalmai Hills to >300 ft (>90 m) around Noakhali town. In the Lalmai Hills there is no clay/silt layer other than the covering soil because the hill is an outcrop of the aquifer material itself. The aquifer is mostly recharged by the indirect infiltration of surface precipitation through this confining layer, although small amounts of recharge are derived from the outcrop areas.

3) The aquifer itself largely consists of a continuous thick layer of sandy materials but in some places (particularly around Lalmai Deltaic Plain area) the aquifer is separated locally by one or more discontinuous layers of clay. In most places, particularly in the upper part the aquifer, there is a clear gradation in grain size, the finer material being at the top and coarsening downwards. The bottom part of the aquifer is occasionally associated with gravels and pebbles. The aquifer maintains a thickness of more than 200 ft (>60 m) in most places which sharply increases to
more than 400 ft (>120 m) towards the southernmost part where the dominant grain size also changes to fine and medium sand.

4) With the exception of Kotwali (Comilla town), the present rate of artificial withdrawal does not produce any undesirable effects on the resources of a regional scale. The seasonal dry-period loss of ground water storage is restored rapidly and regularly which is indicative of a high value of effective infiltration. Moreover, in some places there is a steady rise of maximum water level suggesting an increased availability of the temporary storage. The limited small-scale decline of maximum water level around Comilla town seems to be primarily because of excessive unplanned annual abstraction and can be regarded as a local event. Further study is recommended to determine the exact nature and extent of the problem.

5) The ground water flow pattern is complicated because of its complex relationship with the surface water, with all the perennial rivers maintaining a direct hydraulic continuity with the ground water. Most of the down-stream sections show the characteristics of gaining streams while the upstream sections show characteristics of losing streams except the Little Feni river which shows the reverse characteristics.

6) A similar distribution of resource potential prevails over the entire study area. The annual fluctuation is at a maximum near the places from where maximum amount of ground water is withdrawn during the dry periods. The higher elevation of the water table around Comilla town (which also coincides with the higher fluctuation) to some extent could well be due to the partial blockage of ground water flow by the north-south trending Lalmai Hills located to the west of Comilla town.

7) The analytical results of the step-drawdown test data suggest that most of the test
wells were not properly developed with adequate pumping prior to the test and a significant amount of well development took place during the test exercise. The aquifer loss factor ($B_l$) ranges from a maximum of 19.3 sec/ft$^2$ for Nabinagar to a minimum of 7.0 sec/ft$^2$ for Chandina. The well loss factor ($C_l$) does not indicate any major abnormality and ranges from a maximum of 1.49 sec$^2$/ft$^4$ for Nabinagar to a minimum of 0.96 sec$^2$/ft$^4$ for Laksam and is supported by the minimal differences between the measured and the calculated drawdown values. Highly efficient well conditions are obtained for all the test wells. The fundamental relationship between transmissivity and specific capacity has successfully been demonstrated by the test wells.

It was concluded from the analysis of aquifer test data that the aquifer condition ranges from non-leaky confined to leaky confined. The confined condition prevails in a small area (around Chauddagram and Feni upazilla) located in the eastern part while leaky confined conditions prevail over the remainder of the area. The maximum transmissivity (>1400 m$^2$/d equal to about 94,000 Imp.gal/day-ft) is distributed in the central part around the Haziganj upazilla while the minimum transmissivity (<400 m$^2$/d equal to about 27,000 Imp.gal/day-ft) is recorded in the eastern part. This coincides with the ideal non-leaky part of the aquifer but does not necessarily mean that confined aquifer conditions necessarily provide lower transmissivities. The maximum (41 m/d) and minimum (5 m/d) values for hydraulic conductivity are obtained from the same localities having maximum and minimum transmissivity values. In most places the amount of leakage is quite small. The maximum (BL = 368 m) and minimum (BL = 1930 m) leakage values are obtained around the Burichong and Haziganj upazilla, respectively. The average storativity value ranges from $3.7 \times 10^4$ in Haziganj to $4.1 \times 10^3$ in Chandina.
9) The general distribution of dissolved solids is very low, although the TDS concentration (>1100 mg/L) at well 120 is unusually high in comparison with the rest of the ground water; yet even that concentration is well below the EEC safety limit.

10) The ground water in its initial stage appears to have been an essentially NaHCO₃ type in nature but as it moves in different directions hydrochemical evolution modifies the ground water into a mixed NaHCO₃/Cl type because of ion exchange and mixing with connate water.

11) The hydrochemical evolution is found to have been dominated by the ion exchange processes though other processes particularly mixing, dissolution, and reverse ion exchange, also play important roles in classifying the water types. The combined action of these processes has given rise to two distinct types of water. The first type is the ion exchanged water while the second type is the old brackish water; the first type dominates over the second.

12) The saturation indices calculated using the hydro-chemical PHREEQE model provides some interesting results about equilibrium status because of the rock-water inter-action. The X-Y plot of Calcite and Dolomite revealed the following points: a) the degree of saturation of the water tends to increase with increasing distance from the outcrops, and b) the degree of saturation also increases with increasing depth of water.

13) Although at present most of the ground water in its natural state does not provide any injurious effects on heath, its long-term potability is questionable with a rising concentration for some of the constituents in some of the wells, particularly
potassium, manganese, phosphate and silica. From the irrigation point of view most waters are suitable for most crops, except in a few wells where the mixing of ground water with connate water and sea water has initiated the deterioration of the water quality, and will require regular monitoring.

14) Rainfall replenishment is found to be the most important recharge mechanism followed by influent seepage, irrigation return flow and sub-surface inflow. The highest amount of ground water is discharged by evapotranspiration followed by effluent flow, artificial withdrawal and sub-surface outflow. The annual ground water replenishment calculated by two different methods has produced a three-fold variation in effective infiltration ($I_e$) values which raises some doubt on the quality of the basic raw data (field measurements). The value (1775 mm) obtained by the combined Grindley and Agnew models is the most logical amount of ground water replenishment for an area which enjoys one of the highest rainfalls in the world (about 2900 mm).

15) The water balance computation using the $I_e$ value obtained from the Grindley and Agnew methods suggest a large recharge surplus and categorises the resources at a Youthful state of development. The volume of Perennial Yield is about $5.7 \times 10^9$ m$^3$/year (557.57 mm) and the present amount of ground water withdrawal is about 37 percent of the perennial yield. Available ground water in storage is estimated to be about $1.6 \times 10^{11}$ cubic metres.
9.2 Recommendations:

The following recommendations are suggested on the basis of the problems that were encountered during the collection and analysis of the relatively scarce basic data.

1) In order to encourage new research workers, some of the existing data distribution systems as well as the data retrieval systems need to be changed in order to improve access to the data. The data-bank section of every organization should have a subsection to deal with the data distribution process and make it more efficient.

2) During the analysis and preparation of geological cross-sections it was found that most of the lithological logs could not be identified because of inadequate description of the location. Out of several thousands of logs available, many sites could not be located and only 367 lithological logs with identifiable locations were available. A better representation of the subsurface conditions could have been prepared if all the lithological logs had been used. Any future drilling programme should be accompanied by a more accurate description of the site locations.

3) Even when information is available another major problem is its reliability. The question of reliability was serious during the construction and interpretation of the water table contour maps which are directly and indirectly essential to an understanding of the hydrogeological system. In the water table contour map preparation, some measurements were found which defied logical explanation. This problem could be primarily for two reasons: 1) the measurement of water levels was not properly carried out,
or 2) the ground elevation was not properly determined. Therefore, special precautions are required if beneficial results are expected from the analytical results because an accurate interpretation of incorrect data makes for a meaningless exercise.

4) If the contour maps can be extended towards the natural ground water divides which are located further east in India, by including more ground water records from the Indian part, the true flow pattern would be better understood and delineated.

5) The conduct of the constant rate tests are quite satisfactory, though the wells on which tests were carried out were not uniformly distributed over the area. A more uniform distribution is needed for accurate depiction of the variation in hydraulic properties on which further interpretations are based. Therefore, further pumping tests in selected areas are recommended to up-date the existing hydraulic parameter information. This is particularly so in the southern part where lithological changes were found to be more frequent over short distances. In the present work the hydraulic properties assigned to the southern part of the study area have been grossly idealized and are based on an insufficient number of pumping test analysis results.

6) The step-drawdown test data are probably the worst example of how badly some of the tests were carried out. None of the tests followed any standard procedure. Pumping tests in general, particularly the variable rate tests, are very costly exercises. Therefore it is recommended that more care should be undertaken in carrying out such data collection. Also the interpretation is very frustrating if the basic pump test data are not correct and results in
the miscalculation of various parameters relating to well performances.

7) Any future chemical analysis of ground water samples must include the analysis of potassium and sulphate along with the other major ions in order to make the analysis complete. This is essential for checking the validity of quality data because a meaningful interpretation of existing hydrochemical evolution can only be obtained from reliable sets of data.

8) The ground water is of good quality at the moment under the present rates of withdrawal and there is no sign of any undesirable effects such as deterioration of ground water quality. With increasing withdrawal, the existing limited distribution of inferior quality water and saline ground water could become more widespread and may become a serious cause for concern. Therefore, it is recommended that sampling for chemical analysis should be continued and more ground water wells should be brought into the quality monitoring net-work to safeguard the ground water resources for the greater benefit of the region.

9) The computation of the ground water balance could be more accurate if the influent seepage and irrigation return flow components of ground water recharge as well as the artificial withdrawal component of ground water could be more accurately estimated. To perform any future water balance computation it is therefore recommended that the following steps should be considered: a) the discharge measurement at two different convenient points across the area should be considered for all the rivers, b) the statistics about how many hours the wells are run and how much ground water is withdrawn seasonally and annually from a particular well should be collected as far as
possible. These are the basic data used to estimate the artificial ground water withdrawal component and, c) more realistic ways should be formulated to estimate the irrigation return flow component. The present work suggests that some irrigation water is returning to the ground as irrigation return flow but no attempt has yet been made to quantify such losses. In the present work the estimation has been based on sensible guesses which may not be truly representative. Any return flow effectively reduces the net pumpage from the aquifer, so in the long term its magnitude should be assessed. In the future the irrigation return flow is going to be more meaningful with the continuous increase of ground water withdrawal.

10) It is very important that the users as well as the persons or groups responsible for the maintenance of the wells understand the importance of the ground water resource. They should be instructed to make a record of the actual pumpage and their uses i.e. how much ground water is withdrawn, how much is used for irrigation purposes and how much is used for drinking purposes. To make sure that it has been carried out properly, an inspection team should visit the well site periodically. Certain education programmes should be undertaken by the responsible organizations so that both kinds of people become encouraged spontaneously to protect the resources for the greater benefit of the region.

11) Since considerable amounts of surface water are used continuously to irrigate the low-lying areas adjacent to the rivers, some scheme should be undertaken to prepare a record about how much surface water is used for irrigation purposes. This parameter is also required for the correct interpretation of the irrigation return flow.
12) Without adequate data it is impossible to undertake quantitative studies. Considering the significant time and money spent on data gathering by a variety of authorities in Bangladesh, it is recommended that quality control of all types of data is initiated with joint rather than duplicate monitoring schemes.
REFERENCES


Jones, P. H., 1985: Geology and ground water resources of Bangladesh, Hydrogeology Inc, Baton Rouge, Louisiana, U.S.A.


Rohman, M. N., 1986: Determination of physical properties of some soils on the old Brahmaputra and old Meghna estuarine flood plain, Soil Resources Development Institute (SRDI), Dhaka, Ministry of Agriculture, Govt. of the Peoples Republic of Bangladesh.


UNDTCD/BWDB (GWC)., 1982: The hydrogeologic conditions of Bangladesh, Technical report (DP/UN/BGD-74-009/1).


Wilcox, L. V., 1955: Classification and use of irrigation waters., U.S. Dept. of Agriculture, circ. 969.


APPENDICES
APPENDIX. 4.1: WATER LEVEL MEASUREMENTS USED TO PREPARE VARIOUS TYPES OF CONTOUR MAP AND FLOW PATTERN.

<table>
<thead>
<tr>
<th>BWDB Location</th>
<th>New Location</th>
<th>Elevation of M. P.</th>
<th>Depth of W. L. from M. P.</th>
<th>Elevation of W. L.</th>
<th>Depth of W. L. from M. P.</th>
<th>Elevation of W. L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co 35</td>
<td>2</td>
<td>9.45</td>
<td>3.32</td>
<td>6.13</td>
<td>3.07</td>
<td>6.38</td>
</tr>
<tr>
<td>Co 59</td>
<td>3</td>
<td>8.71</td>
<td>Not available</td>
<td>1.57</td>
<td>7.14</td>
<td></td>
</tr>
<tr>
<td>Co 25</td>
<td>4</td>
<td>8.18</td>
<td>5.45</td>
<td>2.73</td>
<td>1.78</td>
<td>6.40</td>
</tr>
<tr>
<td>Co 36</td>
<td>5</td>
<td>5.43</td>
<td>4.23</td>
<td>1.20</td>
<td>1.27</td>
<td>4.16</td>
</tr>
<tr>
<td>Co 63</td>
<td>8</td>
<td>6.35</td>
<td>7.46</td>
<td>-1.11</td>
<td>6.42</td>
<td>-0.07</td>
</tr>
<tr>
<td>Co 12</td>
<td>10</td>
<td>5.68</td>
<td>5.15</td>
<td>0.53</td>
<td>1.57</td>
<td>5.11</td>
</tr>
<tr>
<td>Co 46</td>
<td>12</td>
<td>6.37</td>
<td>Not available</td>
<td>1.64</td>
<td>4.73</td>
<td></td>
</tr>
<tr>
<td>Co 47</td>
<td>13</td>
<td>10.20</td>
<td>3.93</td>
<td>6.27</td>
<td>1.59</td>
<td>8.61</td>
</tr>
<tr>
<td>Co 24</td>
<td>14</td>
<td>5.44</td>
<td>4.15</td>
<td>1.29</td>
<td>1.40</td>
<td>4.04</td>
</tr>
<tr>
<td>Co 54</td>
<td>16</td>
<td>7.66</td>
<td>5.48</td>
<td>2.18</td>
<td>2.18</td>
<td>5.48</td>
</tr>
<tr>
<td>Co 56</td>
<td>17</td>
<td>4.63</td>
<td>5.28</td>
<td>-0.65</td>
<td>1.54</td>
<td>3.09</td>
</tr>
<tr>
<td>Co 37</td>
<td>19</td>
<td>6.47</td>
<td>5.05</td>
<td>1.42</td>
<td>1.17</td>
<td>5.30</td>
</tr>
<tr>
<td>Co 23</td>
<td>20</td>
<td>6.00</td>
<td>Not available</td>
<td>1.04</td>
<td>4.96</td>
<td></td>
</tr>
<tr>
<td>Co 44</td>
<td>21</td>
<td>5.87</td>
<td>4.26</td>
<td>1.61</td>
<td>3.04</td>
<td>4.26</td>
</tr>
<tr>
<td>Co 1</td>
<td>22</td>
<td>6.86</td>
<td>4.60</td>
<td>2.26</td>
<td>1.32</td>
<td>5.54</td>
</tr>
<tr>
<td>Co 34</td>
<td>23</td>
<td>6.10</td>
<td>5.29</td>
<td>0.81</td>
<td>1.60</td>
<td>4.50</td>
</tr>
<tr>
<td>Co 48</td>
<td>26</td>
<td>6.94</td>
<td>4.46</td>
<td>2.48</td>
<td>0.38</td>
<td>6.56</td>
</tr>
<tr>
<td>Co 2</td>
<td>25</td>
<td>5.62</td>
<td>2.96</td>
<td>2.66</td>
<td>1.50</td>
<td>4.12</td>
</tr>
<tr>
<td>Co 33</td>
<td>30</td>
<td>4.59</td>
<td>2.96</td>
<td>1.63</td>
<td>1.15</td>
<td>3.44</td>
</tr>
<tr>
<td>Co 53</td>
<td>33</td>
<td>6.32</td>
<td>3.50</td>
<td>2.82</td>
<td>1.11</td>
<td>5.21</td>
</tr>
<tr>
<td>Co 3</td>
<td>36</td>
<td>6.55</td>
<td>7.20</td>
<td>-0.65</td>
<td>1.10</td>
<td>5.45</td>
</tr>
</tbody>
</table>

8 March 1985 (Dry Period)  5 August 1985 (Wet Period)
<table>
<thead>
<tr>
<th>BWDB Location</th>
<th>New Location</th>
<th>Elevation of M. P.</th>
<th>Depth of W. L. from M. P.</th>
<th>Elevation of W. L.</th>
<th>Depth of W. L. from M. P.</th>
<th>Elevation of W. L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 March 1985</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Dry Period)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 August 1985</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Wet Period)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Co 26</td>
<td>37</td>
<td>7.75</td>
<td>3.96</td>
<td>3.79</td>
<td>1.40</td>
<td>6.35</td>
</tr>
<tr>
<td>Co 5</td>
<td>38</td>
<td>7.67</td>
<td>Not available</td>
<td></td>
<td>Not available</td>
<td></td>
</tr>
<tr>
<td>Co 4</td>
<td>41</td>
<td>8.14</td>
<td>8.70</td>
<td>-0.56</td>
<td>2.40</td>
<td>5.74</td>
</tr>
<tr>
<td>Co 55</td>
<td>42</td>
<td>7.42</td>
<td>5.50</td>
<td>1.92</td>
<td>1.65</td>
<td>5.77</td>
</tr>
<tr>
<td>Co 52</td>
<td>43</td>
<td>5.29</td>
<td>3.49</td>
<td>1.80</td>
<td>1.88</td>
<td>3.41</td>
</tr>
<tr>
<td>Co 21</td>
<td>45</td>
<td>6.22</td>
<td>5.05</td>
<td>1.17</td>
<td>1.27</td>
<td>4.95</td>
</tr>
<tr>
<td>Co 22</td>
<td>47</td>
<td>5.00</td>
<td>4.01</td>
<td>0.99</td>
<td>1.82</td>
<td>3.18</td>
</tr>
<tr>
<td>Co 65</td>
<td>49</td>
<td>7.07</td>
<td>9.47</td>
<td>-2.40</td>
<td>1.83</td>
<td>5.24</td>
</tr>
<tr>
<td>Co 8</td>
<td>50</td>
<td>6.46</td>
<td>5.01</td>
<td>1.45</td>
<td>2.03</td>
<td>4.43</td>
</tr>
<tr>
<td>Co 11</td>
<td>52</td>
<td>11.46</td>
<td>3.47</td>
<td>7.99</td>
<td>2.03</td>
<td>9.43</td>
</tr>
<tr>
<td>Co 45</td>
<td>53</td>
<td>8.14</td>
<td>5.15</td>
<td>2.99</td>
<td>2.00</td>
<td>6.14</td>
</tr>
<tr>
<td>Co 42</td>
<td>57</td>
<td>6.99</td>
<td>5.10</td>
<td>1.89</td>
<td>1.20</td>
<td>5.79</td>
</tr>
<tr>
<td>Co 6</td>
<td>58</td>
<td>8.68</td>
<td>7.98</td>
<td>0.70</td>
<td>2.22</td>
<td>6.46</td>
</tr>
<tr>
<td>Co 32</td>
<td>61</td>
<td>5.58</td>
<td>3.82</td>
<td>1.76</td>
<td>2.18</td>
<td>3.40</td>
</tr>
<tr>
<td>Co 49</td>
<td>62</td>
<td>10.47</td>
<td>Not available</td>
<td></td>
<td>2.16</td>
<td>8.31</td>
</tr>
<tr>
<td>Co 62</td>
<td>63</td>
<td>5.57</td>
<td>4.09</td>
<td>1.48</td>
<td>0.74</td>
<td>4.83</td>
</tr>
<tr>
<td>Co 19</td>
<td>64</td>
<td>6.09</td>
<td>4.27</td>
<td>1.82</td>
<td>0.89</td>
<td>5.20</td>
</tr>
<tr>
<td>Co 51</td>
<td>65</td>
<td>6.59</td>
<td>4.26</td>
<td>2.33</td>
<td>0.94</td>
<td>5.65</td>
</tr>
<tr>
<td>Co 60</td>
<td>66</td>
<td>6.34</td>
<td>4.66</td>
<td>1.68</td>
<td>2.08</td>
<td>4.26</td>
</tr>
<tr>
<td>Co 57</td>
<td>67</td>
<td>8.08</td>
<td>4.21</td>
<td>3.87</td>
<td>0.93</td>
<td>7.15</td>
</tr>
<tr>
<td>Co 18</td>
<td>68</td>
<td>6.84</td>
<td>4.85</td>
<td>1.99</td>
<td>1.11</td>
<td>5.73</td>
</tr>
<tr>
<td>Co 7</td>
<td>70</td>
<td>6.44</td>
<td>4.89</td>
<td>1.55</td>
<td>1.17</td>
<td>5.27</td>
</tr>
<tr>
<td>Co 50</td>
<td>71</td>
<td>12.01</td>
<td>12.42</td>
<td>-0.41</td>
<td>1.44</td>
<td>10.57</td>
</tr>
<tr>
<td>BWDB Location</td>
<td>New Location</td>
<td>Elevation of M. P.</td>
<td>Depth of W. L. from M. P.</td>
<td>Elevation of W. L.</td>
<td>Depth of W. L. from M. P.</td>
<td>Elevation of W. L.</td>
</tr>
<tr>
<td>---------------</td>
<td>--------------</td>
<td>-------------------</td>
<td>--------------------------</td>
<td>-------------------</td>
<td>--------------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>Co 58</td>
<td>74</td>
<td>7.74</td>
<td>5.30</td>
<td>2.44</td>
<td>1.70</td>
<td>6.04</td>
</tr>
<tr>
<td>Co 20</td>
<td>76</td>
<td>6.48</td>
<td>3.13</td>
<td>3.35</td>
<td>1.44</td>
<td>5.04</td>
</tr>
<tr>
<td>Co 43</td>
<td>77</td>
<td>6.53</td>
<td>4.26</td>
<td>2.27</td>
<td>2.20</td>
<td>4.33</td>
</tr>
<tr>
<td>Co 17</td>
<td>78</td>
<td>5.85</td>
<td>4.36</td>
<td>1.49</td>
<td>1.72</td>
<td>4.13</td>
</tr>
<tr>
<td>Co 13</td>
<td>79</td>
<td>12.59</td>
<td>15.29</td>
<td>-2.70</td>
<td>3.50</td>
<td>9.09</td>
</tr>
<tr>
<td>Co 38</td>
<td>84</td>
<td>9.52</td>
<td>8.00</td>
<td>1.52</td>
<td>3.00</td>
<td>6.52</td>
</tr>
<tr>
<td>Co 14</td>
<td>86</td>
<td>7.24</td>
<td>4.19</td>
<td>3.05</td>
<td>0.89</td>
<td>6.35</td>
</tr>
<tr>
<td>Co 9</td>
<td>89</td>
<td>7.24</td>
<td>4.15</td>
<td>3.09</td>
<td>1.20</td>
<td>6.04</td>
</tr>
<tr>
<td>Co 39</td>
<td>90</td>
<td>11.43</td>
<td>4.17</td>
<td>7.26</td>
<td>1.20</td>
<td>10.23</td>
</tr>
<tr>
<td>Co 16</td>
<td>91</td>
<td>4.58</td>
<td>4.26</td>
<td>0.32</td>
<td>1.45</td>
<td>3.13</td>
</tr>
<tr>
<td>Co 61</td>
<td>92</td>
<td>5.27</td>
<td>4.06</td>
<td>1.21</td>
<td>1.45</td>
<td>3.82</td>
</tr>
<tr>
<td>Co 15</td>
<td>94</td>
<td>5.23</td>
<td>3.17</td>
<td>2.06</td>
<td>1.17</td>
<td>4.06</td>
</tr>
<tr>
<td>Co 10</td>
<td>97</td>
<td>8.62</td>
<td>4.72</td>
<td>3.90</td>
<td>1.67</td>
<td>6.95</td>
</tr>
<tr>
<td>Co 64</td>
<td>98</td>
<td>5.48</td>
<td>3.56</td>
<td>1.92</td>
<td>2.25</td>
<td>3.23</td>
</tr>
<tr>
<td>No 1</td>
<td>99</td>
<td>12.18</td>
<td>not available</td>
<td></td>
<td></td>
<td>Not available</td>
</tr>
<tr>
<td>Co 31</td>
<td>100</td>
<td>7.61</td>
<td>3.81</td>
<td>3.80</td>
<td>1.92</td>
<td>5.69</td>
</tr>
<tr>
<td>Co 40</td>
<td>102</td>
<td>4.58</td>
<td>3.25</td>
<td>1.33</td>
<td>1.27</td>
<td>3.31</td>
</tr>
<tr>
<td>Co 27</td>
<td>104</td>
<td>6.59</td>
<td>4.03</td>
<td>2.56</td>
<td>1.27</td>
<td>5.32</td>
</tr>
<tr>
<td>No 29</td>
<td>105</td>
<td>5.72</td>
<td>5.33</td>
<td>0.39</td>
<td>1.31</td>
<td>4.41</td>
</tr>
<tr>
<td>Co 28</td>
<td>106</td>
<td>3.26</td>
<td>2.69</td>
<td>0.57</td>
<td>1.72</td>
<td>1.54</td>
</tr>
<tr>
<td>Co 41</td>
<td>108</td>
<td>10.47</td>
<td>3.40</td>
<td>7.07</td>
<td>1.83</td>
<td>8.64</td>
</tr>
<tr>
<td>Co 29</td>
<td>111</td>
<td>5.51</td>
<td>2.43</td>
<td>3.08</td>
<td>0.95</td>
<td>4.56</td>
</tr>
<tr>
<td>No 8</td>
<td>112</td>
<td>5.50</td>
<td>3.25</td>
<td>2.25</td>
<td>2.44</td>
<td>3.06</td>
</tr>
<tr>
<td>BWDB Location</td>
<td>New Location</td>
<td>Elevation of M. P.</td>
<td>Depth of W. L. from M. P.</td>
<td>Elevation of W. L.</td>
<td>Depth of W. L. from M. P.</td>
<td>Elevation of W. L.</td>
</tr>
<tr>
<td>---------------</td>
<td>--------------</td>
<td>------------------</td>
<td>--------------------------</td>
<td>------------------</td>
<td>--------------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>No 17</td>
<td>110</td>
<td>7.63</td>
<td>5.44</td>
<td>2.19</td>
<td>1.04</td>
<td>6.59</td>
</tr>
<tr>
<td>No 18</td>
<td>114</td>
<td>5.53</td>
<td>Not available</td>
<td></td>
<td>1.39</td>
<td>4.14</td>
</tr>
<tr>
<td>No 7</td>
<td>115</td>
<td>5.06</td>
<td>4.03</td>
<td>1.03</td>
<td>2.20</td>
<td>2.86</td>
</tr>
<tr>
<td>No 2</td>
<td>118</td>
<td>9.19</td>
<td>2.89</td>
<td>6.30</td>
<td>1.52</td>
<td>7.67</td>
</tr>
<tr>
<td>No 22</td>
<td>120</td>
<td>3.45</td>
<td>2.60</td>
<td>0.85</td>
<td>1.17</td>
<td>2.28</td>
</tr>
<tr>
<td>No 23</td>
<td>123</td>
<td>6.66</td>
<td>4.11</td>
<td>2.55</td>
<td>2.66</td>
<td>4.00</td>
</tr>
<tr>
<td>No 3</td>
<td>124</td>
<td>6.85</td>
<td>3.73</td>
<td>3.12</td>
<td>1.24</td>
<td>5.61</td>
</tr>
<tr>
<td>No 30</td>
<td>126</td>
<td>3.07</td>
<td>4.16</td>
<td>-1.09</td>
<td>1.75</td>
<td>1.32</td>
</tr>
<tr>
<td>No 4</td>
<td>127</td>
<td>-----------------</td>
<td>Not available</td>
<td></td>
<td>------------------------</td>
<td></td>
</tr>
<tr>
<td>No 28</td>
<td>129</td>
<td>4.37</td>
<td>4.01</td>
<td>0.36</td>
<td>1.92</td>
<td>2.45</td>
</tr>
<tr>
<td>No 12</td>
<td>131</td>
<td>4.19</td>
<td>2.94</td>
<td>1.25</td>
<td>1.19</td>
<td>3.00</td>
</tr>
<tr>
<td>No 9</td>
<td>132</td>
<td>6.83</td>
<td>4.17</td>
<td>2.66</td>
<td>1.65</td>
<td>5.18</td>
</tr>
<tr>
<td>No 5</td>
<td>133</td>
<td>6.58</td>
<td>4.21</td>
<td>2.37</td>
<td>1.65</td>
<td>4.93</td>
</tr>
<tr>
<td>No 6</td>
<td>134</td>
<td>4.21</td>
<td>3.96</td>
<td>0.25</td>
<td>2.11</td>
<td>2.10</td>
</tr>
<tr>
<td>No 13</td>
<td>138</td>
<td>6.89</td>
<td>4.72</td>
<td>2.17</td>
<td>1.07</td>
<td>5.82</td>
</tr>
<tr>
<td>No 21</td>
<td>139</td>
<td>7.18</td>
<td>2.36</td>
<td>4.82</td>
<td>1.93</td>
<td>5.25</td>
</tr>
<tr>
<td>No 20</td>
<td>140</td>
<td>4.75</td>
<td>4.51</td>
<td>0.24</td>
<td>1.52</td>
<td>3.23</td>
</tr>
<tr>
<td>No 10</td>
<td>142</td>
<td>5.94</td>
<td>3.32</td>
<td>2.62</td>
<td>0.91</td>
<td>5.03</td>
</tr>
<tr>
<td>No 19</td>
<td>143</td>
<td>5.98</td>
<td>4.44</td>
<td>1.54</td>
<td>1.14</td>
<td>4.84</td>
</tr>
<tr>
<td>No 16</td>
<td>145</td>
<td>6.58</td>
<td>not available</td>
<td></td>
<td>1.19</td>
<td>5.39</td>
</tr>
</tbody>
</table>
APPENDIX. 5.1.1: PUMP TEST DATA B’BARIA (WELL 6) Q = 76997 ft³/d.

Elapsed time (minutes):

1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 14.0 16.0 18.0 20.0 25.0 30.0 35.0 40.0 45.0
50.0 60.0 70.0 80.0 90.0 100.0 120.0 140.0 160.0 180.0 200.0 250.0 300.0 350.0 400.0
500.0 600.0 700.0 800.0 900.0 1000.0 1500.0 2000.0 2500.0 3000.0

Drawdown (feet):

B’Baria O.W. (r = 50 ft)
1.77 2.04 2.04 2.08 2.12 2.12 2.16 2.27 2.52 2.64 2.95 2.89 2.83 2.85 2.83 3.04 3.18
4.62 4.83 4.87 4.93 5.04 5.08 5.29 5.58 5.68 5.77 5.77

B’Baria O.W. (r = 150 ft)
0.42 0.67 0.71 0.62 0.58 0.54 0.50 0.62 0.71 0.71 0.83 0.92 1.17 1.25 1.29 1.33 1.50
1.67 1.83 1.92 1.96 2.00 2.08 2.17 2.25 2.29 2.42 2.50 2.58 2.67 2.75 2.71 3.00 3.08
3.17 3.25 3.42 3.58 3.67 3.71

B’Baria O.W. (r = 400 ft)
0.09 0.09 0.09 0.09 0.09 0.09 0.16 0.21 0.34 0.42 0.59 0.63 0.67
0.73 0.82 0.96 1.00 1.17 1.25 1.42 1.50 1.75 1.79 1.88 1.84 2.00 2.13
2.17 2.21 2.34 2.50 2.75 2.88 2.92

APPENDIX. 5.1.2: PUMP TEST DATA NABINAGAR (WELL 9) Q = 86400 ft³/d.

Elapsed time (minutes):

1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 14.0 16.0 18.0 20.0 22.0 24.0 26.0 28.0 30.0
35.0 40.0 45.0 50.0 55.0 60.0 70.0 80.0 90.0 100.0 110.0 120.0 140.0 160.0 200.0
220.0 240.0 260.0 280.0 300.0 330.0 360.0 390.0 420.0 450.0 480.0 540.0 600.0 660.0
720.0 780.0 840.0 900.0 1000.0 1100.0 1200.0 1300.0 1400.0 1500.0 1600.0 1700.0 1800.0
1900.0 2000.0 2200.0 2400.0 2600.0 2800.0 3000.0 3200.0 3400.0 3600.0 3800.0 4000.0
4100.0

Drawdown (feet):

Nabinagar O.W. (r = 50 ft)
2.29 3.67 4.37 4.87 5.08 5.33 5.50 5.83 5.96 6.17 6.33 6.50 6.75 6.83 7.17 7.29 7.46 7.50
10.42 10.63 10.75 10.87 11.08 11.12 11.25 11.46 11.62 11.71 11.87 11.92 12.00 12.08

Nabinagar O.W. (r = 150 ft)
0.04 0.04 0.04 0.13 0.17 0.21 0.25 0.34 0.48 0.54 0.67 0.76 0.92 1.00 1.09 1.17 1.25 1.42
1.59 1.75 2.00 2.09 2.17 2.34 2.59 2.84 2.84 3.00 3.17 3.34 3.59 3.42 3.50 3.42 3.88 3.89
3.92 4.34 4.42 4.54 4.75 4.84 4.88 4.96 5.04 5.17 5.25 5.40 5.67 5.75 5.86 5.84 5.75 5.92
6.71
APPENDIX. 5.1.3: PUMP TEST DATA DAUDKANDI (WELL 43) \( Q = 172785 \text{ ft}^3/\text{d} \)

Elapsed time (minutes):

<table>
<thead>
<tr>
<th>Elapsed Time (minutes)</th>
<th>1.0</th>
<th>2.0</th>
<th>3.0</th>
<th>4.0</th>
<th>5.0</th>
<th>6.0</th>
<th>7.0</th>
<th>8.0</th>
<th>9.0</th>
<th>10.0</th>
<th>12.0</th>
<th>14.0</th>
<th>16.0</th>
<th>18.0</th>
<th>20.0</th>
<th>25.0</th>
<th>30.0</th>
<th>35.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.08</td>
<td>0.08</td>
<td>0.12</td>
<td>0.16</td>
<td>0.20</td>
<td>0.25</td>
<td>0.33</td>
<td>0.41</td>
<td>0.50</td>
<td>0.54</td>
<td>0.62</td>
<td>0.75</td>
<td>0.83</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>0.87</td>
<td>0.91</td>
<td>1.00</td>
<td>1.16</td>
<td>1.25</td>
<td>1.39</td>
<td>1.45</td>
<td>1.54</td>
<td>1.65</td>
<td>1.75</td>
<td>1.79</td>
<td>1.83</td>
<td>1.91</td>
<td>2.08</td>
<td>2.16</td>
<td>2.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td>2.29</td>
<td>2.33</td>
<td>2.37</td>
<td>2.58</td>
<td>2.58</td>
<td>2.58</td>
<td>2.67</td>
<td>2.79</td>
<td>2.83</td>
<td>2.83</td>
<td>2.83</td>
<td>2.83</td>
<td>2.91</td>
<td>3.08</td>
<td>3.00</td>
<td>3.23</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Drawdown (feet):

<table>
<thead>
<tr>
<th>Daudkandi O.W. (r = 50 ft)</th>
<th>2.05</th>
<th>3.71</th>
<th>4.55</th>
<th>4.80</th>
<th>5.38</th>
<th>6.05</th>
<th>6.13</th>
<th>6.21</th>
<th>6.30</th>
<th>6.38</th>
<th>6.63</th>
<th>6.80</th>
<th>7.00</th>
<th>7.13</th>
<th>7.21</th>
<th>7.30</th>
<th>7.38</th>
<th>7.46</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.67</td>
<td>10.84</td>
<td>10.92</td>
<td>10.92</td>
<td>10.92</td>
<td>10.92</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Calculated recovery:

<table>
<thead>
<tr>
<th>Daudkandi O.W. (r = 50 ft)</th>
<th>Calculated recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.08</td>
<td>1.92</td>
</tr>
<tr>
<td>4.92</td>
<td>5.00</td>
</tr>
</tbody>
</table>
Daudkandi O.W. (r = 150 ft)

Recovery time (minutes)
1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 14.0 16.0 18.0 20.0 25.0 30.0 35.0 40.0 45.0
50.0 55.0 60.0 70.0 80.0 90.0 100.0 110.0 120.0 140.0 160.0 180.0 200.0 220.0 240.0 260.0 280.0 300.0 340.0 380.0 420.0 460.0 500.0 560.0 620.0 680.0 740.0 800.0 860.0
920.0 980.0 1040.0 1100.0 1200.0 1300.0 1400.0 1500.0

Calculated recovery (feet)
0.38 0.62 0.79 1.08 1.25 1.50 1.58 1.75 1.88 2.08 2.21 2.29 2.42 2.58 2.71 2.92 3.13 3.29
3.54 3.63 3.71 3.88 4.00 4.21 4.54 4.58 4.63 4.83 5.04 5.13 5.13 5.13 5.17 5.17 5.17
5.21 5.21 5.25 5.25 5.25 5.29 5.33 5.42 5.58 5.71 5.71 5.75 5.79 5.79 5.79 5.79 5.79
5.79 5.79 5.79

Daudkandi O.W. (r = 400 ft)

Recovery time (minutes)
1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 14.0 16.0 18.0 20.0 25.0 30.0 35.0 40.0 45.0
50.0 55.0 60.0 70.0 80.0 90.0 100.0 110.0 120.0 140.0 160.0 180.0 200.0 220.0 240.0 260.0 280.0 300.0 340.0 380.0 420.0 460.0 500.0 560.0 620.0 680.0 740.0 800.0 860.0
920.0 980.0 1040.0 1100.0 1200.0 1300.0 1400.0 1500.0

Calculated recovery (feet)
0.04 0.13 0.21 0.25 0.33 0.42 0.54 0.63 0.71 0.79 0.88 0.96 1.17 1.21 1.29 1.46 1.75 2.00
2.08 2.21 2.29 2.33 2.38 2.58 2.67 3.00 3.04 3.13 3.17 3.38 3.46 3.46 3.46 3.50 3.58
3.58 3.58 3.58 3.58 3.58 3.62 3.63 3.88 4.00 4.04 4.08 4.08 4.08 4.08 4.16 4.16 4.16
4.16 4.16 4.16

APPENDIX. 5.1.4: PUMP TEST DATA BURICHONG (WELL 46) Q = 76962 ft³/d

Elapsed time (minutes):
1.0 2.0 3.0 4.0 5.0 6.0 8.0 10.0 12.0 14.0 16.0 18.0 20.0 25.0 30.0 35.0 40.0 45.0 50.0
55.0 60.0 70.0 80.0 90.0 100.0 110.0 120.0 140.0 160.0 180.0 200.0 220.0 240.0 260.0 280.0 300.0 350.0 400.0 450.0 500.0 550.0 600.0 700.0 800.0 900.0 1000.0 1200.0 1400.0 1600.0 1800.0 2000.0 2200.0 2400.0 2700.0 3000.0

Drawdown (feet):

Burichong O.W. (r = 100 ft)
0.04 0.25 0.21 0.12 0.21 0.39 0.37 0.37 0.39 0.37 0.17 0.21 0.39 0.21 0.12 0.12 0.21 0.04
0.00 0.04 0.13 0.21 0.29 0.33 0.38 0.50 0.46 0.71 0.71 0.67 0.88 0.92 0.96 1.04 1.08 1.13
1.29 1.38 1.54 1.50 1.54 1.59 1.63 1.63 1.67 1.69 1.71 1.75 1.79 1.83 1.90 1.96 1.94 1.96
1.96

Burichong O.W. (r = 150 ft)
0.3 7.703 8.704 0.204 0.804 2.004 3.504 5.404 6.204 6.604 7.704 9.305 1.005 2.205 3.505 5.005
4.4 0.6 5.006 5.406 6.006 6.206 6.406 5.806 5.8
**Burichong O.W. (r = 250 ft)**

<table>
<thead>
<tr>
<th>Elapsed time (minutes)</th>
<th>Drawdown (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.04 0.08 0.04 0.04 0.04 0.08 0.13 0.17 0.23 0.33 0.40 0.50 0.58 0.71 0.79 0.88</td>
<td>0.02 0.13 0.17 0.27 0.27 0.29 0.31 0.33 0.33 0.38 0.38 0.38 0.42 0.42 0.44 0.46 0.46</td>
</tr>
<tr>
<td>0.92 1.04 1.13 1.21 1.33 1.42 1.50 1.79 2.00 2.08 2.13 2.25 2.29 2.38 2.50 2.54 2.63</td>
<td>0.46 0.50 0.54 0.56 0.58 0.58 0.60 0.60 0.62 0.60 0.65 0.69 0.88 0.88 0.88 0.88</td>
</tr>
<tr>
<td>2.71 2.79 2.83 2.88 2.92 3.00 3.06 3.08 3.08 3.08 3.08 3.08 3.08 3.08 3.08 3.08</td>
<td>Chandina O.W. (r = 150.0 ft)</td>
</tr>
</tbody>
</table>

**APPENDIX. 5.1.5: PUMP TEST DATA CHANDINA (WELL 55) Q = 84662 ft³/d**

**Chandina O.W. (r = 50 ft)**

<table>
<thead>
<tr>
<th>Elapsed time (minutes)</th>
<th>Drawdown (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 14.0 16.0 18.0 20.0 22.0 24.0 26.0 28.0 30.0 35.0</td>
<td>0.02 0.13 0.17 0.08 0.08 0.13 0.13 0.17 0.21 0.17 0.17 0.25 0.21 0.21 0.25 0.25</td>
</tr>
<tr>
<td>40.0 45.0 50.0 55.0 60.0 70.0 80.0 90.0 100.0 120.0 140.0 160.0 180.0 200.0 250.0 300.0</td>
<td>0.27 0.27 0.27 0.29 0.29 0.31 0.33 0.33 0.33 0.38 0.38 0.38 0.42 0.42 0.44 0.46 0.46</td>
</tr>
<tr>
<td>350.0 400.0 500.0 600.0 700.0 800.0 900.0 1000.0 1100.0 1200.0 1300.0 1400.0 1500.0</td>
<td>0.46 0.50 0.54 0.56 0.58 0.58 0.60 0.60 0.62 0.60 0.65 0.69 0.88 0.88 0.88 0.88 0.88</td>
</tr>
<tr>
<td>1600.0 1700.0 1800.0 1900.0 2000.0 2100.0 2600.0 3000.0 3300.0 3600.0</td>
<td>Chandina O.W. (r = 400 ft)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Elapsed time (minutes)</th>
<th>Drawdown (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 14.0 16.0 18.0 20.0 22.0 24.0 26.0 28.0 30.0 35.0</td>
<td>0.04 0.09 0.13 0.17 0.25 0.25 0.29 0.42 0.42 0.42 0.42 0.54 0.54 0.59 0.63 0.63 0.67 0.71</td>
</tr>
<tr>
<td>40.0 45.0 50.0 55.0 60.0 70.0 80.0 90.0 100.0 120.0 140.0 160.0 180.0 200.0 250.0 300.0</td>
<td>0.75 0.79 0.94 0.84 0.92 0.96 1.00 1.04 1.13 1.13 1.17 1.29 1.29 1.38 1.42 1.42 1.50 1.54</td>
</tr>
<tr>
<td>350.0 400.0 500.0 600.0 700.0 800.0 900.0 1000.0 1100.0 1200.0 1300.0 1400.0 1500.0</td>
<td>1.67 1.67 1.75 1.75 1.75 1.84 1.88 1.88 1.88 1.92 1.92 1.96 1.96 2.00 2.00 2.0 02.09 2.09</td>
</tr>
<tr>
<td>1600.0 1700.0 1800.0 1900.0 2000.0 2100.0 2600.0 3000.0 3300.0 3600.0</td>
<td>Calculated recovery Chandina O.W. (r = 150.0 ft)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Recovery time (minutes)</th>
<th>Calculated recovery (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.0 7.0 8.0 9.0 10.0 12.0 14.0 16.0 18.0 22.0 24.0 26.0 28.0 30.0 35.0 40.0 45.0 50.0 55.0</td>
<td>0.06 0.08 0.15 0.17 0.17 0.17 0.25 0.31 0.28 0.46 0.52 0.50 0.63 0.69 0.71 0.83 0.92 1.00 1.11</td>
</tr>
<tr>
<td>60.0 70.0 80.0 90.0 100.0 120.0 140.0 160.0 180.0 200.0 250.0 300.0 350.0 400.0 500.0</td>
<td>1.15 1.25 1.40 1.52 1.56 1.67 1.51 1.90 1.98 2.08 2.08 2.17 2.25 2.33 2.33 2.40 2.44 2.46</td>
</tr>
<tr>
<td>600.0 700.0 800.0 900.0 1000.0 1100.0 1200.0 1300.0 1800.0 2000.0</td>
<td>2.49 2.52 2.50 2.52 2.54 2.58 2.61 2.65</td>
</tr>
</tbody>
</table>
Calculated recovery Chandina O.W. (r = 400 ft)

Recovery time (minutes)
2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 14.0 16.0 18.0 24.0 26.0 28.0 30.0 35.0 40.0 45.0
50.0 55.0 60.0 70.0 80.0 90.0 100.0 120.0 140.0 160.0 180.0 200.0 250.0 300.0 350.0
400.0 500.0 600.0 700.0 800.0 900.0 1000.0 1100.0 1200.0 1300.0 1800.0 2000.0

Calculated recovery (feet)
0.08 0.13 0.17 0.25 0.29 0.37 0.42 0.42 0.50 0.50 0.54 0.57 0.59 0.71 0.71 0.79 0.79 0.83 0.82 0.96 1.00 1.04 1.08 1.13 1.21 1.25 1.29 1.33 1.38 1.46 1.50 1.54 1.58 1.61 1.67 1.63 1.68 2.25 2.25 2.25 2.25 2.25 2.19 2.15 2.27 2.27 2.27 1.96 1.96 1.96 2.04 2.67 2.67 2.25 2.25 2.38 2.54 2.60 2.60 2.60 2.60 2.60

APPENDIX. 5.1.6: PUMP TEST DATA KOTWALI (WELL 59) Q = 76982 ft²/d

Elapsed time (minutes)
1.0 2.0 3.0 4.0 5.0 6.0 8.0 10.0 12.0 14.0 16.0 18.0 20.0 22.0 24.0 26.0 28.0 30.0 32.0
34.0 36.0 38.0 40.0 42.0 44.0 46.0 48.0 50.0 52.0 54.0 56.0 58.0 60.0 65.0 70.0 75.0 80.0
85.0 90.0 95.0 100.0 105.0 110.0 115.0 120.0 130.0 140.0 150.0 160.0 170.0 180.0 190.0
200.0 210.0 220.0 230.0 240.0 260.0 280.0 300.0 320.0 340.0 360.0 380.0 400.0 420.0
440.0 460.0 480.0 500.0 520.0 540.0 560.0 580.0 600.0 620.0 640.0 660.0 700.0 720.0 740.0 760.0 780.0 800.0 820.0 840.0 860.0 880.0 900.0 920.0 940.0 960.0 980.0
1000.0 1020.0 1040.0 1220.0 1400.0 1460.0 1520.0 1580.0 1640.0 1700.0 1800.0 1900.0 2100.0
2300.0 2600.0 2900.0 2960.0

Drawdown (feet)

Kotwali O.W. (r = 50 ft)
0.34 1.17 1.75 2.42 2.75 3.29 3.76 3.76 3.92 4.09 4.25 4.39 4.50 4.42 4.67 4.73 4.88
5.00 5.09 5.09 4.88 4.84 4.96 4.96 4.88 5.04 5.00 5.00 5.11 5.13 5.13 5.23 5.34 5.27
5.25 5.38 5.34 5.50 5.59 5.59 5.67 5.67 5.71 5.84 5.77 5.75 5.90 5.84 5.86 5.92

Kotwali O.W. (r = 150 ft)
0.08 0.25 0.50 0.75 1.00 1.25 1.50 1.83 2.00 2.10 2.20 2.42 2.54 2.58 2.64 2.75 2.79 2.92
3.42 3.44 3.44 3.54 3.54 3.56 3.62 3.67 3.69 3.75 3.77 3.83 3.87 3.89 3.96 4.00 4.00 4.00
4.75 5.04 4.96 5.00 5.00 4.98 5.00 5.00 5.00 5.04 5.08 5.08 5.12 5.17

Kotwali O.W. (r = 400 ft)
0.04 0.04 0.04 0.04 0.08 0.08 0.12 0.29 0.37 0.42 0.46 0.46 0.46 0.21 0.28 0.12 0.17 0.21 0.06
0.12 0.04 0.07 0.13 0.13 0.04 0.21 0.17 0.17 0.13 0.29 0.29 0.23 0.21 0.21 0.31 0.46 0.38
0.38 0.42 0.42 0.58 0.54 0.50 0.46 0.58 0.58 0.75 0.78 0.79 0.82 0.88 1.00 1.00 1.00 1.12
1.17 1.29 1.29 1.43 1.50 1.56 1.69 1.69 1.79 1.88 1.88 1.88 2.13 2.13 2.13 1.54 1.54
1.54 1.67 1.63 1.63 1.63 1.68 2.25 2.25 2.25 2.25 2.19 2.15 2.27 2.27 2.27 1.96 1.96 1.96
2.04 2.67 2.67 2.25 2.25 2.38 2.54 2.60 2.60 2.60 2.60 2.60 2.60 2.60

378
APPENDIX. 5.1.7: PUMP TEST DATA BARURA (WELL 69) Q = 76982 ft³/d

Elapsed time (minutes)

1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 14.0 16.0 18.0 20.0 22.0 24.0 26.0 28.0 30.0 35.0 40.0 45.0 50.0 55.0 60.0 70.0 80.0 90.0 100.0 120.0 140.0 160.0 180.0 200.0 250.0 300.0 350.0 400.0 450.0 500.0 600.0 700.0 800.0 900.0 1000.0 1200.0 1400.0 1600.0 1800.0 2000.0 2200.0 2700.0 3000.0

Drawdown (feet)

Barura O.W. (r = 50 ft)
0.08 0.15 0.15 0.19 0.19 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.23 0.27 0.30 0.30 0.37 0.37 0.37 0.37 0.37 0.37 0.37 0.37 0.33 0.41 0.41 0.50 0.50 0.50 0.58 0.62 0.62 0.66 0.70 0.83
0.87 0.95 1.00 1.00 1.21 1.33 1.45 1.53 1.62 1.70 1.83 2.00 2.29 2.37 2.54 2.75 3.04 3.20

Barura O.W. (r = 150 ft)
0.15 0.50 1.00 1.20 1.25 1.54 1.58 1.66 1.70 1.87 2.00 2.08 2.12 2.16 2.20 2.25 2.25 2.29 2.29 2.38 2.38 2.41 2.41 2.45 2.50 2.54 2.58 2.60 2.62 2.62 2.66 2.79 2.79 2.83 2.83 2.91 2.95 3.00 3.00 3.00 3.07 3.07 3.07 3.10 3.16 3.20 3.20 3.22 3.25 3.29 3.33 3.37 3.37

Barura O.W. (r = 400 ft)
0.04 0.08 0.16 0.25 0.37 0.41 0.50 0.58 0.62 0.66 0.75 0.87 0.91 0.95 0.95 1.00 1.04 1.08 1.12 1.16 1.20 1.25 1.29 1.29 1.33 1.37 1.41 1.45 1.45 1.54 1.58 1.62 1.62 1.64 1.70 1.75 1.75 1.79 1.83 1.83 1.86 1.91 1.91 1.94 1.97 2.00 2.00 2.04 2.08 2.08 2.16 2.16

Calculated recovery Barura O.W. (r = 150 ft)

Recovery time (minutes)
1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 14.0 16.0 18.0 20.0 22.0 24.0 26.0 28.0 30.0 35.0 40.0 45.0 50.0 55.0 60.0 70.0 80.0 90.0 100.0 120.0 140.0 160.0 180.0 200.0 250.0 300.0 350.0 400.0 450.0 500.0 600.0 700.0 800.0 900.0 1000.0 1200.0 1400.0 1600.0 1800.0 2000.0 2200.0 2700.0

Calculated recovery (feet)
0.71 1.00 1.21 1.37 1.50 1.62 1.71 1.75 1.83 1.87 1.96 2.04 2.04 2.17 2.21 2.29 2.29 2.29 2.33 2.33 2.37 2.46 2.50 2.50 2.62 2.62 2.57 2.71 2.77 2.75 2.79 2.85 2.87 2.87 2.87 2.92 2.96 2.96 3.04 3.12 3.17 3.04 3.08 3.12 3.12 3.12 3.12 3.12 3.17 3.17 3.21

APPENDIX. 5.1.8: PUMP TEST DATA HAZIGANJ (WELL 82) Q = 180273 ft³/d

Elapsed time (minutes)

1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 14.0 16.0 18.0 20.0 25.0 30.0 35.0 40.0 45.0 50.0 55.0 60.0 70.0 80.0 90.0 100.0 110.0 120.0 140.0 160.0 180.0 200.0 220.0 240.0 260.0 280.0 300.0 340.0 380.0 420.0 460.0 500.0 560.0 620.0 680.0 740.0 800.0 860.0 920.0 980.0 1040.0 1100.0 1200.0 1300.0 1400.0 1500.0 1600.0 1700.0 1800.0 1900.0 2000.0 2100.0 2200.0 2300.0 2400.0 2500.0 2600.0 2700.0 2800.0 2900.0 3000.0
### APPENDIX 5.1.9: PUMP TEST DATA CHAUDHGRAM (WELL 101) \( Q = 86604 \text{ ft}^3/\text{d} \)

**Chauddagram O.W. (r = 50 ft)**

**Elapsed time (minutes)**
- 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 14.0 16.0 18.0 20.0 25.0 30.0 35.0 40.0 45.0
- 50.0 55.0 60.0 70.0 80.0 90.0 100.0 110.0 120.0 130.0 140.0 150.0 160.0 170.0 180.0
- 190.0 200.0 220.0 240.0 260.0 280.0 300.0 330.0 360.0 390.0 420.0 450.0 480.0 510.0
- 540.0 570.0 600.0 700.0 750.0 800.0 850.0 900.0 950.0 1000.0 1100.0 1200.0 1300.0
- 1400.0 1500.0 1600.0 1700.0 1800.0 1900.0 2000.0 2100.0 2200.0 2300.0 2400.0 2500.0
- 2600.0 2700.0 2800.0 2900.0 3000.0 3100.0 3200.0 3300.0 3400.0 3500.0 3600.0 3700.0
- 3800.0 3900.0 4000.0 4100.0 4200.0 4290.0

**Drawdown (feet)**
- 0.12 0.17 0.21 0.25 0.33 0.42 0.46 0.54 0.67 0.79 0.96 1.16 1.33 1.50 1.79 2.29 2.67
- 3.00 3.33 3.58 3.83 4.09 4.50 5.04 5.25 5.50 5.83 6.13 6.33 6.54 6.77 7.04 7.17 7.25 7.32
- 15.08 15.17 15.33 15.42 15.46 15.58 15.62 15.62 15.66 15.71 15.79 15.83

**Chauddagram O.W. (r = 150 ft)**

**Elapsed time (minutes)**
- 0.5 1.0 1.5 2.0 2.5 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 12.0 14.0 16.0 18.0 20.0 25.0 30.0 35.0
- 40.0 45.0 50.0 55.0 60.0 70.0 80.0 90.0 100.0 110.0 120.0 130.0 140.0 150.0 160.0 170.0
- 180.0 190.0 200.0 220.0 240.0 260.0 280.0 300.0 330.0 360.0 390.0 420.0 450.0 480.0
- 510.0 540.0 570.0 600.0 700.0 750.0 800.0 850.0 900.0 950.0 1000.0 1100.0 1200.0 1300.0
- 1400.0 1500.0 1600.0 1700.0 1800.0 1900.0 2000.0 2100.0 2200.0 2300.0 2400.0 2500.0
- 2600.0 2700.0 2800.0 2900.0 3000.0 3100.0 3200.0 3300.0 3400.0 3500.0 3600.0 3700.0
- 3800.0 3900.0 4000.0 4100.0 4200.0 4290.0

**Chauddagram O.W. (r = 1000 ft)**

**Elapsed time (minutes)**
- 0.12 0.17 0.21 0.25 0.33 0.42 0.46 0.54 0.67 0.79 0.96 1.16 1.33 1.50 1.79 2.29 2.67
- 3.00 3.33 3.58 3.83 4.09 4.50 5.04 5.25 5.50 5.83 6.13 6.33 6.54 6.77 7.04 7.17 7.25 7.32
- 15.08 15.17 15.33 15.42 15.46 15.58 15.62 15.62 15.66 15.71 15.79 15.83
### Chauddagram O.W. (r = 1000 ft)

<table>
<thead>
<tr>
<th>Elapsed time (minutes)</th>
<th>Drawdown (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.0</td>
<td>0.00</td>
</tr>
<tr>
<td>30.0</td>
<td>0.00</td>
</tr>
<tr>
<td>35.0</td>
<td>0.00</td>
</tr>
<tr>
<td>40.0</td>
<td>0.00</td>
</tr>
<tr>
<td>45.0</td>
<td>0.00</td>
</tr>
<tr>
<td>50.0</td>
<td>0.00</td>
</tr>
<tr>
<td>55.0</td>
<td>0.00</td>
</tr>
<tr>
<td>60.0</td>
<td>0.00</td>
</tr>
<tr>
<td>65.0</td>
<td>0.00</td>
</tr>
<tr>
<td>70.0</td>
<td>0.00</td>
</tr>
<tr>
<td>75.0</td>
<td>0.00</td>
</tr>
<tr>
<td>80.0</td>
<td>0.00</td>
</tr>
<tr>
<td>85.0</td>
<td>0.00</td>
</tr>
<tr>
<td>90.0</td>
<td>0.00</td>
</tr>
<tr>
<td>95.0</td>
<td>0.00</td>
</tr>
<tr>
<td>100.0</td>
<td>0.00</td>
</tr>
<tr>
<td>105.0</td>
<td>0.00</td>
</tr>
<tr>
<td>110.0</td>
<td>0.00</td>
</tr>
<tr>
<td>115.0</td>
<td>0.00</td>
</tr>
<tr>
<td>120.0</td>
<td>0.00</td>
</tr>
<tr>
<td>125.0</td>
<td>0.00</td>
</tr>
<tr>
<td>130.0</td>
<td>0.00</td>
</tr>
<tr>
<td>135.0</td>
<td>0.00</td>
</tr>
<tr>
<td>140.0</td>
<td>0.00</td>
</tr>
</tbody>
</table>

### Feni O.W. (r = 50 ft)

<table>
<thead>
<tr>
<th>Elapsed time (minutes)</th>
<th>Drawdown (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.87</td>
</tr>
<tr>
<td>2.0</td>
<td>3.17</td>
</tr>
<tr>
<td>3.0</td>
<td>3.71</td>
</tr>
<tr>
<td>4.0</td>
<td>4.17</td>
</tr>
<tr>
<td>5.0</td>
<td>4.33</td>
</tr>
<tr>
<td>6.0</td>
<td>4.67</td>
</tr>
<tr>
<td>7.0</td>
<td>4.75</td>
</tr>
<tr>
<td>8.0</td>
<td>4.87</td>
</tr>
<tr>
<td>9.0</td>
<td>5.05</td>
</tr>
<tr>
<td>10.0</td>
<td>5.17</td>
</tr>
<tr>
<td>11.0</td>
<td>5.37</td>
</tr>
<tr>
<td>12.0</td>
<td>5.58</td>
</tr>
<tr>
<td>13.0</td>
<td>5.67</td>
</tr>
<tr>
<td>14.0</td>
<td>5.71</td>
</tr>
<tr>
<td>15.0</td>
<td>5.83</td>
</tr>
<tr>
<td>16.0</td>
<td>6.05</td>
</tr>
<tr>
<td>17.0</td>
<td>6.25</td>
</tr>
<tr>
<td>18.0</td>
<td>6.37</td>
</tr>
<tr>
<td>19.0</td>
<td>6.50</td>
</tr>
<tr>
<td>20.0</td>
<td>6.58</td>
</tr>
<tr>
<td>21.0</td>
<td>6.75</td>
</tr>
<tr>
<td>22.0</td>
<td>6.83</td>
</tr>
<tr>
<td>23.0</td>
<td>6.95</td>
</tr>
<tr>
<td>24.0</td>
<td>7.08</td>
</tr>
<tr>
<td>25.0</td>
<td>7.21</td>
</tr>
<tr>
<td>26.0</td>
<td>7.27</td>
</tr>
<tr>
<td>27.0</td>
<td>7.46</td>
</tr>
<tr>
<td>28.0</td>
<td>7.58</td>
</tr>
<tr>
<td>29.0</td>
<td>7.71</td>
</tr>
<tr>
<td>30.0</td>
<td>7.87</td>
</tr>
<tr>
<td>31.0</td>
<td>7.95</td>
</tr>
<tr>
<td>32.0</td>
<td>8.12</td>
</tr>
<tr>
<td>33.0</td>
<td>8.33</td>
</tr>
<tr>
<td>34.0</td>
<td>8.37</td>
</tr>
<tr>
<td>35.0</td>
<td>8.54</td>
</tr>
<tr>
<td>36.0</td>
<td>8.65</td>
</tr>
<tr>
<td>37.0</td>
<td>8.75</td>
</tr>
<tr>
<td>38.0</td>
<td>8.83</td>
</tr>
<tr>
<td>39.0</td>
<td>8.87</td>
</tr>
<tr>
<td>40.0</td>
<td>9.00</td>
</tr>
<tr>
<td>41.0</td>
<td>9.17</td>
</tr>
<tr>
<td>42.0</td>
<td>9.33</td>
</tr>
<tr>
<td>43.0</td>
<td>9.41</td>
</tr>
<tr>
<td>44.0</td>
<td>9.54</td>
</tr>
<tr>
<td>45.0</td>
<td>9.66</td>
</tr>
<tr>
<td>46.0</td>
<td>9.79</td>
</tr>
<tr>
<td>47.0</td>
<td>9.92</td>
</tr>
<tr>
<td>48.0</td>
<td>10.00</td>
</tr>
<tr>
<td>49.0</td>
<td>10.08</td>
</tr>
<tr>
<td>50.0</td>
<td>10.25</td>
</tr>
<tr>
<td>51.0</td>
<td>10.37</td>
</tr>
<tr>
<td>52.0</td>
<td>10.49</td>
</tr>
<tr>
<td>53.0</td>
<td>10.67</td>
</tr>
<tr>
<td>54.0</td>
<td>10.75</td>
</tr>
<tr>
<td>55.0</td>
<td>10.83</td>
</tr>
<tr>
<td>56.0</td>
<td>10.91</td>
</tr>
<tr>
<td>57.0</td>
<td>11.00</td>
</tr>
<tr>
<td>58.0</td>
<td>11.12</td>
</tr>
<tr>
<td>59.0</td>
<td>11.33</td>
</tr>
<tr>
<td>60.0</td>
<td>11.39</td>
</tr>
<tr>
<td>61.0</td>
<td>11.50</td>
</tr>
<tr>
<td>62.0</td>
<td>11.58</td>
</tr>
<tr>
<td>63.0</td>
<td>11.66</td>
</tr>
<tr>
<td>64.0</td>
<td>11.70</td>
</tr>
<tr>
<td>65.0</td>
<td>11.87</td>
</tr>
<tr>
<td>66.0</td>
<td>12.04</td>
</tr>
<tr>
<td>67.0</td>
<td>12.12</td>
</tr>
<tr>
<td>68.0</td>
<td>12.16</td>
</tr>
<tr>
<td>69.0</td>
<td>12.18</td>
</tr>
<tr>
<td>70.0</td>
<td>12.20</td>
</tr>
</tbody>
</table>

APPENDIX. 5.1.10: PUMP TEST DATA FENI (WELL 117) Q = 161553 ft³/d
### Feni O.W. (r = 400 ft)

**Elapsed time (minutes)**

<table>
<thead>
<tr>
<th></th>
<th>3.0</th>
<th>4.0</th>
<th>5.0</th>
<th>6.0</th>
<th>7.0</th>
<th>8.0</th>
<th>9.0</th>
<th>10.0</th>
<th>12.0</th>
<th>14.0</th>
<th>16.0</th>
<th>18.0</th>
<th>20.0</th>
<th>25.0</th>
<th>30.0</th>
<th>35.0</th>
<th>40.0</th>
<th>45.0</th>
<th>50.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drawdown</td>
<td>0.04</td>
<td>0.08</td>
<td>0.16</td>
<td>0.20</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
</tbody>
</table>

### Feni O.W. (r = 1000 ft)

**Elapsed time (minutes)**

<table>
<thead>
<tr>
<th></th>
<th>18.0</th>
<th>20.0</th>
<th>25.0</th>
<th>30.0</th>
<th>35.0</th>
<th>40.0</th>
<th>45.0</th>
<th>50.0</th>
<th>55.0</th>
<th>60.0</th>
<th>65.0</th>
<th>70.0</th>
<th>75.0</th>
<th>80.0</th>
<th>85.0</th>
<th>90.0</th>
<th>95.0</th>
<th>100.0</th>
<th>105.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drawdown</td>
<td>0.04</td>
<td>0.08</td>
<td>0.17</td>
<td>0.21</td>
<td>0.29</td>
<td>0.33</td>
<td>0.41</td>
<td>0.46</td>
<td>0.54</td>
<td>0.62</td>
<td>0.75</td>
<td>0.88</td>
<td>1.00</td>
<td>1.04</td>
<td>1.08</td>
<td>1.16</td>
<td>1.42</td>
<td>1.54</td>
<td>1.67</td>
</tr>
</tbody>
</table>

### Senbagh O.W. (r = 50 ft)

**Elapsed time (minutes)**

<table>
<thead>
<tr>
<th></th>
<th>1.0</th>
<th>2.0</th>
<th>3.0</th>
<th>4.0</th>
<th>5.0</th>
<th>6.0</th>
<th>7.0</th>
<th>10.0</th>
<th>12.0</th>
<th>14.0</th>
<th>16.0</th>
<th>18.0</th>
<th>20.0</th>
<th>20.0</th>
<th>25.0</th>
<th>30.0</th>
<th>35.0</th>
<th>40.0</th>
<th>45.0</th>
<th>50.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drawdown</td>
<td>0.00</td>
<td>3.42</td>
<td>3.58</td>
<td>3.85</td>
<td>4.17</td>
<td>4.17</td>
<td>4.42</td>
<td>4.42</td>
<td>4.58</td>
<td>4.67</td>
<td>4.74</td>
<td>5.00</td>
<td>5.00</td>
<td>5.25</td>
<td>5.33</td>
<td>5.53</td>
<td>5.75</td>
<td>5.75</td>
<td>5.75</td>
<td></td>
</tr>
</tbody>
</table>

### APPENDIX. 5.1.11: PUMP TEST DATA SENBAGH (WELL 117) Q = 86604 ft³/d
### Senbagh O.W. (r = 150 ft)

<table>
<thead>
<tr>
<th>Elapsed time (minutes)</th>
<th>Drawdown (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 2.0 3.0 4.0 5.0 6.0 7.0 10.0 12.0 14.0 16.0 18.0 20.0 20.0 25.0 30.0 35.0 40.0 45.0</td>
<td>0.87 0.87 0.91 1.12 1.29 1.37 1.45 1.66 1.70 1.79 1.91 2.12 2.24 2.37 2.54 2.62 2.71 2.87</td>
</tr>
<tr>
<td>50.0 55.0 60.0 70.0 80.0 90.0 100.0 120.0 140.0 160.0 180.0 200.0 240.0 280.0 320.0 360.0 400.0 460.0 520.0</td>
<td>3.00 3.05 3.71 3.25 3.29 3.41 3.50 3.58 3.66 3.74 3.79 3.83 3.95 4.04 4.08 4.29 4.29 4.29</td>
</tr>
<tr>
<td>580.0 640.0 700.0 760.0 820.0 880.0 940.0 1000.0 1200.0 1300.0 1500.0 1600.0 1700.0 1800.0 1900.0 2000.0 2300.0 2400.0</td>
<td>4.29 4.33 4.54 4.58 4.62 4.67 4.71 4.75 4.83 4.83 4.83 4.83 4.83 4.87 4.87 4.90 4.92</td>
</tr>
<tr>
<td>2500.0 2600.0 2700.0 2800.0 2900.0 3000.0 3100.0 3200.0 3300.0 3400.0 3500.0 3600.0 3700.0 3800.0 3900.0 4000.0 4100.0</td>
<td>4.92 4.92 4.92 4.92 4.96 4.96 5.04 5.04 4.96 4.96 4.96 5.08 5.08 5.08 5.08 5.12 5.12</td>
</tr>
<tr>
<td>5.04 5.04 5.04 5.04 5.08 5.08 5.08 5.08 5.08 5.08 5.08 5.08 5.08 5.12 5.12</td>
<td>5.04 5.04 5.04 5.04 5.08 5.08</td>
</tr>
</tbody>
</table>

### Senbagh O.W. (r = 400 ft)

<table>
<thead>
<tr>
<th>Elapsed time (minutes)</th>
<th>Drawdown (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.0 7.0 8.0 9.0 10.0 12.0 14.0 16.0 18.0 20.0 25.0 30.0 35.0 40.0 45.0 50.0 55.0 60.0 70.0</td>
<td>0.04 0.04 0.12 0.16 0.21 0.33 0.33 0.33 0.42 0.50 0.58 0.71 0.79 0.87 0.95 1.00 1.08 1.12</td>
</tr>
<tr>
<td>80.0 90.0 100.0 120.0 140.0 160.0 180.0 200.0 240.0 280.0 320.0 360.0 400.0 460.0 520.0</td>
<td>1.21 1.29 1.33 1.37 1.50 1.54 1.62 1.71 1.71 1.83 1.88 1.92 2.00 2.08 2.17 2.17 2.21 2.29</td>
</tr>
<tr>
<td>580.0 640.0 700.0 760.0 820.0 880.0 940.0 1000.0 1100.0 1200.0 1300.0 1400.0 1500.0 1600.0 1700.0 1800.0 1900.0 2000.0</td>
<td>2.33 2.33 2.38 2.38 2.38 2.42 2.46 2.62 2.71 2.58 2.62 2.58 2.58 2.58 2.58 2.71 2.67 2.67 2.71</td>
</tr>
<tr>
<td>2800.0 2900.0 3000.0 3100.0 3200.0 3300.0 3400.0 3500.0 3600.0 3700.0 3800.0 3900.0 4000.0 41000.0 4200.0</td>
<td>2.79 2.79 2.79 2.79 2.79 2.79 2.79 2.79 2.79 2.79 2.79 2.79 2.79 2.79 2.79 2.79 2.79 2.79 2.79</td>
</tr>
</tbody>
</table>

383
APPENDIX. 5.2.1: RUSHTON NUMERICAL (RADIAL FLOW) MODEL.

C RUSHTON NUMERICAL TEST PUMPING MODEL
C CONFINED OR WATER TABLE AQUIFER
C NO VERTICAL FLOW
C IN THIS VERSION THE DRAWDOWNS AT ONE SPECIFIED
C OBSERVATION POINT ARE CALCULATED BY LOGARITHMIC
C INTERPOLATION AND SUBSEQUENTLY PLOTTED USING
C DEPT.HYDRO.RUSHPLOT. THE RADIAL DISTANCE OF THE
C OBSERVATION POINT (ROBS) MUST BE READ IN THE DATA FILE,
C ON THE SAME LINE AS RWELL AND RMAX, IN FREE FORMAT.
C IF THE OBSERVATION POINT IS THE PUMPING WELL ITSELF
C THEN SET ROBS EQUAL TO RWELL.
C SPECIFY DOUBLE PRECISION
IMPPLICIT DOUBLE PRECISION(A-H),DOUBLE PRECISION(O-Z)
DIMENSION R(100),RR(100),D(100),OLDD(100),T(100),H(100),
1RECH(100),A(100),B(100),C(100),E(100),U(100),V(100),NODE(6),
2X(100),Y(100),RDIST(6),DDN(6),LINE(20),
3XPLOT(300),YPLOT(300)
C READ IN TITLES AND PARAMETERS
READ(5,5999)LINE
5999 FORMAT(20A4)
WRITE(6,6105)LINE
6105 FORMAT(' RUSHTON NUMERICAL TEST PUMPING MODEL'/
11X,20A4)/
READ (5,*)PERM,SCON,SUNCON,ALPHA
READ (5,*)WELLOS,BL
BL2=BL*BL
WRITE(6,6000)PERM, SCON, SUNCON, ALPHA, BL/WELLOS
6000 FORMAT(* PERMEABILITY', 11X,F12.1/'  S(CONFINED)',12X,F12.7/
1' S(UNCONFINED)',12X,F12.1/'  ALPHA',20X,F10.5/
2' LEAKAGE FACTOR',11X,F10.5/'  WELL LOSS',16X,F10.2)
READ (5,*) RWELL,RMAX,ROBS
WRITE(6,6010)RWELL,RMAX,ROBS
6010 FORMAT(' R(WELL)',16X,F12.3/' R(MAX)',17X,F12.1/
1' ROBS ',18X,F12.3)
C
C SET UP RADIAL MESH
DO 10 N=1,100
AN=0.16666666667*FLOAT(N-2)
R(N)=RWELL*10.0**AN
IF(R(N).LT.RMAX) GO TO 10
R(N)=RMAX
RR(N)=RMAX*RMAX
NMAX=N
NMONE=N-1
GO TO 20
10 RR(N)=R(N)*R(N)
20 DELA=0.383765
DELA2=DELA*DELA
C NOTE THAT ALL LEVELS MEASURED DOWNWARDS FROM DATUM
READ(5,*) TOP,BASE,WLEVEL,RCH
WRITE(6,6020) TOP,BASE,WLEVEL,RCH

6020 FORMAT(' TOP OF AQUIFER',9X,F12.3/' BASE OF AQUIFER',8X,F12.3/   
1' STARTING WATERLEVEL',3X,F12.3/' RECHARGE',15X,F12.3)

C
C SET INITIAL CONDITIONS
DO 30 N=1,NMAX
   RECH(N)=RCH
   Y(N)=0.000
   D(N)=WLEVEL
   X(N)=0.0
30 OLDD(N)=WLEVEL
READ(5,*) JFIX
READ(5,*) NNODES
IF(JFIX.EQ.1) WRITE(6,6030)
IF(JFIX.EQ.1) GOTO 32
WRITE(6,6031)

6030 FORMAT(22H ** FIXED BOUNDARY** )
6031 FORMAT(22H ** FREE BOUNDARY ** )
32 READ(5,*) (NODE(J),J=1,NNODES)
   WRITE(6,6040) (NODE(J),J=1,NNODES)

6040 FORMAT(' NODES CHOSEN',5X,6I3/)
   TSTART=0.0
   READ(5,*)QPUMP,TSTOP
   WRITE(6,6050)QPUMP,TSTOP

6050 FORMAT(' PUMPING RATE =',F12.3,' M3/DAY FOR',F12.3,' DAYS'/)
C
C CONVERT ABSTRACTION TO QABST
   PI=4.0*ATAN(1.0)
   QABST=0.5*QPUMP/(PI*DELA)
   IND=0
C
C INITIAL TIME AND DELT
   TIME=0.0
   DELI=0.025*RR(1)*SCON/(PERM*(BASE-TOP))
   DELT=DELI
   DO 35 I=1,NNODES
      Il=NODEa)
35 RDIST(I)=R(H)
WRITE(6,6100)(NODE(J),J=1,NNODES)

6100 FORMAT(' TIME (DAYS)',6X,' TIME (MINS)',15X,
   1'DRAWDOWN AT NODE/DISTANCE',43X,' PWELL ',19F9.2' R(MAX)'
   2' ROBS',6I9,
   WRITE(6,6111)R(I),ROBS,(RDIST(J),J=1,NNODES),R(NMAX)

6111 FORMAT(' CUM PUMP CUM PUMP ',
   19F9.2)/
C
C CALC FOR A SPECIFIC TIME, IND=0 FOR LAST STEP
   ICOUNT=0
40 IF(ICOUNT.EQ.0) GO TO 42
   XPLOT(ICOUNT)=SSTIME
   YPLOT(ICOUNT)=SOBS
42 CONTINUE
TIME=TIME+DELT
TPLOT=TSTART+(0.1/1440.0)
IF(TIME.GE.TPLOT) ICOUNT=ICOUNT+1
IF(TIME.LT.TSTOP) GO TO 50
DELT=TSTOP-TIME+DELT
TIME=TSTOP
IND=100
50 CONTINUE
C
C DELAYED YIELD
FACA=0.0
FACB=1.0
FACC=0.0
IF(ALPHA.EQ.0.0)GO TO 15
F=ALPHA*DELT
IF(F.GT.100.0) GO TO 45
FACA=EXP(-F)
45 FACB=1.0-FACA
FACC=FACB/(ALPHA*DELT)
DO 55 N=1,NMAX
X(N)=FACA*Y(N)
55 RECH(N)=ALPHA*SUNCON*X(N)+RCH
15 CONTINUE
C
C CALC. REPEATED 4 TIMES FOR CONVERGANCE
DO 60 NUM=1,4
DO 70 N=1,NMONE
C
C TAKE AV. SAT. DEPTH BETWEEN N AND N+1
SD=BASE-0.5*(D(N)+D(N+1))
STOR=SUNCON+FACB*SUNCON
IF(SD.LT.(BASE-TOP)) GO TO 80
SD=BASE-TOP
80 H(N)=DELA2/(SD*PERM)
IF(BL.NE.O.O)RECH(N)=PERM*SD*(OLDD(N)-WLEVEL)/BL2
70 T(N)=DELT/(STOR*RR(N))
C
C WELL LOSS ADJUSTMENT,CLOSEST 6 NODES
DO 300 N=2,7
H(N)=H(N)*WELLOS
300 CONTINUE
C
C REPRESENT WATER IN WELL
H(1)=0.0001*H(1)
T(1)=2.0*DELT*DELA/RR(2)
T(2)=2.0*T(2)
H(NMAX-1)=DLOG(R(NMAX)-DLOG(R(NMAX-1)))*(DLOG(R(NMAX))-DLOG(1(R(NMAX-1)))/(SD*PERM))
H(NMAX)=1.0E+10
T(NMONE)=2.0*DELT*DELA/((R(NMAX)-R(NMONE-1))*STOR*R(NMONE))
T(NMAX)=1.0*DELT*DELA/((R(NMAX)-R(NMONE))*STOR*R(NMAX))
IF (JFIX.EQ.1) T(NMAX)=1.0E-10*T(NMAX)

C GAUSSIAN ELIMINATION
C COEFFICIENTS
C EQUATION IS-A(N)*D(N-1)+B(N)*D(N)-C(N)*D(N+1)=E(N).
B(1)=1.0/H(1)+1.0/T(1)
C(1)=1.0/H(1)
E(1)=OLDD(1)/T(1)+QABST
DO 90 N=2,NMONE
A(N)=1.0/H(N-1)
B(N)=1.0/H(N-1)+1.0/H(N)+1.0/T(N)
C(N)=1.0/H(N)
90 E(N)=OLDD(N)/T(N)-RR(N)*RECH(N)
A(NMAX)=1.0/H(NMONE)
B(NMAX)=1.0/H(NMONE)+0.5yT(NMAX)
E(NMAX)=0.5*OLDD(NMAX)/T(NMAX)-0.5*RR(NMAX)*RECH(NMAX)

C ELIMINATION
U(1)=B(1)
V(1)=E(1)
DO 100 N=2,NMAX
U(N)=B(N)-(A(N)*C(N-1))/U(N-1)
100 V(N)=E(N)+(A(N)*V(N-1))/U(N-1)
D(NMAX)=V(NMAX)/U(NMAX)
DO 110 NN=1,NMONE
N=NMONE-NN+1
110 D(N)=(V(N)+C(N)*D(N+1))/U(N)

C DELAYED YIELD
DO 115 N=1,NMAX
115 Y(N)=X(N)+FACC*(D(N)-OLDD(N))

C TEST FOR EXCESSIVE DRAWDOWNS
DRAWMX=0.9*BASE+0.1*TOP
IF(D(1).LT.DRAWMX) GO TO 60
WRITE(6,580)
580 FORMAT(* EXCESSIVE DRAWDOWN')
STOP
60 CONTINUE

C OUTPUT AND THEN CHANGE PARAMETER
TIMIN=TIME-TSTART
STIMIN=TIMIN*1440
SSTIME=TIME*1440
DO 120 I=1,NNODES
Il=NODEa)
120 DDN(I)=D(I1)
DO 46 N=2,100
IF(R(N-1).LT.ROBS.AND.R(N).GE.ROBS)THEN
DOBS=-(LOG(ROBS)-LOG(R(N-1)))/(LOG(R(N))-LOG(R(N-1)))
SOBS=D(N-1)+DOBS*(D(N)-D(N-1))
GO TO 43
ENDIF
46 CONTINUE
43 CONTINUE
IF(TIME.LT.TPLOT) GO TO 44
WRITE(6,560) TIME,TIMIN,SSTIME,STIMIN,D(1),SOBS,
1(DDN(J),J=1,NNODES),D(NMAX)
44 CONTINUE
DO 130 N=1,NMAX
130 OLDD(N)=D(N)
IF(ALPHA.EQ.0.0) GO TO 6
DELT=TIMIN*0.21143
GO TO 7
6 DELT=TIMIN*0.25892
7 CONTINUE
IF(IND.EQ.0) GO TO 40
C
C END OF CALC FOR A SPECIFIC TIME
DELT=DELI
IND=0
TST ART=TIME
C
C INPUT NEW PUMPING PHASE
READ(5,*)QPUMP,TSTOP
QABST=0.5*QPUMP/(PI*DELA)
IF(QPUMP.LT.0.0) GO TO 41
WRITE(6,6050) QPUMP,TSTOP
WRITE(6,6100)(NODE(J), J= 1,NNODES)
WRITE(6,6111)R(1),(RDIST(J),J=1,NNODES),R(NMAX)
GO TO 40
41 XPLOT(ICOUNT)=SSTIME
YPLOT(ICOUNT)=SOBS
WRITE(4,595)ICOUNT
595 FORMAT(I3)
WRITE(4, *) (XPLOT (J), J=1 ,ICOUNT)
WRITE(4, *) (YPLOT (J), J=1 ,ICOUNT)
WRITE(4,600) PERM,SCON,SUNCON,RWELL,RMAX,JFIX
WRITE(4,605) ALPHA,BL,WELLOS,RCH
600 FORMAT(3(1X,F10.5),2(1X,F10.3),1X,I1)
605 FORMAT(4(1X,F10.5))
STOP
END

APPENDIX. 5.2.2: MODEL DATA PLOTTING PROGRAM.

C THIS PROGRAM PRODUCES A STRAIGHT LINE PLOT FOR UP TO 300
C DRAWDOWN VALUES. DRAWDOWNS UP TO A MAXIMUM OF 36 UNITS
C (METRES OR FEET) CAN BE ACCOMMODATED. THE SCALE OF THE
C DRAWDOWN AXIS IS ADJUSTED AUTOMATICALLY. DRAWDOWNS AT
C TIMES FROM 0.1 TO 10 000 MINUTES CAN BE PLOTTED. SITE
INFORMATION AND UNITS FOR DRAWEEDOWN ARE PRINTED ON THE PLOT
USING THE ARRAYS NAME AND UNIT. THE GRID PRODUCED IS
COMPATABLE WITH CHARTWELL GRAPH PAPER REF 5541. THE CALL
AXISCA LINE MUST BE ALTERED IF PLOTTING DRAWEEDOWNS GREATER
THAN 36 UNITS.

DIMENSION X(300),Y(300),NAME(20),UNIT(20),XX(300),YY(300)
READ(5,15)NAME
READ(5,15)UNIT
15 FORMAT(20A4)
READ(5,2) J
2 FORMAT(I3)
READ(5,*)X(N),N=1,J
READ(5,3)Y(N),N=1,J
3 FORMAT(16F5.0)
READ(3,2)I
READ(3,*)XX(N),N=1,I
READ(3,*)YY(N),N=1,1
READ(3,*) PERM,SCON,SUNCON,RWELL,RMAX,JFIX
READ(3,*) ALPHA,BL,WELLOS,RCH
S=Y(1)
DO 99 M=2,J
IF (Y(M).GT.S)THEN
S=Y(M)
ENDIF
99 CONTINUE
IF (S.LE.0.45)S=0.45
IF (S.LE.0.9.AND.S.GT.0.45)S=0.9
IF (S.LE.3.6.AND.S.GT.0.9)S=3.6
IF (S.LE.9.0.AND.S.GT.3.6)S=9.0
IF (S.LE.18.0.AND.S.GT.9.0)S=18.0
IF (S.LE.36.0.AND.S.GT.18.0)S=36.0
IF (S.GT.36.0) GO TO 98
CALL V80
CALL UNITS(0.8)
CALL PICCLE
CALL DEVPAP(350.0,320.0,0)
CALL WINDOW(2)
CALL AXIPOS(1,30.0,20.0,312.5,1)
CALL AXIPOS(1,30.0,20.0,180.0,2)
CALL AXISCA(3,18,S,0.00,2)
CALL AXISCA(4,0,0.1,10000.0,1)
CALL GRID(3,0,0)
CALL GRID(-2,1,1)
CALL PENSEL(2,0.3,1)
CALL GRASYM(X,Y,J,3,0)
CALL GRACUR(XX,YY,I)
CALL PENSEL(1,0.3,1)
CALL MOVTO2(40.0,33.0)
CALL CHAHOL('K= *.')
CALL CHAFIX(PERM,-10,5)
CALL MOVTO2(100.0,33.0)
CALL CHAHOL('S= *.')
CALL CHAFIX(SCON,-10,5)
CALL MOVTO2(165.0,33.0)
CALL CHAHOL('SY= *.'
CALL CHAFIX(SUNCON,-10,5)
CALL MOVTO2(225.0,33.0)
CALL CHAHOL('Rw= *.'
CALL CHAFIX(RWELL,-10,3)
CALL MOVTO2(285.0,33.0)
CALL CHAHOL('Rmax= *.'
CALL CHAFIX(RMAX,-10,3)
CALL MOVTO2(40.0,23.0)
CALL CHAHOL('JFIX= *.'
CALL CHAINT(JFIX,-1)
CALL MOVTO2(90.0,23.0)
CALL CHAHOL('ALPHA= *.'
CALL CHAFIX(ALPHA,-10,5)
CALL MOVTO2(149.0,23.0)
CALL CHAHOL('BL= *.'
CALL CHAFIX(BL,-10,5)
CALL MOVTO2(215.0,23.0)
CALL CHAHOL('WELLOS= *.'
CALL CHAFIX(WELLOS,-7,3)
CALL MOVTO2(285.0,23.0)
CALL CHAHOL('RCH= *.'
CALL CHAFIX(RCH,-10,5)
CALL MOVTO2(65.0,235.0)
CALL CHAHOL('STRAIGHT LINE METHOD : TIME-DRAWDOWN PLOT*.'
CALL MOVTO2(65.0,230.0)
CALL CHAARR(NAME,20,4)
CALL MOVTO2(65.0,220.0)
CALL CHAHOL('FIELD DATA INDICATED BY CROSSES*.'
CALL MOVTO2(65.0,215.0)
CALL CHAHOL('RADIAL FLOW MODEL INDICATED BY CONTINUOUS
1 LINE*.'
CALL MOVTO2(165.0,10.0)
CALL CHAHOL('TIME (MINUTES)*.'
CALL MOVTO2(13.0,100.0)
CALL CHAHAR(3,1)
CALL CHAHOL('DRAWDOWN ( )*.'
CALL MOVTO2(13.0,139.0)
CALL CHAARR(UNIT,20,4)
CALL DEVEND
GO TO 96
98 CONTINUE
WRITE(6,97)
97 FORMAT(' MAX. DRAWDOWN GREATER THAN 36 UNITS. MODIFY
1 PROGRAM SO S CAN BE GREATER THAN 36 IN THE CALL AXISCA
1 STATEMENT FOR THE Y 1AXIS*.'
96 CONTINUE
STOP
END
APPENDIX. 5.2.3: PROGRAM TO DRAW TIME DRAWDOWN TYPE CURVE PLOT.

C THIS PROGRAM PRODUCES A PLOT FOR TYPE CURVE MATCHING. THE
C PROGRAM CAN ACCOMMODATE UP TO 300 DRAWDOWN VALUES.
C DRAWDOWNS CAN BE PLOTTED IN THE RANGE 0.01 TO 100 UNITS
C (METRES OR FEET) AND TIME IN THE RANGE 0.1 TO 100 000 MINUTES.
C SITE INFORMATION AND UNITS FOR DRAWDOWN ARE PRINTED ON THE
C PLOT USING THE ARRAYS NAME AND UNIT. THE GRID PRODUCED IS
C COMPATABLE WITH CHARTWELL GRAPH PAPER REF 5846.

DIMENSION X(300), Y(300)
CHARACTERS NAME(20), UNIT(2)
READ 19, NAME
READ 18, UNIT

18 FORMAT(2A4)
19 FORMAT(20A4)
READ 10, J

10 FORMAT(I3)
READ 30, (X(N), N=1,J)

30 FORMAT(13F6.1)
READ 40, (Y(N), N=1,J)

40 FORMAT(16F5.2)
CALL DEVBEG
CALL DEVPAP(340.0, 250.0, 0)

C CALL UNITS(0.5)
CALL PICCLE
CALL WINDOW(2)
CALL AXIPOS(1,20.0, 20.0, 300.0, 1)
CALL AXIPOS(1, 20.0, 20.0, 180.0, 2)
CALL AXISCA(4, 0, 0.1, 10000.0, 1)
CALL AXISCA(4, 0, 0.1, 100.0, 2)
CALL GRID(-3,1,1)
CALL PENSEL(2,0.3,1)
CALL GRASYM(X,Y,J,3,0)
CALL PENSEL(1,0.3,1)
CALL MOVTO2(70.0, 225.0)
CALL CHAHOL(‘TYPE CURVE : TIME-DRAWDOWN PLOT*.’)
CALL MOVTO2(70.0, 215.0)
CALL CHAARR(NAME,20,4)
CALL MOVTO2(140.0, 10.0)
CALL CHAHOL(‘TIME (MINUTES)*.’)
CALL MOVTO2(10.0, 75.0)
CALL CHAHAR(3,1)
CALL CHAHOL(‘DRAWDOWN ( )*.’)
CALL MOVTO2(10.0, 105.0)
CALL CHAARR(UNIT,2,4)
CALL DEVEND
STOP
END
APPENDIX. 5.2.4: PROGRAM TO DRAW TIME DRAWDOWN TYPE CURVE PLOT.

C THIS PROGRAM PRODUCES A STRAIGHT LINE PLOT FOR UP TO 300
C DRAWDOWN VALUES. DRAWDOWNS UP TO A MAXIMUM OF 36 UNITS
C (METRES OR FEET) CAN BE ACCOMMODATED. THE SCALE OF THE
C DRAWDOWN AXIS IS ADJUSTED AUTOMATICALLY. DRAWDOWNS AT
C TIMES FROM 0.1 TO 10 000 MINUTES CAN BE PLOTTED. SITE
C INFORMATION AND UNITS FOR DRAWDOWN ARE PRINTED ON THE PLOT
C USING THE ARRAYS NAME AND UNIT. THE GRID PRODUCED IS
C COMPATABLE WITH CHARTWELL GRAPH PAPER REF 5541. THE CALL
C AXISCA LINE MUST BE ALTERED IF PLOTTING DRAWDOWNS GREATER
C THAN 36 UNITS.
DIMENSION X(300),Y(300)
CHARACIER*4 NAME(20),UNIT(2)
READ 15,NAME
READ 14,UNIT
14 FORMAT(2A4)
15 FORMAT(20A4)
READ 2, J
2 FORMAT(I3)
   READ 3,(X(N),N=1,J)
3 FORMAT(13F6.1)
   READ 5,(Y(N),N=1,J)
5 FORMAT(16F5.2)
S=Y(1)
DO 99 M=2J
   IF (Y(M).GT.S)THEN
      S=Y(M)
   PRINT *,S
99 CONTINUE
   IF (S.LE.0.45)THEN
      S=0.45
   ELSEIF (S.LE.0.9.AND.S.GT.0.45)THEN
      S=0.9
   ELSEIF (S.LE.3.6.AND.S.GT.0.9)THEN
      S=3.6
   ELSEIF (S.LE.9.0.AND.S.GT.3.6)THEN
      S=9.0
   ELSEIF (S.LE.18.0.AND.S.GT.9.0)THEN
      S=18.0
   ELSEIF (S.LE.36.0.AND.S.GT.18.0)THEN
      S=36.0
   ELSEIF (S.LE.54.0.AND.S.GT.36.0)THEN
      S=54.0
   ELSE
      GO TO 98
98 ENDIF
   CALL DEVBEG
   CALL DEVPAP(350.0,320.0,0)
C CALL UNITS(0.5)
C CALL WINDOW(2)
APPENDIX. 5.2.4: (CONTINUED)

CALL PICCLE
CALL AXIPOS(1,30.0,20,0,312.5,1)
CALL AXIPOS(1,30.0,20,0,180.0,2)
CALL AXISCA(3,18,S,0.00,2)
CALL AXISCA(4,0,0.1,10000.0,1)
CALL GRID(3,0,0)
CALL GRID(-2,1,1)
CALL PENSEL(2,0,3,1)
CALL GRASYM(X,Y,1,3,0)
CALL PENSEL(1,0,3,1)
CALL MOVTO2(65.0,240.0)
CALL CHAHOL('STRAIGHT LINE METHOD : TIME-DRAWDOWN PLOT*.
')
CALL MOVTO2(65.0,230.0)
CALL CHAARR(NAME,20,4)
CALL MOVTO2(155.0,4.0)
CALL CHAHOL('TIME (MINUTES)*.
')
CALL MOVTO2(7.0,100.0)
CALL CHAHAR(3,1)
CALL MOVTO2(7.0,75.0)
CALL CHAHOL('DRAWDOWN ( FEET )*.
')
CALL DEVEND
GO TO 96
98 CONTINUE
PRINT 97
97 FORMAT(' MAX. DRAWDOWN GREATER THAN 36 UNITS. MODIFY
PROGRAM SO
1S CAN BE GREATER THAN 36 IN THE CALL AXISCA STATEMENT FOR Y
AXIS
1*.
')
96 CONTINUE
STOP
END
Appendix 5.3.1.A: Comparison of (a) Manual and (b) Model result from B'Baria OW1.
Appendix 5.3.1.B: Comparison of (a) Manual and (b) Model result from B'Baria OW2.
Appendix 5.3.1.C: Comparison of (a) Manual and (b) Model result from B'Baria OW3.
Appendix 5.3.2.A: Comparison of (a) Manual and (b) Model result from Daudkandi OW1.
Appendix 5.3.2.B: comparison of (a) Manual and (b) Model result from Daudkandi OW2.
Appendix 5.3.2.C: Comparison of (a) Manual and (b) Model result from Daudkandi OW3.
Appendix 5.3.3.A: Comparison of (a) Manual and (b) Model result from Burichong OW1.
Appendix 5.3.3.B: Comparison of (a) Manual and (b) Model result from Burichong OW2.
STRAIGHT LINE METHOD: TIME-DRAWDOWN PLOT
BURICHONG PIEZO WELL AT A DISTANCE R = 250.0 FT Q = 76962.28FT3/D
FIELD DATA INDICATED BY CROSSES
RADIAL FLOW MODEL INDICATED BY CONTINUOUS LINE

Appendix 5.3.3.C: Comparison of (a) Manual and (b) Model result from Burichong OW3.
Appendix 5.3.4.A: Comparison of (a) Manual and (b) Model results from Chandina OW1.
Appendix 5.3.4.B: Comparison of (a) Manual and (b) Model result from Chandina OW2.
Appendix 5.3.4.C1: Comparison of (a) Manual and (b) Model result from Chandina OW3.
Appendix 5.3.4.C2: Comparison of (a) Manual and (b) Model result from Chandina OW3.

(a) STRAIGHT LINE METHOD: TIME-DRAWDOWN PLOT
CALC. REC. DATA CHANDINA PIEZO. WELL AT A DISTANCE R = 400.0 FT/3/D
FIELD DATA INDICATED BY CROSSES
RADIAL FLOW MODEL INDICATED BY CONTINUOUS LINE

(b) STRAIGHT LINE METHOD: TIME-DRAWDOWN PLOT
CALC. REC. DATA CHANDINA PIEZO. WELL AT A DISTANCE R = 400.0 FT/3/D
FIELD DATA INDICATED BY CROSSES
RADIAL FLOW MODEL INDICATED BY CONTINUOUS LINE
Appendix 5.3.5.A: Comparison of (a) Manual and (b) Model result from Kotwali OW1.
Appendix 5.3.5.B: Comparison of (a) Manual and (b) Model result from Kotwali OW2.
Appendix 5.3.5.C: Comparison of (a) Manual and (b) Model result from Kotwali OW3.
Appendix 5.3.6.A: Comparison of (a) Manual and (b) Model result from Barura OWI.
Appendix 5.3.6.B: Comparison of (a) Manual and (b) Model result from Barura OW2.

(a) STRAIGHT LINE METHOD: TIME-DRAWDOWN PLOT
BARURA PIEZO. WELL AT A DISTANCE R = 150.0 FT Q = 76982.40 FT3/D
FIELD DATA INDICATED BY CROSSES
RADIAL FLOW MODEL INDICATED BY CONTINUOUS LINE

(b) STRAIGHT LINE METHOD: TIME-DRAWDOWN PLOT
BARURA PIEZO. WELL AT A DISTANCE R = 150.0 FT Q = 76982.40 FT3/D
FIELD DATA INDICATED BY CROSSES
RADIAL FLOW MODEL INDICATED BY CONTINUOUS LINE
Appendix 5.3.6.C: Comparison of (a) Manual and (b) Model result from Barura OW3.
Appendix 5.3.7.A: Comparison of (a) Manual and (b) Model result from Haziganj OW1.
Appendix 5.3.7.B: Comparison of (a) Manual and (b) Model result from Haziganj OW2.
Appendix 5.3.7.C: Comparison of (a) Manual and (b) Model result from Haziganj OW3.
Appendix 5.3.8.A: Comparison of (a) Manual and (b) Model result from Chauddagram OW1.
Appendix 5.3.8.B: Comparison of (a) Manual and (b) Model result from Chauddagram OW2.
Appendix 5.3.8.C: Comparison of (a) Manual and (b) Model result from Chauddagram OW3.
Appendix 5.3.9.A: Comparison of (a) Manual and (b) Model result from Senbagh OW1.
Appendix 5.3.9.B: Comparison of (a) Manual and (b) Model result from Senbagh OW2.
Appendix 5.3.9.C: Comparison of (a) Manual and (b) Model result from Senbagh OW3.
APPENDIX. 6.1: PROGRAM TO ANALYZE STEP DRAWDOWN TESTS (EDEN AND HAZEL METHOD).

C THIS PROGRAM RECALCULATES AND PLOTS TIME/DRAWDOWN DATA FOR THE EDEN AND HAZEL (1973) ANALYSIS OF STEP TESTS. THIS PROGRAM IS WRITTEN SPECIFICALLY FOR THE DATA FOR SAUDIA ARABIA FROM LEWIS CLARK'S PAPER (1977). SOME FORMAT AND WRITE STATEMENTS MUST BE MODIFIED FOR TESTS WHICH DO NOT HAVE 7 STEPS. SIMILARLY SOME OF THE PLOTTING ROUTINES WILL NEED TO BE ALTERED, INCLUDING THOSE WHICH SCALE THE AXES. I = NUMBER OF STEPS. J = NUMBER OF DRAWDOWN MEASUREMENTS. I AND J TO BE GIVEN ON THE FIRST DATA CARD IN 12,13 FORMAT. MAXIMUM CAPACITY OF PROGRAM IS 10 STEPS AND 300 MEASUREMENTS. DQ( ) IS AN ARRAY CONTAINING THE STEP DISCHARGE INCREMENTS. DTIME( ) IS AN ARRAY CONTAINING THE TIMES AT WHICH EACH STEP STARTS. TIME( ) IS AN ARRAY CONTAINING THE TIMES AT WHICH DRAWDOWNS, CONTAINED IN THE ARRAY Y, ARE MEASURED. DQLOGT( , ) IS AN ARRAY CONTAINING THE RECALCULATED TIME DATA. ARRAY X IS AN ARRAY CONTAINING THE RECALCULATED TIME DATA SUMMED OVER THE STEPS. IF PLOTTING IS NOT REQUIRED REMOVE RELEVANT LINES. REMEMBER THE VALUE FOR 'VEND' IN THE CALL AXISCA ROUTINE FOR THE X AXIS WILL DEPEND ON THE MAXIMUM VALUE CALCULATED BY THE PROGRAM FOR ARRAY X. (SO RUN THE PROGRAM WITHOUT THE PLOTTING ROUTINES TO DETERMINE THIS VALUE). THE VALUE FOR 'VEND' FOR THE Y AXIS WILL ALSO DEPEND ON THE MAXIMUM DRAWDOWN.

DIMENSION DQ(10), DTIME(10), TIME(300), X(300), Y(300)
DIMENSION V(300,10), DQLOGT(300,10)
DATA DQLOGT/3000*0.0/
READ 1, I, J
1 FORMAT(2I3)
READ 2,(DQ(K), K=1,I)
READ 2,(DTIME(K), K=1,I)
2 FORMAT(3F10.1)
READ 4,(TIME(N), N=1,J)
READ 3,(Y(N), N=1,J)
4 FORMAT(16F5.2)
3 FORMAT(16F5.2)

DO 12 K=1,I
DO 11 N=1,J
V(N,K)=TIME(N)-DTIME(K)
IF(V(N,K),LE.1.0) THEN
GO TO 11
ELSE
DQLOGT(N,K)=DQ(K)*ALOG10(V(N,K))
ENDIF
11 CONTINUE
12 CONTINUE
DO 13 N=1,J
APPENDIX. 6.1: (CONTINUED).

XST=0.0
DO 14 K=1,I
   XST=XST+DQLOGT(N,K)
14 CONTINUE
X(N)=XST
13 CONTINUE
PRINT 20,(DQ(K),K=1,1)
20 FORMAT('015X,'DQ(1)=',F10.1,1X,'DQ(2)=',F10.1,
   11X,'DQ(3)=',F10.1)
PRINT 21
21 FORMAT('06X,*TIME',5X,'DQLOGT(N,1)',1X,'DQLOGT(N,2)
   1,1X,'DQLOGT(N,3)',1X,'X(N)',8X,'Y(N)"
DO 50 N=1,J
   PRINT 23,TIME(N),DQLOGT(N,1),DQLOGT(N,2),DQLOGT(N,3),X(N),Y(N)
23 FORMAT(F10.1,7F12.1,F12.0,F12.3)
50 CONTINUE
CALL DEVBEG
C  CALL UNITS(0.5)
   CALL PICCLE
   CALL DEVPAP(320.0,270.0,0)
   CALL AXIPOS(1,15.0,15.0,280.0,1)
   CALL AXIPOS(1,15.0,15.0,230.0,2)
   CALL AXISCA(3,50,0.0,500000.0,1)
   CALL AXISCA(3,5,0.0,5.0,2)
   CALL GRID(3,0,0)
   CALL GRID(-2,1,1)
   CALL GRASYM(X,Y,J,2,0)
   CALL MOVTO2(35.0,260.0)
   CALL CHAHOL('EDEN & HAZEL STEP TEST ANALYSIS\*'.)
   CALL MOVTO2(35.0,250.0)
   CALL CHAHOL('DRAWDOWN AGAINST SUMDQLOG(T-TX)*'.)
   CALL DEVEND
   STOP
   END
APPENDIX. 7.1: PROGRAM TO PLOT TRILINEAR DIAGRAM.

This program writes out the date (IDATE), time (ITIME), sample number (ISPLE), temperature (TEMP), field pH (PHF), laboratory pH (PHL), and the concentrations of Ca(X(1)), Mg(X(2)), Na(X(3)), K(X(4)), field HC03(X(5)), laboratory HC03(X(6)), SO4(X(7)), Cl(X(8)), NO3(X(9)) in mg/l supplied by the user with a format similar to that used by the Institute of Geological Sciences. This program also calculates and writes out milliequivalents per litre (F(I)) for each ionic species, sums of equivalents per litre of cations (SUMC) and anions (SUMA) and percentage milliequivalents per litre (PF (I)). Where data is not available, the program writes out 0.0. CFEPM is a table of equivalent weights for Ca, Mg, Na, K, HC03 (twice), SO4, Cl, NO3. The maximum capacity of this program is 200 samples.

```
DIMENSION X(9), CFEPM(9), F(9), IDATE(200), ITIME(200), ISPLE(200), TEMP(200), PHF(200), PHL(200), SUMC(200), SUMA(200)
  2, PFCA(200), PFMG(200), PFNAK(200), PFHC03(200), PFSO4(200)
  3, PFCLNO(200), TDS(200)
DATA CFEPM/0.0499, 0.0822, 0.0435, 0.0256, 0.0164, 0.0164, 0.0208, 0.0282, 0.0161/
READ 1, N
  1 FORMAT(13)
PRINT 10
10 FORMAT('0', 2X, 'DATE', 2X, 'TIME', 1X, 'SAMPLE', 1X, 'TEMP', 2X, 'PHF', 1X, 1X, 'PHL', 3X, 'ION CONCENTRATION 1ST IN MG/L 2ND IN EPM 3RD IN% EPM', 8X, '2X', 'SUM 'CATION', 1X, 'SUM ANION')
PRINT 11
DO 400 J = 1, N
READ 2, IDATE(J), ITIME(J), ISPLE(J)
  2 FORMAT(I6, 1X, I4, 1X, I6)
READ 3, TEMP(J), PHF(J), PHL(J)
  3 FORMAT(51X, F4.1, 1X, 2F5.2)
READ 4, X
  4 FORMAT(6X, F7.1, F7.2, F8.1, F7.2, F6.1, F6.1, F7.1, F8.1, F7.2)
IF(X(5).EQ.0.0) THEN
X(5)=X(6)
ENDIF
TDS(J)=X(1)+X(2)+X(3)+X(4)+X(5)+X(7)+X(8)+X(9)
DO 20 I = 1, 9
F(I)=X(I)*CFEPM(I)
20 CONTINUE
SUMC(J)=F(1)+F(2)+F(3)+F(4)
SUMA(J)=F(5)+F(7)+F(8)+F(9)
PFCA(J)=F(1)/SUMC(J)
PFMG(J)=F(2)/SUMC(J)
PFNAK(J)=(F(3)+F(4))/SUMC(J)
PFHC03(J)=F(5)/SUMA(J)
PFSO4(J)=F(7)/SUMA(J)
```

PFCLNO(J) = (F(8) + F(9)) / SUMA(J)

PRINT *
PRINT 12, IDATE(J), ITIME(J), ISPLE(J), TEMP(J), PHF(J), PHL(J), X

12 FORMAT( '  ', I6, 2X, I4, 1X, F4.1, F5.2, F5.2, 1X, F5.1, 1X, F5.2)

PRINT 13, F, SUMC(J), SUMA(J)

13 FORMAT( '  ', 36X, F5.3, 1X, F5.3, 1X, F6.3, 3X, F5.3, 5X, F5.3)

PRINT 14, PFCA(J), PFMG(J), PFNAK(J), PFHC03(J), PFSO4(J), PFCLNO(J)

14 FORMAT( '  ', 36X, F5.3, 1X, F5.3, 5X, F5.3)

400 CONTINUE

PAUSE
CALL T4010
CALL PICCLE
CALL DEVPAP(184., 140., 1)
CALL WINDOW(2)
CALL SHIFT2(90.0, 120.0)
CALL ROTAT2(-120.0)
CALL SHEAR2(2.1.0/SQRT(3.0))
CALL SCALE2(1.0, SQRT(3.0)/2.0)

C DRAW PIPER DIAGRAM
CALL MOVTO2(0., 0.)
CALL LINTO2(50., 0.)
CALL LINTO2(50., 50.)
CALL LINTO2(0., 50.)
CALL LINTO2(0., 0.)
DO 72 L = 1, 5
  A = L * 10.
  CALL MOVTO2(A, 0.)
  CALL LINTO2(A, 50.)
  CALL MOVTO2(0., A)
  CALL LINTO2(50., A)
72 CONTINUE

CALL MOVTO2(60., 0.)
CALL LINTO2(110., 0.)
CALL LINTO2(60., 50.)
CALL LINTO2(60., 0.)
DO 73 L = 1, 5
  A = L * 10.
  CALL MOVTO2(60. + A, 0.)
  CALL LINTO2(60. + A, 50. - A)
  CALL LINTO2(60., 50. - A)
  CALL LINTO2(110. - A, 0)
73 CONTINUE

CALL MOVTO2(0., 60.)
CALL LINTO2(0., 110.)
CALL LINTO2(50., 60.)
CALL LINTO2(0., 60.)
DO 74 L = 1, 5
  A = L * 10.
  CALL MOVTO2(0., 60. + A)
  CALL LINTO2(50. - A, 60. + A)
  CALL LINTO2(50. - A, 60.)

APPENDIX. 7.1: (continued).
CALL LINTO2(00.,110.-A)
74 CONTINUE
CALL CHAMOD
C PLOTTING ROUTINE
DO 30 J=1,N
CALL MOVTO2(50.0*PFHCO3(J),110.0-50.0*(PFSO4(J)+PFHCO3(J)))
CALL DOT(0.5)
CALL MOVTO2(110.0-50.0*(PFMG(J)+PFNAK(J)),50.0*PFNAK(J))
CALL DOT(0.5)
30 CONTINUE
DO 33 J=1,N
CALL MOVTO2(50.0*PFHCO3(J),50.0*PFNAK(J))
CALL DOT(TDS(J)/500.0)
33 CONTINUE
CALL DEVEND
STOP
END

APPENDIX. 7.1: (continued)
Appendix. 7.2.1: (a): Plot showing constituents of ground water samples in terms of major ion percentages. (b): Piper - Hill (1944) sub-division for classification of ground water types.
Appendix. 7.2.2: (a): Plot of the constituents of ground water samples in terms of major ion percentages. (b): Back’s (1961, 1966) classification diagram for anion and cation facies.
APPENDIX. 8.1: PROGRAM TO DRAW RIVER DISCHARGE HYDROGRAPH.

C THIS PROGRAM WORKS OUT TOTAL DISCHARGE FOR WATER YEAR
C SUPPLIED FOR RIVER ITCHEN AND PLOTS ANNUAL HYDROGRAPH.
C REMOVE GRAPHIC SUBROUTINE CALLS IF TOTAL DISCHARGE ONLY IS
C REQUIRED. EDIT THE CALL CHAHOL LINE FOR YEARS OTHER THAN
C THOSE GIVEN.
C
DIMENSION Y(370),X(370)
YSUM=0.0
READ 10,(Y(I),I=1,366)
10 FORMAT(13F6.2)
DO 20 J=1,366
  YSUM=YSUM+Y(J)
  IF(Y(J).GT.400.0)THEN
    Y(J)=400.0
  ENDIF
20 X(J)=J
PRINT 1, YSUM
1 FORMAT(F8.2)
CALL DEVBEG
CALL PICCLE
C CALL V80
C CALL UNITS(0.5)
CALL DEVPA(268.0,350.0,0)
C CALL WINDOW(2)
CALL AXIPOS(1,40.0,40.0,160.0,1)
CALL AXIPOS(1,40.0,40.0,230.0,2)
CALL AXISCA(3,19,0.0,380.0,1)
CALL AXISCA(3,20,0.0,400.0,2)
CALL PENSEL(1,0.3,3)
CALL GRID(3,0,0)
CALL GRID(-2,1,1)
CALL MOVT02(40.0,20.0)
CALL CHAHOL('UPSTREAM DISCHARGE COMILLA STATION *.')
CALL MOVT02(40.0,12.0)
CALL CHAHOL('RIVER GUMTI DAILY FLOW, CUMECS, 1979-1980*.')
CALL MOVT02(40.0,5.0)
CALL CHAHOL('TOTAL ANNUAL FLOW, CUMEC-DAYS: *.')
CALL MOVT02(90.0,30.0)
CALL CHAHOL('DAYS SINCE START OF WATER YEAR*.')
CALL MOVT02(25.0,160.0)
CALL CHAHAR(3,1)
CALL CHAHOL('DISCHARGE (CUMECS)*.')
CALL MOVT02(160.0,5.0)
CALL CHAHAR(3,0)
CALL CHAFIX(YSUM,14,4)
CALL GRAPOL(X,Y,365)
CALL DEVEND
STOP
END
APPENDIX. 8.2: PROGRAM TO SEPARATE BASE-FLOW FROM HYDROGRAPH


DIMENSION Q(365,4), NP(73), NT(73),BNT(73)
DIMENSION Q1(365), Q2(365), Q4(365)
DATA Q /1460*0.0/
QSUM=0.0
READ 51,(Q(I,2),I=1,365)
51 FORMAT(13F6.2)
C SUM ANNUAL TOTAL FLOW
DO 91 I=1,365
  Q(I,1) = I
91 QSUM = QSUM + Q(I,2)
C FIND MINIMUM Q IN PENTAD
IN = 0
DO 100 I=1,361,5
  D= 10**6
  IN = IN+1
  DO 110 J=1,5
    IF ( Q(I+J-1,2).GE.D) THEN
      GOTO 110
    ENDIF
    D=Q(I+J-1,2)
    JJ=J
  110 CONTINUE
NP(IN) = I+JJ-1
Q(I+JJ-1,3)=D
 100 CONTINUE
C FIND TURNING POINTS AND SUM BASEFLOW

L=NP(1)
NT(1) = L
Q(L,4)=Q(L,2)
NTP = 1
BF = Q(L,4)*L
DO 200 I=2,72
  LA=NP(I-1)
  LB=NP(I)
  LC=NP(I+1)
  D=0.9*Q(LB,3)
  200
APPENDIX. 8.2 (CONTINUED).

IF(D.LE.Q(LA,3).AND.D.LE.Q(LC,3)) THEN
  Q(LB,4)=Q(LB,2)
  NTP=NTP+1
  NT(NTP)=LB
  LD=NT(NTP-1)
  BF = BF+ 0.5*(LB-LD)*Q(LB,4) + Q(LD,4))
ENDIF

200 CONTINUE

C ADD IN EFFECT OF LAST PENTAD

NT(NTP+1) = LC
Q(LC,4) = Q(LC,2)
IF(NT(NTP).NE.NP(72))THEN
  LD=NT(NTP)
  BF = BF+0.5*(LC-LD)*Q(LC,4) + Q(LD,4))
ELSE
  BF = BF + 0.5*(LC-LB)*Q(LC,4) + Q(LB,4))
ENDIF
  BF = BF+(365-LC)*Q(LC,4)
DO 300 K=1,(NTP+1)
  BNT(K)=FLOAT(NT(K))
  N=NT(K)
  Q4(K)=Q(N,4)
300 CONTINUE

DO 400 L=1,365
  Q1(L)=Q(L,1)
  Q2(L)=Q(L,2)
400 CONTINUE

C RESULTS

7  BFI = BF/QSUM
PRINT 500, BFI , BF , QSUM


CALL DEVBEG
CALL PICCLE

C CALL UNITS(0.5)
C CALL V80
CALL DEVPAP(268.0,350.0,0,0)
C CALL WINDOW(2)
CALL AXIPOS(1,40.0,0.0,0.0,1)
CALL AXIPOS(1,40.0,50.0,0.0,2)
CALL AXISCA(3,19.0,0.0,380.0,0.1)
CALL AXISCA(3,20.0,0.0,400.0,0.2)
CALL PENSEL(1,0.3,3)
CALL GRID(3,0,0)
CALL GRID(-2,1,1)
CALL MOVT02(40.0,30.0)
CALL CHAHO('UPSTREAM DISCHARGE AT COMILLA STATION *.'
CALL MOVT02(40.0,22.0)
CALL CHAHOL('RIVER GUMTI DAILY FLOW, CUMECs, 1980-1981 *.')
CALL MOVTO2(90.0,40.0)
CALL CHAHOL('DAYS SINCE START OF WATER YEAR *.')
CALL MOVTO2(40.0,15.0)
CALL CHAHOL('TOTAL ANNUAL FLOW CUMEC-DAYS: *.')
CALL MOVTO2(150.0,15.0)
CALL CHAFIX(QSUM,14,4)
CALL MOVTO2(40.0,8.0)
CALL CHAHOL('BASEFLOW, CUMEC-DAYS:*.')
CALL MOVTO2(150.0,8.0)
CALL CHAFIX(BF,14,4)
CALL MOVTO2(40.0,1.0)
CALL CHAHOL('BASEFLOW INDEX:*.')
CALL MOVTO2(150.0,1.0)
CALL CHAFIX(BFI,14,4)
CALL MOVTO2(25.0,160.0)
CALL CHAHAR(3,1)
CALL CHAHOL('DISCHARGE (CUMECS)*.')
CALL PENSEL(1,0.3,3)
CALL GRAPOL(Q1,Q2,365)
CALL GRAPOL(BNT,Q4,(NTP+1))
CALL DEVEND
STOP
END