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Groundwater Investigations and Mapping in the
Upper Indus Plain

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Foreword

Groundwater has played a vital role in agriculture development of Pakistan where over 60% of the irrigation water requirements are met from it. Moreover, over 90% drinking water and almost 100% water used in industry comes from groundwater.

Various kinds of technologies are being used to pump groundwater for different purposes. In 1960, the number of tubewells in Pakistan was about 20,000 which have now increased to over one million. This drastic and indiscriminate installation of tubewells has changed the hydro-salinity behavior of the Indus basin and groundwater is depleting in many canal commands and almost in all urban settlements.

However, no systematic and holistic work has been done to assess the groundwater potential over the last four decades. PCRWR took this initiative in 2003 and started groundwater mapping in the Upper Indus basin with the financial support of the Government of Pakistan through Ministry of Science and Technology. Various techniques such as electrical resistivity, seismic, induced polarization and gravity were used to determine the quantity and quality of groundwater. Moreover, exploratory well drilling was also used for the purpose of ground truthing.

Four doabs (the area between the two rivers) i.e. Thal, Chaj, Rechna and Bari have been mapped. The groundwater mapping is very important for the design of tubewells and developing operational strategies. This is a remarkable work and would help manage groundwater in the Indus basin.

Dr. Muhammad Ashraf
Chairman, PCRWR
Executive Summary

Groundwater is a finite natural resource and Indus Plain is the major source of groundwater in Pakistan. Groundwater is meeting over 90% drinking water requirements in the country. It is playing an important role by supplementing about 60% irrigational requirement in agriculture. Seepage from Indus Basin Irrigation System (IBIS) is the major source of groundwater recharge. Being natively saline due to its marine origin, the recharge from surface water helps to decrease salinity in the groundwater by developing a fresh water layer. The overexploitation of groundwater has resulted several groundwater management issues. In some areas, the annual pumpage has already surpassed the annual safe yields resulting in decline of water table.

Being an underground resource, its management is critically important for sustainable use. In the past, most of the groundwater-related studies conducted in the Indus Basin were in bits and pieces; and were confined to either soil-water-plant relationship or waterlogging and salinity. The management of groundwater requires the knowledge of hydro-geology and hydro-salinity for proper design and operation of the tube wells.

Main objective of the present study was to demarcate and map fresh groundwater quality zones in the Upper Indus Plain and its marginal areas; to predict the future behavior of groundwater regime in response to pumping/recharge in different groundwater zones; and to quantify the safe yield in different groundwater zones.

An integrated methodology consisting of grid-based geophysical survey, physical groundwater explorations, water quality, isotopic analysis and groundwater modeling have been applied. This research report provides a macro picture about the spatial variations in groundwater quality, quantification of usable groundwater, identification of sources of recharge, surface water-groundwater interaction, and determination of safe yield of the four doabs.

Generally, the groundwater salinity increases with depth in the four doabs (Thal, Chaj, Rechna, Bari). However, the spatial pattern remains the same. The groundwater mining is mainly taking place in the districts of Lodhran, Multan, Lahore, parts of Sheikhupura, Khanewal, Narowal, Jhang, Toba Tek Singh and Sargodha. The highest safe yield of about 9 BCM per Mha is calculated in the Thal doab followed by the Chaj and Rechna doabs. The average safe yield is quantified about 7.5 BCM per Mha which makes a minimum annual recharge of about 80.3 BCM having total area of about 10.7 Mha.

Based on analysis, it is summarized that sufficient potential of groundwater is available in the Upper Indus Plain. However, indiscriminate installation of tubewells and pumping
are threatening the aquifer in many parts. It is also important to mention here that results of one time investigation may be hampered due to climatic extreme events at spatio-temporal scales. Remote Sensing applications such as GRACE (Gravity Recovery and Climate Experiment) may be applied to monitor groundwater storage changes at regular intervals.

The lateral and vertical variations in groundwater quality and estimation of useable groundwater resource provides the basis for effective management in Upper Indus Plain. The information related to the patterns of groundwater recharge and its dating is particularly important for effective aquifer management. The identification of different groundwater recharging zones and their sources, helps the groundwater managers to maintain the balance between recharge and abstraction by applying relevant recharge enhancement techniques. Moreover, the doab-wise projected scenarios highlight the groundwater system behavior. The future trends in groundwater system are useful for the managers and policy makers to devise appropriate strategies and policies for sustainable groundwater management at each doab scale. The scientific information and knowledge shared in this report is useful for provincial water and agriculture management departments such as, Irrigation Department, Agriculture Department, On-Farm water Management Department, etc. This information is also helpful for PHEDs, WASAs, TMAs, etc who are associated with the provision of drinking water supply in the urban areas.
1. Introduction

The groundwater has emerged as one of the most important and valuable natural resources in many countries of the World. Almost all main municipalities either solely or partly depend on groundwater whereas about 80% rural population is using groundwater for drinking purposes. In addition to human uses, groundwater is a source of supply for agriculture, ecosystems, and maintains the stream flows through base flow. The significance of groundwater increases manifolds for the agriculture based economies such as Pakistan to supplement the irrigation water supplies. Therefore, its significance cannot be overlooked in the planning and management of water resources.

The Indus Plains, covering about 20 million hectares (Mha) possess one of the largest volumes of groundwater resource in the world, comprising huge, continuous, well transmissive and deep alluvium aquifer. The native groundwater in the Indus Basin is saline because of its marine origin. Seepage from conveyance and irrigation network has however, developed freshwater layer of varying thickness that overlay deeper saline groundwater. The thickness of fresh groundwater is more near the recharging sources and less with an increase in the distance from recharging sources (Ashraf et al., 2012).

The groundwater has played a major role in increasing the overall cropping intensity in Pakistan from about 63% in 1947 to 150% in 2015. Over 60% of irrigation water at farm gate is being met from groundwater (Qureshi et al., 2003). There were about 88,000 tube wells in 1970 which are now over one million (Punjab Development Statistics, 2012). In some regions, the annual pumpage has already surpassed the safe yields resulting in the decline of water table. Bhutta et al., (2000) reported that out of 43 canal commands, the water table had declined in 26 canal commands due to rapid increase in groundwater abstraction. On one hand, the extensive groundwater pumping has helped to address the two menace of water logging and salinity in Punjab Province (Fig. 1), on the other, the over exploitation has resulted in depletion in many parts of the Upper Indus Plain Aquifer (UIPA). Based on IWASRI Classification, the groundwater depletion issue mainly exists in Lower Bari followed by some parts of Rechna doabs. Particularly, the areas of Lodhran, Multan, Khanewal, Vehari, Pakpattan districts are under high groundwater depletion, whereas the areas of Sahiwal, Chiniot, Toba Tek Singh and Lahore districts are partially depleted.

Most of the groundwater-related studies conducted in the Indus Basin were in bits and pieces; and were confined to either soil-water-plant relationship or waterlogging and salinity (Ashraf et al., 2012; Khan et al., 2008; Qureshi et al., 2008). The management of groundwater requires knowledge of hydro-geology and hydro-salinity for proper design.
and operation of the tube wells. The main objective of the present study was to
demarcate and map fresh groundwater quality zones in the Upper Indus Plain and its
marginal areas; to predict the future behavior of groundwater regime in response to
pumping/recharge in different groundwater zones; and to quantify the safe yield in
different groundwater zones.
Fig. 1: Average Depth to Water table variations in 2014 over UIPA (Punjab Irrigation Department, Lahore)
2. Methodology

The investigation was carried out in the four Doabs (the area between two rivers): Thal (the area between Indus and Chenab and Jhelum rivers), Chaj (the area between Chenab and Jhelum rivers), Rechna (the area between Ravi and Chenab rivers) and Bari (the area between Bias and Ravi rivers) covering total area of about 10.7 Mha.

A comprehensive methodology was adopted using geophysical methods, isotopic techniques and groundwater modeling. The tools like electrical resistivity, induced polarization, seismic and gravity methods were applied for detailed groundwater investigations. The electrical resistivity was used as main surface geophysical method for investigations whereas the data of exploratory wells drilling were used for the validation of the geophysical surveys. The relationship developed between earth resistivity and groundwater quality is shown in Annexure-24 and 25.

Generally, the regression indicates that resistivity values less than 10 Ohm-m pertains to brackish quality of groundwater with clay and silt subsurface lithology. The resistivity zone 11-24 Ohm-m refers to marginal-saline quality with clayey sand or silty sand subsurface geology. Similarly, the resistivity values from 25-34 indicate that the groundwater is fresh but, of low quality or subsurface geology is sandy clay with some silt. However, the resistivity greater than 34 Ohm-m pertains to good quality fresh groundwater with sandy subsurface geological formation.

The variations in polynomial equations are attributed to the subsurface geological variations in Thal and Bari doabs. In Thal doab, there is more prevalence of sand with boulder and kankers whereas, medium to fine sand with clay lenses are more dominant subsurface geological formations in Chaj, Rechna and Bari doabs. Having almost similar geological conditions, the regression developed for Bari doab is extended for Chaj and Rechna doabs. These useful relationships are applied for the conversion of resistivity values into electrical conductivity for the demarcation of groundwater. Table 1 shows the generalized form of inter-relationship of electrical resistivity, rock formation and type of water that could be applied over the UIP.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Resistivity (Ohm-m)</th>
<th>Water quality if sandy sediments prevails</th>
<th>Geology if groundwater is fresh</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&gt; 35</td>
<td>Fresh</td>
<td>Sand (fine silty)</td>
</tr>
<tr>
<td>2</td>
<td>25-39</td>
<td>Fresh, low quality</td>
<td>Sand, clay, Silt</td>
</tr>
<tr>
<td>3</td>
<td>11-24</td>
<td>Marginal water to saline water</td>
<td>Clayey sand, silty sand</td>
</tr>
<tr>
<td>4</td>
<td>&lt;10</td>
<td>Saline water</td>
<td>Clay, Silt</td>
</tr>
</tbody>
</table>
To economize the financial resources and time involved while meeting the scope of the survey, a grid of 5 km x 5 km was adopted by conducting about 4,000 resistivity probes for the shallow depth up to 300 m. The Induced Polarization (IP) was conducted for deep layers up to the depth of 1 km (1000 m) at a regular grid of 20 km x 20 km covering 250 probes in the entire Upper Indus Plain Aquifer.

The seismic data collected from Directorate General of Petroleum Concession (DGPC), Government of Pakistan was used for the delineation of alluvium thickness. The available gravity data at regular surface gravity grid of 9 km x 9 km collected by oil companies during 1990s was also used as supplementary information for the identification of depth to bedrock and basement structures underlain by the alluvium aquifer, where the seismic data were not available.

The geophysical investigations were supported by information derived from 154 exploratory wells drilled at a regular grid of 25 km x 25 km to a uniform depth of 90 m. Water as well as soil samples from exploratory wells were collected at regular depth interval of 3 m. In this way, more than 4,300 water and 4,600 soil samples were analyzed for the processing and interpretation of the geophysical data. Supplementary information was also derived from the United State Geological Survey (USGS) and Water and Power Development Authority (WADPA) bore holes drilled during late 1950s as some deep holes up to the depth of 270 m provided useful information for the interpretation of deeper horizons.

The survey data of resistivity and induced polarization were processed and analyzed using IX1D and ArcGIS softwares. The modeling of gravity and seismic data provided evaluation of the alluvium thickness required for the quantification of usable groundwater resource.

The groundwater quality was divided into four water quality zones: freshwater (<1.5 dS/m), marginal quality water (1.5-2.5 dS/m), saline water (2.6-4.0 dS/m) and highly saline water (>4.0 dS/m) from 0 to 300 m depth at an interval of 50 m depth. The groundwater quality maps were verified from USGS maps (work done in 1950s with WAPDA) and Drainage Atlas of IWASRI/WAPDA.

In collaboration with Pakistan Institute of Nuclear Science & Technology (PINSTECH), the sources of groundwater recharge were identified and groundwater dating was determined by analyzing the oxygen and hydrogen isotopes. For analysis purpose, about 660 isotope samples were collected from various sources such as shallow groundwater (hand pump), deep groundwater (tubewell), surface water (canals, rivers) and rainfall. The hand pumps and tubewells installation depths vary spatially over study
area however, the maximum depths are considered as 30 and 70 m respectively. The rationing of $\sigma^{18}O$ and $\sigma^2H$ was used for the determination of recharging sources coming either from rainfall, river, or mixture of both. The groundwater residence time for different recharging sources was calculated by analyzing the variations in tritium isotope which was achieved by dividing the samples into four time intervals; (<5 years, <50 years, about 50 years and >50 years) at shallow and deep depths.

In the UIPA, the groundwater flows were simulated and safe yield was determined using Visual ModFlow (VMOD). For each doab, individual groundwater models were developed with a uniform grid size of 2.5 km x 2.5 km. The water balance was simulated and the predictive scenarios were developed for 2015 and 2025 to study the groundwater behavior under different scenarios. These scenarios would help to develop appropriate groundwater management strategies. The calibration of groundwater model is based on the long term data of about 141 piezometers collected from SCARP Monitoring Organization (SMO), over the period from 1984 to 2009. The observed data scarcity in terms of both temporal frequency and spatial coverage are the major limitations of this study. The survey details are summarized in Table 2.
Table 2: Details of field survey in each doab

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Doab</th>
<th>Shallow ERS Grid</th>
<th>Shallow ERS Probes</th>
<th>Deep **IP Grid</th>
<th>Deep IP Probes</th>
<th>Exploratory Well Drilling Grid</th>
<th>No. of Exploratory Wells</th>
<th>No. of Soil Samples</th>
<th>No. of Water Quality Samples</th>
<th>Isotope Parameters</th>
<th>Isotope Sampling Features</th>
<th>No. of Isotope Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Thal</td>
<td>5 km x 5 km</td>
<td>1200</td>
<td>20 km x 20 km</td>
<td>80</td>
<td>25 km x 25 km</td>
<td>56</td>
<td>1675</td>
<td>1580</td>
<td>Oxygen &amp; Hydrogen</td>
<td>Rivers, Canals, Hand pumps, Tube wells</td>
<td>200</td>
</tr>
<tr>
<td>2</td>
<td>Chaj</td>
<td>5 km x 5 km</td>
<td>500</td>
<td>20 km x 20 km</td>
<td>30</td>
<td>25 km x 25 km</td>
<td>12</td>
<td>355</td>
<td>320</td>
<td>Oxygen &amp; Hydrogen</td>
<td>Rivers, Canals, Hand pumps, Tube wells</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>Rechna</td>
<td>5 km x 5 km</td>
<td>1200</td>
<td>20 km x 20 km</td>
<td>72</td>
<td>25 km x 25 km</td>
<td>32</td>
<td>950</td>
<td>900</td>
<td>Oxygen &amp; Hydrogen</td>
<td>Rivers, Canals, Hand pumps, Tube wells</td>
<td>180</td>
</tr>
<tr>
<td>4</td>
<td>Bari</td>
<td>5 km x 5 km</td>
<td>1100</td>
<td>20 km x 20 km</td>
<td>68</td>
<td>25 km x 25 km</td>
<td>54</td>
<td>1620</td>
<td>1500</td>
<td>Oxygen &amp; Hydrogen</td>
<td>Rivers, Canals, Hand pumps, Tube wells</td>
<td>180</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>4000</strong></td>
<td><strong>250</strong></td>
<td><strong>154</strong></td>
<td><strong>4600</strong></td>
<td><strong>4300</strong></td>
<td><strong>-</strong></td>
<td><strong>-</strong></td>
<td></td>
<td></td>
<td><strong>660</strong></td>
</tr>
</tbody>
</table>

*ERS = Electrical Resistivity Survey
**IP = Induced Polarization


3. **Results and Discussion**

3.1 **Groundwater Mapping**

The groundwater in the Indus Plain Aquifer is basically saline due to its marine origin and its salinity increases with depth (Ashraf *et al.*, 2012). Over a period of time, a fresh water layer has developed due to the recharge mainly from rivers, irrigation system and rainfall. This freshwater layer is thick along the rivers and generally becomes thin at the center of doabs. The groundwater quality varies, both lateral and vertical, depending upon the geological characteristics and sources of recharge. The spatial patterns in groundwater quality have been analyzed by developing the maps at every 50 m depth interval in each doab up to the depth of 300 m.

In Thal doab, the upper 50 m layer (Fig. 2) is mainly underlain by fresh quality of groundwater except some parts of Khushab, Layyah and Muzaffargarh districts. The lithological and isotopic analyses show that the presence of clay lenses and the recharge from the limited rainfall are two possible reasons of salinity in this area (Fig. 3). This upper 50 m layer gets recharge mainly from the Indus River with less than 50 years resident time (Fig. 4). The areas near River Jhelum towards the center of the Thal doab falling in the districts of Khushab and Bhakkar are dominantly recharged through rainfall (Fig. 3). Most of the areas of Mianwali, Bhakkar, Jhang, Layyah and Muzaffargarh districts are under fresh groundwater quality. The area under Thal desert is underlain by fresh quality of groundwater that has not been exploited so far. This area has a great potential to enhance agricultural productivity and future food security of the country.

Figure 5 shows the spatial variations in groundwater quality from 50 to 100 m depth. The pattern of groundwater quality is almost similar in comparison with upper layer. Most of the area of the Thal doab is under usable groundwater quality (EC <2.5 dS/m) whereas the hydro-salinity has increased in Khushab district. This increase in groundwater salinity may be due to geological conditions. Table 2 shows an overall decrease of about 5% in usable area at 100 m depth in comparison with 50 m depth. Figures 3 and 4 show that the groundwater in the areas of Khushab, Bhakkar and Layyah along the River Jhelum are being recharged mainly through rainwater or both rain plus river water. This groundwater is more than 50 years old.
Table 3: Details of area coverage under different groundwater quality zonation and active storage

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Doab</th>
<th>Groundwater Quality (dS/m)</th>
<th>Area Coverage (km²)</th>
<th>Percentage of total area (km²)</th>
<th>Active Storage (BCM)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0-50 m)</td>
<td>(51-100 m)</td>
<td>(101-150 m)</td>
</tr>
<tr>
<td>1</td>
<td>Thal</td>
<td>Fresh (0-1.5)</td>
<td>21350</td>
<td>18514</td>
<td>17667</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Marginal (1.6-2.5)</td>
<td>4693</td>
<td>5017</td>
<td>4740</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Saline (2.6-4.0)</td>
<td>3102</td>
<td>3764</td>
<td>3869</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Highly Saline (&gt; 4.0)</td>
<td>4400</td>
<td>6251</td>
<td>7269</td>
</tr>
<tr>
<td>2</td>
<td>Chaj</td>
<td>Fresh (0-1.5)</td>
<td>9872</td>
<td>7382</td>
<td>6609</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Marginal (1.6-2.5)</td>
<td>2422</td>
<td>2436</td>
<td>2576</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Saline (2.6-4.0)</td>
<td>1405</td>
<td>1857</td>
<td>1781</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Highly Saline (&gt; 4.0)</td>
<td>473</td>
<td>2497</td>
<td>3207</td>
</tr>
<tr>
<td>3</td>
<td>Rechna</td>
<td>Fresh (0-1.5)</td>
<td>21609</td>
<td>19252</td>
<td>17767</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Marginal (1.6-2.5)</td>
<td>6305</td>
<td>6930</td>
<td>6119</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Saline (2.6-4.0)</td>
<td>2281</td>
<td>3561</td>
<td>4432</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Highly Saline (&gt; 4.0)</td>
<td>1008</td>
<td>1460</td>
<td>2886</td>
</tr>
<tr>
<td>4</td>
<td>Bari</td>
<td>Fresh (0-1.5)</td>
<td>15672</td>
<td>15600</td>
<td>12417</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Marginal (1.6-2.5)</td>
<td>8468</td>
<td>7559</td>
<td>6633</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Saline (2.6-4.0)</td>
<td>4260</td>
<td>4252</td>
<td>7132</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Highly Saline (&gt; 4.0)</td>
<td>382</td>
<td>1372</td>
<td>2600</td>
</tr>
</tbody>
</table>

1 MAF = 1.234 BCM
Fig. 2: Groundwater quality from 0-50 m depth in Thal Doab
Fig. 3: Sources of shallow groundwater (<30 m depth) recharge in Thal Doab
Fig. 4: Shallow groundwater (<30 m depth) dating in Thal Doab
Fig. 5: Groundwater quality from 50-100 m depth in Thal Doab
It is evident from isotopic analysis (Figs 6 and 7) that less recharge in the form of older rainwater of more than 50 years are the major reasons for this increase in salinity at deeper depths (>50 m depth). The unfavorable geological conditions having clay lenses in the areas along the River Jhelum further support the increase in salinity. It is generally observed that fresh to usable quality groundwater is available in the areas where the major source of recharge is either river or mix of both with dominant river contribution and favorable geological conditions.

Based on geophysical investigations and groundwater quality mapping, a fresh groundwater quality zone is discovered in the Thal desert (Fig. 8). An area of about 0.7 Mha is found with good quality groundwater spreading over about 48%, 42%, 27% and 11% areas of Bhakkar, Jhang, Khushab and Layyah districts, respectively. It is newly explored fresh groundwater zone which remained unidentified in the past due to sand dunes. This fresh groundwater can irrigate an area of about 0.7 Mha of land which is presently uncultivated.

In the upper 50 m layer of the Chaj doab, about 87% area is under fresh quality except some areas of Gujrat and Sargodha where the salinity patches are found (Fig. 9). Figures 10 and 11 show that Gujrat district and central areas of the doab are dependent on rainwater recharge whereas the areas along the River Jhelum and Chenab are being recharged from the river. The clay lenses are found in Gujrat and Sargodha districts which causes the degradation in groundwater quality by limiting the recharge. Due to this reason, an increase in hydro-salinity is observed in these areas. Resultantly, the salinity has increased from 13% to 31% while moving down from 50 m to 100 m depth (Fig. 11; Table 2). The spatial pattern of groundwater quality at deeper depths (100 – 300 m depth) remains almost the same. However, salinity in terms of area coverage as well as severity of the issue, increases especially in Gujrat, Sargodha (lower parts of the doab) and Jhang districts. The groundwater quality in the most areas of district Mandi Bahauddin, Chiniot and Sargodha is relatively fresh due to recharge from the rivers and favorable geology (sandy soil).
Fig. 6: Sources of deep groundwater (30-70 m depth) recharge in Thal Doab
Fig. 7: Deep groundwater (30-70 m depth) dating in Thal Doab
Fig. 8: Newly explored fresh groundwater body (0-50 m depth) in Thal Doab
Figure 13 shows the spatial variations in groundwater quality at 50 m depth in Rechna doab. About 89% area is under usable quality of groundwater, mostly in the areas of Sialkot, Narowal, Chiniot and Jhang districts. The salinity issue is found mainly in Hafizabad district with some parts of Nankana Sahib, Sheikhupura and Toba Tek Singh districts. The isotopic analysis (Fig.14) shows that the upper parts of the doab (Sialkot, Narowal, Gujranwala and Sheikhupura districts) are mainly recharged by rainwater. The river recharge is mainly found in the lower Rechna doab covering Chiniot, Jhang, Khanewal and parts of Faisalabad, Hafizabad and Toba Tek Singh districts.
Fig. 9: Groundwater quality from 0-50 m depth in Chaj Doab
Fig. 10: Sources of shallow groundwater (<30 m depth) recharge in Chaj Doab
Fig. 11: Groundwater quality from 50-100 m depth in Chaj Doab
Fig. 12: Sources of deep groundwater (30-70 m depth) recharge in Chaj Doab
Fig. 14: Sources of shallow groundwater (<30 m depth) recharge in Rechna Doab
Figure 15 shows that the groundwater recharge in the central areas of doab is less than 5 years. The age of rest of the recharging water is more than 50 years. Most of the area of Sialkot and Narowal districts with some parts of Nankana Sahib and Sheikhupura districts are recharged by rainwater (Fig. 14). The river recharge is mainly found in Chiniot, Jhang, Khanewal, Faisalabad and in some parts of Toba Tek Singh districts. The major recharge takes place either from river or rainwater being less than 5 years of age (Fig. 15). The recharge at the center of doab and the areas of districts Gujranwala, Sheikhupura, Faisalabad, Chiniot and Sialkot is found to be over 50 years.

The groundwater quality is found to be further degraded at 100 m depth (Fig. 16). The hydro-salinity is high in Toba Tek Singh, Sheikhupura and Hafizabad districts. Actually, a layer of clay prevents the groundwater recharge in the central areas of lower Rechna doab (Hafizabad, Sheikhupura, Nankana Sahib, Toba Tek Singh districts). Figure 17 shows the sources of groundwater recharge at deeper depth. That the river recharge is mainly available along the rivers. This fact is further supported by isotopic analysis (Figs. 17 and 18) which indicates that the water recharged in this area is greater than 50 years old.

In Bari doab, the upper layer up to 50 m depth (Fig. 19) comprises usable groundwater quality (84%) mainly recharged from the river (Fig. 20). The hydro-salinity issue is found mainly in Khanewal, Lodhran, Vehari and the central parts of doab covering Lahore, Kasur, Okara, Pakpattan, Sahiwal and Multan districts. Figure 21 shows a further increase in hydro-salinity from 51-100 m depth.

The area and extent with increased hydro salinity is more in lower Bari doab (Khanewal, Lodhran, Vehari and Multan districts). The major reason for this increase in salinity is the low recharge from the river and rainwater (average rainfall is less than 250 mm and little flows in the eastern rivers of Ravi and Sutlej). Most of recharge in Bari doab at shallow depths is from river and mostly of less than 50 years old (Fig. 21). In some areas of Okara, Pakpattan and Vehari districts, the recharging water is much younger (less than 5 years of age) whereas the age of water which is recharged from the river in the areas of Multan and some parts of Lodhran districts is about 50 years old. The salinity further increases with depth and the area under useable groundwater quality also decreases from 50-100 m depth (Fig. 22).

On an average from 0-300 m depth, the area under usable groundwater quality is calculated as 79%, 71%, 67% and 67% in Rechna, Bari, Thal and Chaj doabs, respectively (Table 2). Generally, the groundwater becomes more saline at deeper depths, especially from 150-300 m depth. However, the spatial pattern remains the same but the area under usable groundwater quality decreases
(Annexure 1-23). Figures 23 and 24 show the overall picture of spatial variations in groundwater quality from 0-100 m depth.

The doab-wise active storage is also calculated and summarized in Table 2. The active storage is basically quantum of usable water (0-2.5 dS/m) which could be drawn out from the Upper Indus Plain Aquifer after meeting the specific retention. The active storage is calculated by considering an average specific yield as 12% of the total volume of alluvium in the UIPA as estimated by USGS (Bennet et al., 1967). The results indicate that the highest active storage of about 871 BCM of usable groundwater is available in Rechna doab followed by Thal (800 BCM), Bari (731 BCM) and Chaj (335 BCM).
Fig. 15: Shallow groundwater (<30 m depth) dating in Rechna Doab
Fig.16: Groundwater quality from 50-100 m depth in Rechna Doab
Fig. 17: Deep sources of groundwater (30-70 m depth) recharge in Rechna Doab.
Fig. 18: Deep groundwater (30-70 m depth) dating in Rechna Doab
Fig. 19: Groundwater quality from 0-50 m depth in Bari Doab
Fig. 20: Sources of shallow groundwater (<30 m depth) recharge in Bari Doab
Fig. 21: Shallow groundwater (<30 m depth) dating in Bari Doab
Fig. 22: Groundwater quality from 50-100 m depth in Bari Doab
The freshwater is a function of availability of recharge source, its distance from the aquifer and subsurface geological formation. The recharge is mainly available as a seepage from irrigation network, floods events and precipitation. The underlying alluvium aquifer is composed of the admixture of sand, clay and kankers. The aquifer is fairly uniform but the lenticular clay patches are irregular with different proportions. In some areas clay patches retards the surface recharge. Therefore, the lateral and vertical variations exist in the groundwater quality over the UIPA. The fresh groundwater lies along the rivers whereas, the central parts of doabs are generally with saline water. In the case of Thal doab, the upper eastern part is underlain mainly by saline water due to close proximity of salt range. The saline water along the River Jhelum both in Thal and Chaj doabs, is due to fine clay deposits which retards the recharge. The reason for the salinity in the central parts of Rechna and Bari doabs is due to less recharge from the bounding rivers.

Figure 23 shows water quality of four doabs in the upper 50 m of the UIPA. This part of aquifer is most important and active due to extensive groundwater abstraction for irrigation purposes. The area under fresh groundwater quality is about 64% whereas, marginal quality area is about 20%. Both the freshwater and marginal quality groundwater is usable for irrigation. The remaining 16% is either saline or highly saline which is not directly usable for conventional cropping under existing irrigation practices.

Figure 24 shows the spatial variations in groundwater quality from 50-100 m depth over the UIPA. The area under saline water has increased by 8% as compared to 0-50 m depth. The area under useable groundwater quality is about 76% covering both freshwater (56%) and marginal (20%). The remaining 24% area is either with saline or highly saline groundwater, which is not usable for conventional cropping. It is important to note that Chaj doab is more sensitive in salinity with depth followed by Thal and Rechna doabs. In Bari doab, the variations in salinity are almost the same at 50-100 m depth in comparison with 0-50 m depth.

The isotopic analysis shows that most of the areas of UIPA are being recharged through seepage from surface water system (Fig. 25). It constitutes the recharge from rivers and canals including return flow from agricultural fields. The rainfall induced recharge is only available in the upper parts of Chaj, Rechna and central parts of Thal doabs due to subsurface lithological irregularity such clay lenses (Bennet et al., 1967). This rainfall recharge is possible from upper catchment falling in Indian Territory.
Fig. 23: Groundwater quality from 0-50 m depth in the Upper Indus Plain
Fig. 24: Groundwater quality from 50-100 m depth in the Upper Indus Plain Aquifer.
Fig. 25: Sources of shallow groundwater (<30 m depth) recharge in the Upper Indus Plain Aquifer
4. **Regional Groundwater Flow Modeling**

The groundwater modeling provides a scientific mean for the simulation of various management scenarios required for deriving effective groundwater management strategies. Being an underground resource, groundwater system is very complex in its nature evolving a number of challenges for sustainable management. The study of surface water–groundwater interaction is important to understand the flow dynamics of the groundwater. The groundwater flow patterns define the behavior of groundwater system in response to its anthropogenic uses. The climate induced variations in spatio-temporal patterns of rainfall and exponential increase in population growth are driving factors (Schewe *et al.*, 2014) for putting more pressure on groundwater resources. Therefore, it is very critical to have comprehensive knowledge and understanding of a set of questions which are still unknown or partially known to the policy makers in general and to the research community in particular. These questions include; what are the spatial patterns of groundwater flow? What are the sources of groundwater recharge? What is the surface groundwater interaction in different doabs? How groundwater system behaves under different stress periods? What is specific yield at each doab level? What are management strategies for sustainable groundwater management in the UIPA? To answer all these questions, a detailed study of groundwater flow modeling was carried out for each doab.

4.1 **Groundwater Flow Pattern**

The flow direction is a critical information required to help characterize the areas of recharge as well as the areas with overexploitation of groundwater. The groundwater flow is generally governed by topography and hydrology of the area. The hydraulic gradient, availability of hydraulic structures and the aquifer properties define the flow patterns. Figure 26 shows the equi-potential flow lines in the UIPA. The flow directions are normally calculated at right angle to the equi-potential lines. For detailed study, the groundwater flows are commonly divided into three components as; local, intermediate and regional. Generally, the local flows are characterized by relatively shallow flow paths that extend only from recharge to adjacent discharging areas, especially along the rivers in the UIPA.

In Thal doab, the regional flow direction is from north east to south west. The equi-potential lines indicate several local flows. The distortion in the patterns of equi-potential lines along the River Indus in the west is due to several hydraulic structures; barrages, dams and weirs on the Indus River. Generally, the direction of regional groundwater flow is parallel to the bounding rivers in the Chaj doab. The flow direction in the Upper Chaj doab is mainly westward along both the rivers. However, the flow is influenced by the...
Rasul Barrage on the River Jhelum. Equi-potential lines in the Lower Chaj doab indicate change in direction of flow from westward to southward due to the change in direction of boundary conditions.

In the Rechna doab, equi-potential lines indicate groundwater flow in the south-west direction parallel to bounding the Rivers Ravi and Chenab whereas, the velocity of flow varies in upper, middle and lower part of the doab. The velocity is high in the Upper and Central Rechna doab but low in the Lower Rechna doab due to change in slope. In the Bari doab, the simulated groundwater flow direction is towards the south-west along the bounding Rivers Ravi and Sutlej. However, the influence of these rivers is low due to non-perennial flow. Locally developed sink in Lahore city has distorted regional flow direction in the Bari doab. In this area, the flow is towards Lahore city due to the development of hydraulic gradient resulted by extensive pumping.

### 4.2 Simulated Hydraulic Head

To study the detailed aquifer behavior under various stress periods, the simulated hydraulic heads are analyzed separately at upper, central and lower parts of each doab. The details of the areas covered under different segregation of each doab are listed below:

- **Upper Thal Doab**: Mianwali, Khushab and upper parts of Jhang districts
- **Central Thal Doab**: Bhakhar, upper parts of Layyah and lower parts of Jhang districts
- **Lower Thal Doab**: Lower parts of Layyah and Muzaffargarh districts
- **Upper Chaj Doab**: Gujrat district
- **Central Chaj Doab**: Mandi Bahauddin district
- **Lower Chaj Doab**: Sargodha and part of Jhang districts
- **Upper Rechna Doab**: Narowal, Sialkot, Gujranwala and Sheikhupura districts
- **Central Rechna Doab**: Nankana Sahib, Hafizabad, Faisalabad and upper part of Chiniot district
- **Lower Rechna Doab**: Toba Tek Sing and part of Jhang districts
- **Upper Bari Doab**: Lahore, Kasur and Okara districts
- **Central Bari Doab**: Sahiwal, Pakpattan and Vehari districts
- **Lower Bari Doab**: Khanewal, Multan and Lodhran districts.
Fig. 26: Equi-potential lines representing the flow patterns in the Upper Indus Plain Aquifer
The analysis of average simulated heads shows an initial increasing trend (1.6 m) in the Upper Thal doab whereas, a decreasing trend is found in the Central Thal doab (0.6 m) over the model calibration period (1984-2009). The situation in the Lower Thal is more or less stable as no significant changes in heads are observed. After 2009, a considerable head drop (4.0 m) is recorded in the Upper Thal doab areas during the predictive scenarios up to 2025. This head drop is predominantly caused by excessive pumping with less recharge due to the presence of clay deposits along the right side of the River Jhelum (Khushab district). The isotopic analysis reveals that the Upper Thal doab receives major recharge from the River Indus covering the areas along the river with some contribution from rainfall. This pumping effect is significantly observed during the analysis of water balance components for this period.

In the Central Thal, there is considerable recharge from both rivers (Indus and Jhelum) as well as seepage from irrigation system due to the sandy soil along with the moderate pumping. The Lower Thal doab is a narrow strip shaped area where the bounding rivers are close. Based on ground knowledge, some parts of the Lower Thal are still waterlogged indicating a situation of more recharge than pumping. The long-term analysis from 1984 to 2025 reflects an average depletion of about 2.4 m in the Upper Thal whereas the parts of Central and Lower Thal are more or less stable with no appreciable changes in heads.

Being the smallest in area with large surface water availability, the simulated heads show an increasing trend in the Upper (1.6 m) and the Lower Chaj doab (1.1 m) areas from 1984-2009 whereas a decreasing trend (1.7 m) is noticed in the Central Chaj doab. The increasing trends in the Upper and Lower Chaj are the reflection of more recharge than pumping. The recharge from rivers, Mangla dam, intensive seepage from irrigations system and rainfall induced recharge has contributed in raising the heads. The higher density of about 0.18 tubewells per hectare due to exponential growth in tubewells, has caused the significant depletion in the Central Chaj during 1984-2009. The implications of severe drought event (1999-2002) also aggravated the situation. It has been reported that the water levels in the Central Chaj doab are depleted more significantly than the Upper Chaj doab during the period 1985 to 2005 (Ashraf and Ahmad, 2008). The analysis of statistics data suggest that the Central Chaj doab (Mandi Bahauddin district) has higher tubewells density of about 0.18 tubewells per hectare than others parts of the doab (Punjab Development Statistics, 2012).

The analysis of predictive scenarios (2009-2025) shows an increasing trend in water table both in the Upper and Central Chaj doab. The situation in the Lower Chaj is different where a significant head drop of about 3.3 m exists. It shows that the areas of the Upper and Central Chaj are safe whereas the water table depletion predicts a
groundwater mining situation in the lower parts of Chaj doab. Due to small distance from rivers, these areas receive enough recharge in terms of interconnected flow from bounding rivers. The significant depletion in the Lower Chaj is envisaged due to the less recharge than pumping. The presence of clay deposits along the River Jhelum restricts the recharge from the River Jhelum. These areas are being recharged through River Chenab, rainfall and seepage through irrigation network.

The results of Visual Mod Flow model indicate a water-table depletion in the Upper (4.4 m) and the Lower (1.3 m) Rechna doabs whereas a rise of about 1.6 m in the water table is noticed in the Central Rechna doab from 1984-2025. It is learnt from the results of isotopic analysis that the Upper Rechna doab is not being recharged through rivers and irrigations system but through rainfall. The geology of area reveals the presence of alternate layers of clay, sand and silt which provides the basis for controlled recharge (Bannet et al., 1967; Greenman et al., 1967). Due to comparatively high growth of about 0.33 million tubewells, the pumping dominates the recharge in the Rechna doab (Punjab Development Statistics, 2012).

Similarly, the excessive pumping, low flows in the River Ravi, less recharge and low rainfall in these areas contribute towards the groundwater depletion. A groundwater mining situation is predicted due to the water-table depletion ranging from 10-20 m over the period 2002 to 2025 in the lower parts of Rechna doab has also been reported by Khan et al., (2008). However, in the Central doab, there is no significant change noticed from 1984-2025.

The analysis indicates an overall depletion in the Upper (4.0 m), the Central (1.0 m) and the Lower (3.2 m) Bari doab over the period from 1984 to 2025. It reveals that the areas of the Upper and Lower Bari doabs are under more stress as compared to the Central doab due to imbalance between recharge and pumping. The significant depletion in the Upper Bari doab is attributed to the excessive groundwater pumping in Lahore city. The drastic growth in urbanization and reduced discharges in Ravi River has reduced groundwater recharge in Lahore. The depletion in the Lower Bari doab is due to more dependence on groundwater for irrigation requirements with low recharge (Basharat and Tariq, 2013). The piezometric analysis indicates that the water table has been depleting at an average rate of 0.38, 0.24 and 0.18 m per year in Multan, Lodhran and Khanewal districts, respectively during the last decade (2005-2015).

The synthesis of Visual Mod Flow simulated hydraulic heads resulted in 2.7 m, 1.4 m, 1.2 m and 0.1 m depletion in Bari, Rechna, Thal and Chaj doabs, respectively from 1984 to 2025 (Fig. 27). Due to small area and inter mixed phenomenon of recharge and pumping, the Chaj doab is more stable than the others. It reveals that the Bari doab
followed by the Rechna, the Upper Thal and the Lower Chaj are under more stress due to over exploitation of groundwater. Due to high depletion in the Bari doab followed by Rechna and Thal doabs, the groundwater sustainability is at risk after 2015. The predictive scenarios suggest careful management with controlled pumping to avoid any detrimental impacts on these aquifers.

![VMOD simulated average annual hydraulic head variations in the UIPA](image)

**Fig. 27 : VMOD simulated average annual hydraulic head variations in the UIPA**

### 4.3 Determination of Safe Yield

The average safe yield is calculated in 12 zones of the UIPA which are given in Table 3. The safe yield is estimated based on the groundwater flow modeling in different parts of the UIPA. The highest safe yield of about 9 BCM per Mha is calculated in the Thal doab followed by the Chaj (8.7 BCM per Mha) and Rechna doabs (7.7 BCM per Mha). The lowest safe yield is found in the Bari doab (4.5 BCM) due to controlled surface water flows in the Eastern Rivers (Sutlej and Ravi) by India after Indus Basin Treaty and less rainfall. The average safe yield of the UIPA is found about 7.5 BCM per Mha which makes a minimum annual recharge of about 80.3 BCM in the UIPA having total area of about 10.7 Mha.
Table 4: Safe yield of different zones of the UIPA (BCM/Mha)

<table>
<thead>
<tr>
<th>Zone</th>
<th>Thal Doab</th>
<th>Chaj Doab</th>
<th>Rechna Doab</th>
<th>Bari Doab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper</td>
<td>8.0</td>
<td>9.0</td>
<td>7.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Central</td>
<td>9.0</td>
<td>9.0</td>
<td>8.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Lower</td>
<td>10.0</td>
<td>8.0</td>
<td>8.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Average</td>
<td>9.0</td>
<td>8.7</td>
<td>7.7</td>
<td>4.5</td>
</tr>
<tr>
<td>Average safe yield for Upper Indus Plain Aquifer</td>
<td>7.5 BCM per Mha</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Average Annual Recharge in the UIPA</td>
<td>80.3 BCM</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5. **Major Findings and Recommendations**

5.1 **Findings**

This research report provides a macro picture about the spatial variations in groundwater quality, quantification of usable groundwater, identification of sources of recharge, surface water groundwater interaction, and safe yield of the four doabs.

The overall findings are as follows:

i. The area investigated under the Upper Indus Plain (Thal, Chaj, Rechna and Bari doabs) have sufficient potential of groundwater with varying quality for irrigation and drinking purposes.

ii. The overall usable groundwater available in alluvium is 9120 BCM with active storage of 2736 BCM. The total water stored in alluvium cannot be pumped out because of specific retention.

iii. The average safe yield is estimated as 7.5 BCM per Mha in the UIPA with total average annual recharge of about 80.3 BCM.

iv. Total area under usable water quality is 7.7 Mha which is about 71% of total area under all the four doabs.

v. The groundwater mining is mainly taking place in the districts of Lodhran, Multan, Lahore, parts of Sheikhupura, Khanewal, Narowal, Jhang, Toba Tek Singh and Sargodha.

vi. The seepage from irrigation system constitute the major sources of groundwater recharge covering mainly the areas along the rivers. Mostly, the recharged groundwater is of less than 50 years old.

5.2 **Recommendations**

i) There is sufficient potential of groundwater in the Upper Indus plain. However, indiscriminate installation of tubewells and pumping are deteriorating the aquifer in many parts. Therefore, there is an immediate need for groundwater legislation for the installation and operation of the tubewells.

ii) Immediate measures are required in the areas of groundwater mining such as Upper and Lower parts of Bari and Rechna doabs. In such areas, rainwater harvesting and artificial groundwater techniques should be promoted.
iii) The existing piezometric groundwater monitoring network is limited, both spatially and temporally. Therefore, it is recommended to increase the spatial coverage with monthly data collection.

iv) The results of one time investigation may be hampered due to climatic extreme events like; flooding, heavy rainfall and droughts. It is recommended to update the existing data after the occurrence of any extreme hydrologically important event.

v) Keeping in view the latest advancements in the field of space technology, the remote sensing applications are potentially useful and need to be further explored for groundwater resource management in the Basin.
Reference


Annexures
Annexure 1: Groundwater quality from 100-150 m depth in Thal Doab
Annexure 2: Groundwater quality from 150-200 m depth in Thal Doab
Annexure 3: Groundwater quality from 200-250 m depth in Thal Doab
Annexure 4: Groundwater quality from 250-300 m depth in Thal Doab
Annexure 5: Groundwater quality from 300-350 m depth in Thal Doab
Annexure 6: Groundwater quality from 350-400 m depth in Thal Doab
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Annexure 8: Groundwater quality from 500-600 m depth in Thal Doab
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Annexure 22: Groundwater quality from 200-250 m depth in Bari Doab
Annexure 23: Groundwater quality from 250-300 m depth in Bari Doab.
Annexure-24: Relationship between earth resistivity and groundwater quality in Thal Doab

\[ y = -5 \times 10^{-6} x^2 + 0.0071x - 0.3433x + 6.5849 \]

\[ R^2 = 0.9544 \]

Groundwater Quality (dS/m)
Earth Resistivity (ohm-m)

Annexure-25: Relationship between earth resistivity and groundwater quality in Bari Doab

\[ y = -6 \times 10^{-6} x^3 + 0.0017x^2 - 0.1499x + 4.6171 \]

\[ R^2 = 0.6657 \]

Groundwater Quality (dS/m)
Earth Resistivity (ohm-m)
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