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Groundwater Resource of Indus Plain Aquifer of Pakistan Investigations, Evaluation and Management

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Abstract: Indus Plain Aquifer is World's second largest aquifer andyielding more than 80 Billion Cubic Meters (BCM) of the groundwaterannually. Extensive pumping of aquifer iscausing groundwater mining in many parts of the Indus Plain.The aquifer management is becoming complicated because of lack of technical knowledge. This paper has investigated various aspects of groundwater of the Indus Plain Aquifer. Total of 4000 electrical resistivity probeswere conducted at 5 x 5 km grid for the investigated depth of 300 m. The self-potential and vertical electrical sounding were conducted to the depth of 1000 m at regular grid of 20km x20 km. Seismic as well as gravity data was processed in some areas for determination of depth of alluvium aquifer. Groundwater as well as lithological samples were collated at vertical interval of 3m.Several water samples were analyzed for water quality. Electrical resistivity and groundwater quality maps were prepared at vertical interval of 50 m. Groundwater mapping yielded that about 70.6 percent of study area is underlain by usable groundwater. A new fresh groundwater body spreading over an area of 0.81 Mha was discovered inThal Doab.The bulk of groundwater resource was calculated forfour water quality zones.Numerical code Visual Mudflow Premium 4.3 was used for simulation of aquifer system. The simulation of Doabs indicated that average safe yield of Upper Indus Plain Aquifer (UIPA) is about 7.5 BCM /Mha.

Key words: Indus Plain Aquifer · Electrical resistivity · Well drilling · Water quality isotopes · Computermodeling · Safe yield

INTRODUCTION

Groundwater has emerged as one of the most important and valuable natural resource in many countries of the World. The main source of groundwater in Pakistan is Indus Plainwhich is underlain by huge, continuous, well transmissive and deep alluvium aquifer. The Upper Indus Plain Aquifer (UIPA) is flat fan shaped area with the average length of 400 km and average width of 270 km making about 10.8 Mha of land (Figure 1). The UIPA is bounded by mountain ranges in east, north and west with wide Lower Indus Plain in south. It consists of four main units bounded by rivers, called Doabs. Thal Doab, Chaj Doab, Rechna Doab and Bari Doab with area of about 3.35 Mha, 1.36 Mha, 3.12 Mha and 2.96 Mha, respectively. These are four independent hydrological units with almost uniform lithology but different recharge scales and safe yields. The study area is with south - westward low relief. The UIPA is overlain by fertile Indus Plain under canal commands of World's Largest Contiguous Irrigation System known as Indus Basin Irrigation System (IBIS). The quality of the groundwater in the UIPA varies widely. The areas in the upper parts of the Indus Plain which receive heavy rainfall and consequently greater recharge are underlain by freshwater to great depths. Similarly, groundwater recharge occurring along the main rivers over geologic times has resulted in the development of wide and deep belts of fresh aquifers.

The population growth in Pakistan remained highin the past. So high rate pumping of groundwater started in early 1980s [1]. The continuous groundwater exploitation and long term droughts after 1982 resulted the lowering of water table and the aquifer reached to the stage of safe yield in late 1990s and is under stress now.

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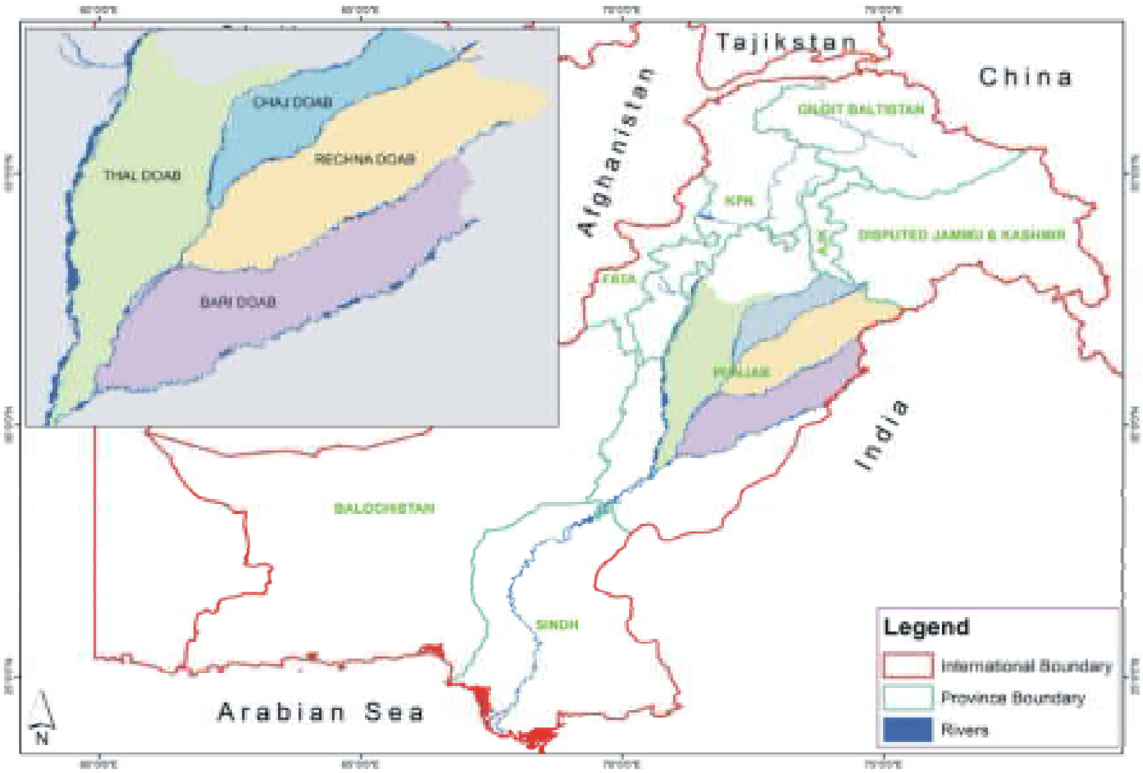

Fig. 1: Location Map of Study Area

The groundwater management in UIPA requires immediate legal framework for governance. Groundwater governance itself needs complete knowledge of aquifer which does not exist in the country. The stage existing knowledge is wrapped up as under;

The documented groundwater investigation in Punjab started in 1870 when observation wells were installed in irrigated areas to monitor effect of irrigation on water table. These observations were mainly on semi- annual frequency. The program was later further extended in 1915, when salinity and water logging emerged as a main hazard for irrigated agriculture in the Indus Basin. Generally this study remained inconclusive and misleading [2]. However, the data analyses indicated that the rise inwater table is related to the monsoon rainfalls.

[3] conducted geophysical survey to locate the depth of the subterranean rock under the Punjab Plains. The results of investigations by [3] were verified from boreholes sunk under a regular program in 1954 when a comprehensive soil and water investigations were started under the cooperative agreement between Government of Pakistan and the US International Cooperation Administration (USAID). The analog model analysis of the steady state conditions, which existed prior to the period of year 1935, indicated that the value of coefficient of transmissivity may be on the order of$1.49x10^{-5}$ per day/meter [4]. The higher value of transmissivity was inferred from steady state analysis under the assumption that rivers act as constant head boundaries. Many other studies ([2], [5], [6], [7]) were conducted time to time. Pakistan Council of Research in Water Resources (PCRWR) started detailed investigations and aquifer evaluation program in 2004. The available conventional and modern tools were applied to investigate, map and evaluate the UIPA. The present paper has highlighted these investigations.

Methodology Adopted: Groundwater investigation and evaluation is a tedious task and can be best handled by integrating several disciplines. The conventional disciplines and tools used in groundwater investigation such as geology, hydrogeology and hydrochemistry are now complemented with the methods of geophysics, isotope hydrology, remote sensing and mathematical modeling. Such integration facilitates the complete understanding of aquifer and establishing a conceptual model of a groundwater system and identifying the aquifer geometry and boundaries as well as the flow regime, residence time and origin of groundwater.

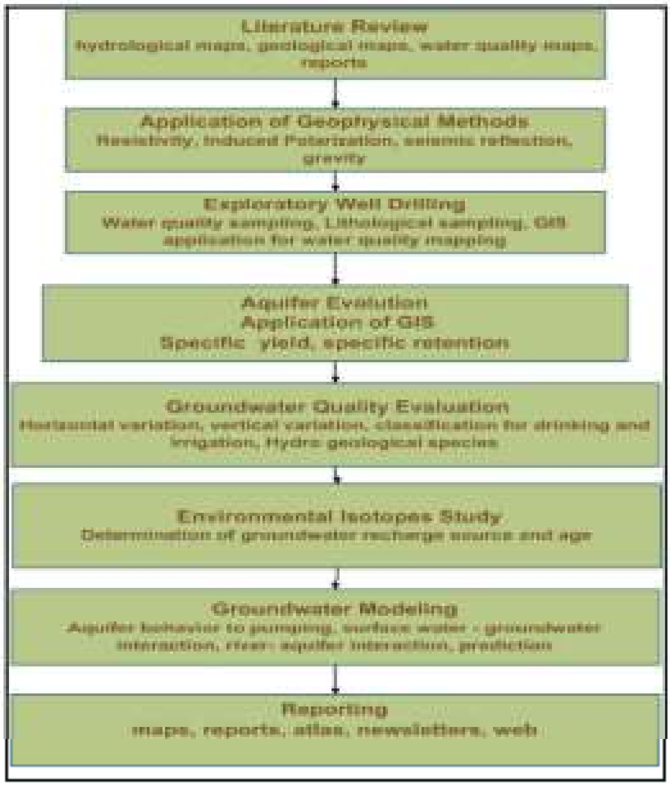

Fig. 2: Schematic Diagram of methodology applied in UIPA

This part of paper describes the methodology applied in investigations and evaluation of groundwater resources in UIPA, The schematic diagram of different tools applied is given in Figure 2.

Geophysical Survey: Several geophysical techniques can be applied for hydrogeological investigation depending upon the purpose and scope at hand ([8], [9], [10]). The electrical resistivity is most powerful method applied to hydrogeological studies especially for evaluating the groundwater quality aspects ([11], [12], [13]). [14] Interpreted lithology of an aquifer in the coastal region of Mamora Plain located on the Atlantic coast of Morocco [15] used electrical resistivity to study groundwater conditions in the Korin Basin Iran [16]. Applied resistivity method for hydrogeological investigations in Jeddah, Saudi Arabia [17]. Delineated the geometry of an aquifer in Korba area of Cap-Bon, Tunisia.

In present study, electrical resistivity, Induced polarization, seismic and gravity are applied for subsurface investigations. The induced polarization, seismic and gravity data processing is completed in only Thal part of aquifer and other areas are still being worked out. Therefore only resistivity mapping is presented here. In UIPA the electrical resistivity survey was conducted for; shallow as well deep investigations. Shallow investigations up to 300 meters were conducted at fine grids of 5x5km whereas deep investigations up to the depth of 1000 meters were conducted at 20x20km grid. Self-potential measurements were also supplemented during coarse grid to differentiate between clay and saline water in case of low resistivity. In this way total 4000 shallow electrical resistivity and 400 deep probes of electrical resistivity survey and induce polarization were conducted in all four Doabs. The measured resistivities were then converted into true resistivities using IX1D software to yield sub-surface electrical layers. These layers need a correlation with the subsurface information obtained from test holes, tube wells and other data of previous investigations conducted in the area.

GIS Mapping of Resistivity Data: Geographic Information System (GIS) was used for the presentation of surveyed data and mapping of the resistivity at different depths. ESRI software, Arc GIS 9.3 was applied for the preparation and analysis of resistivity maps. After relating the spatial and resistivity data, the mapping of the field data was performed by using the Inverse Distance Weightage (IDW) method. The GIS maps were developed for various depthswhich are shown in Figures 3.

Exploratory Well Drilling and Water Quality Evaluation: Geophysical methods are always supported by the exploratory well drilling. The well drilling to the depth of 90 meters was carried out at regular grid of 25x25 km. The lithological as well as water samples were collected at vertical interval of 3 meters. Total of 156 exploratory sites were drilled in all four Doabs by using percussion rigs. Total 4435 water samples were collected and analyzed for detailed water quality analysis. Collected water samples were analyzed for seven parameters which make up nearly 95 percent of all water solutes; calcium, magnesium, sodium, potassium, chloride, sulfate and bicarbonate ([18], [19]). EC, TDS and pH of these samples were also measured in laboratory at room temperature. SAR and RSC of each sample were calculated for the assessment of criteria for use of water for irrigation. Standard protocols (APHA, AWWA and WEF, D.E 1992) were followed for sampling, preservation, transportation, field and laboratory testing of water samples for calcium, magnesium, sodium, potassium, chloride, sulfate and bicarbonate and pH, similarly total of 5340 soil samples were collected and analyzed for soil textural analysis.

QuantitativeGroundwater Evaluation: In water table aquifer, the volume of water released from groundwater storage per unit surface area of aquifer per unit decline in the water table is known as the specific yield, Sy, also known as the drainable porosity. Hydrologists divide water storage in the ground into, the part that will drain under the influence of gravity (called specific yield) and the part that is retained as a film on rock surfaces and in very small openings (called specific retention). Specific Yield either can be assessedby the texture of the formation or it can be derived from aquifer test.

USGS report of aquifer tests in UIPA [4] indicates wide range of Specific Yield i.e. from 0.08 to 0.5. The average value of specific yield was taken as 0.12 and was used for groundwater evaluation in UIPA. The calculation is simple as it is the function of total volume of alluvium, its porosity and specific yield. Total water content in alluvium and active storage (function of specific yield and volume of alluvium) was estimated for fresh and marginal quality groundwater.

Application of Isotopes Hydrology: Evaluation of recharge areas and groundwater residence time are two key aspects that have significant implication for groundwater management. Environmental isotopes and chemical tracers are used to evaluate the origin and residence time of groundwater in the arid region. Groundwater movement can be studied by injecting tracers and following their pathway and resident time of groundwater at place. Environmental isotopes signatures have extensively been used in management of freshwater resources [20] applied environmental isotope techniques for assessment of recharge mechanisms of Mullusa aquifer (East Rutba) [21]. Studied the distribution of oxygen 18 and detrium in surface water across the USA [22]. Used Deuterium and oxygen 18 as natural tracers to investigate the hydraulic relationship between the Columbia River and the Blue Lake gravel aquifer near Portland, Oregon [23]. Used stable isotope values of oxygen and hydrogen to identify the seasonal contribution ratios of precipitation to groundwater recharge in the Hualien River basin of eastern Taiwan [24]. Used natural concentrations of stable isotopes of hydrogen and oxygen to determine the water balance of lakes situated in a sub-humid climate in southwestern Turkey [25]. Used this technique to assess the capability of stable isotope analysis (δD- δ18O) to refine the understanding on recharge of karstic aquifer system in Sierra de Gador-Campo de Dalias (southeastern Spain) [26]. Used stable isotopes (δ18O, δ2H), tritium (3H) and helium (3He, 4He) for the evaluation of groundwater recharge sources, flow paths and residence times of three watersheds in the Cape Verde Islands (West Africa) [27]. Conducted environmental isotopes (δ18O and δD) study to get insight into the hydrological processes of the Ganga Alluvial Plain, northern India.

In UIPA the total of 619 water samples were collected from study area (Thal Doab 159, Bari 169, Rechna 156, Chaj 155). Surface water samples were collected form rivers, dams, Barrages and canals. The groundwater samples were collected form shallow as well as deep groundwater sources. In addition to this precipitation samples collected from different areas. The water samples were analyzed in PINSTECH Lab for environmental isotopes to assess recharge sources, groundwater – surface water-interaction and resident time of groundwater at specific location.

For determining the oxygen isotopic composition of water samples, CO2 equilibration method was used ([28], [29]). For hydrogen isotope ratio (2H/1H) analysis, water samples were first reduced to hydrogen gas using zinc reduction method. The produced hydrogen was then measured on a mass spectrometer [29]. Tritium (3H) content of water samples was determined by liquid scintillation counting after electrolytic enrichment. The enrichment was carried out by using cells with stainless steel anodes and phosphate mild steel cathodes. Starting with 250 ml of initial volume, about 20fold enrichment was done for subsequent measurement by liquid scintillation counting. Concentration of tritium is expressed in tritium units (TU), which is equal to 3H/1H ratio of 10-18 and 1TU is equivalent to 0.12 Bq/kg of water. The standard error of measurement is of the order of ±1 TU [30].

Regional Groundwater Flow Modeling: Groundwater modeling emerged as effective tools in management of aquifers. The models of different scale and scope have been developed for different groundwater systems [31]. Used for the first time analytical solutions to investigate groundwater flow in hypothetical small drainage basins [32, 33]. Was the first to use numerical models to simulate steady state regional flow patterns in hypothetical layered aquifer system. Large scale work on regional flow modeling of 28 regional groundwater systems was indicated by USGS in 1978 under Regional Aquifer Systems Analysis (RASA) [34]. [35] Simulated Death Valley Regional Groundwater Flow System by using MODFLOW-2000. In another modeling study MODFLOW-88 was used to construct the groundwater flow model of the Great Artesian Basin (GAB) in Australia [36]. Local groundwater modeling has extensively been used to resolve the local problem in almost all over the world [37]. Modeled an unconfined aquifer in Uluova Plain of Traurkey by using MODFLOW [38]. Applied a two-dimensional finite difference model to assess the groundwater flow in an alluvial basin in southwest New Mixico [39]. Used groundwater flow model (MODFLOW) to simulate study flows in the area of Lake City, Florida [40]. Simulated groundwater flow in Azul river basin by using MODFLOW [41]. Applied MODFLOW to model water level change in the complex multi-layer aquifer system of Azraq Basin. In Indus Basin many local models are developed to study different subsets of IPA and even smaller areas [42]. Simulated Rechna Doab of Pakistan by using USGS model MODFLOW coupled with the MT3D solute transport simulator under a PMWIN environment. [43] Applied finite element code; Feflowfor modeling of Upper Jhelum SCARP area in Indus Basin [44]. Used Visual MODFLOW of the Waterloo 2007 for modeling of Quetta Valley Aquifer.

In present study numerical code Visual Mudflow Premium 4.3 was used to simulate four regional systems of UIPA. The purpose of modeling was to workout flow pattern, system behavior, quantum of different mass balance components, groundwater- surface water-interaction, safe yield of different parts of aquifer and predictive scenarios for future management of the aquifer.

Development of UIPA Model

Discretization: UIPA constitute a large continuous alluvium aquifer with land surface as its upper horizontal boundary. The length of Doabs varies from 227 to 447 Km with the average width 180 to 50 m. Geological formation here is alluvium consisting of very fine to medium sand slit and clay interclaises. The clay inteclaises are irregular in pattern and no boundary can be formulated on the basis of lithology. Generally the depth of aquifer varies from 220 m to 850 m. The model was based on three vertical boundaries. The first layer consists of aquifer part which extends from ground surface to 50 meters depth. Almost entire pumping in the Doab was from this part of aquifer which needed real concentration. The second layer was set from 51-201 m depth. The maximum depth of pumping in near future could be expected from this part of the aquifer. The third layer extends right up to the bed rock and its thickness varied from place to place based on topography and depth of bed rock. All four sub systems of UIPA were simulated as independent aquifers. The finite difference cell size was 2.5km x 2.5 km and was kept uniform over all four Doabs.

Hydraulic Boundaries: All fours Doabs are bounded by rivers longitudinally. The data of river stage and width were collected from Federal Flood Commission. The FFC have modeled all major streams and rivers for stage-discharge relationship at different gauging points. The surface recharge was calculated as combined effects of percolation through precipitation, seepage form irrigation canals, water courses and return flow of pumping. The evapotranspiration in irrigated area was calculated for different land covers in different climate zones in study area.

Model Parameter: The model code requires permeability and storativivty for flow modeling. Data of 141 pumping tests conducted by the USGS in late sixties was processed and at least seven zones were identified on the basis of aquifer characteristics [4]. Single value of each hydraulic parameter was assigned by taking simple average of all tests falling in particular zone. On average 6 -8 hydraulic conductivity zones were assigned to each Doab. Resultantly the UIPA flow model was based on 30 conductivity zones.

Calibration: The groundwater pumping in IPA started in early 1980s. Therefore steady state or pre-development simulation was calibrated for the year 1984. The calibrations of models were performed manually by using hit and trial method. The conductivity of different zones was changed to bring calculated heads close to the observed heads. During calibration the normalized RMS was kept below 4.0.

The calculated hydraulic heads during steady state were used as initial conditions for transient simulations. For calibration of four transient periods the recharge was adjusted as return flow from pumping and extension in irrigation area increased net recharge rate. Also the recharge is induced by increasing pumping due to change in hydraulic gradient.

The data of Pizometers installed by IWASRI (WAPDA) was used for calibration. On average the long term data of 40 Piezometers was available for calibration in each Doab. In this way the data of more than 120 Piezometers was used in calibration of UIPA.The models were calibrated for four stress periods; 1984 to 1991, 1992 to 1996, 1997 to 2004, 2005-2009.

Predictive Scenarios: After satisfactory calibration of stress periods the predictive scenarios were generated for 2015 and 2025. For predictive scenarios the pumping was increased at the rate of increase observed during last stress period in each Doab.

RESULTS AND DISCUSSIONS

The outcome of geophysical survey, exploratory well drilling, evaluation of groundwater quality, assessment of groundwater recharge source along with resident time and numerical computer modeling is expressed in this section of the paper.

Electrical Resistivity Survey Mapping: The resistivity contouring maps are prepared for different depths; 0-50m, 50-100m, 100-150m, 150-200m, 200-250 and 250-300m. The detailed discussion about the spatial trends in groundwater quality is given below for 100 to 150 m and 150 to 200 m as these are the most commonly used depths for pumping. Other details can be provided to interested readers on demand.

Resistivity Map100-150 Meters Depths: Figure 3(a) is depicting the resistivity distribution in this layer. In Thal Doab, thecontours are similar to those in upper layers in general expect area below Jhang which is the command area of Rangpur Canal. The increase in area under green contours is attributed to the high recharge from Trimu Barrage on Chenab River upto greater depths and also good recharge from Rangpur Canal.In Chaj Doab, the distribution of resistivity is similar to upper layers. The high resistivity values are still with good areal coverage in Upper Chaj Doab as well as Central and Lower Chaj Doab along River Chenab. This indicates the deposition of coarse grained material by River Chenab to greater depths. The low value resistivity contours are also prominent in central part of upper Chaj. In Rechna Doab the distribution of resistivity is similar to second layer as shown by contours patterns and high values contours are still with good density in Upper Rechna Doab. The distribution of resistivity contours in Bari Doab is also similar to upper layers along Sutlej and Ravi River especially the area along Ravi in lower Bari Doab in Khenwal District. Further, the intensity of low value contours (red) is also reduced as compare to those in Figure 3(b) indicating subsurface recharge from rivers.

Resistivity Map; 150-200 Meters Depth: Figure 3(b) shows the resistivity distribution for 150-200 meters depth. The trend of resistivity counters is similar to that in Figure 3(a) with the little increase in area under green counter below Trimu in Jhang and layyha District, because of clean sand due torecharge from Trimu Barrage and Chenab River. In Chaj, the trend of resistivity counters is similar to that in Figure 3(a) wherein high values contours are with good density along Chenab River in its Upper, Central and Lower Reaches. However the high values contours are dense in central part of Doab along River Chenab. Whereas, the low (pink) resistivity contours are dense in Lower Chaj along Jhelum River. The pattern of resistivity counters Rechna is similar to those Figure 3(a) wherein high values contours are with good density in Upper Rechna Doab. The resistivity distribution is almost similar in these two maps with the little decrease in area under green and pink colored contours. In Bari Doab, the pattern of resistivity contours is similar to those in Figure 3(a) depicting a little change in water quality at this deep horizons.

Correlation between Resistivity and Water Quality: The processed resistivity data gives electrical sections indicating resistivity of different layers at different depths. These sections are then converted into hydro-geological sections by correlating water quality and rock core obtained from drilling at the points of resistivity survey. For this purpose, exploratory wells were drilled at regular grid of 25x25km in four Doabs by using the Cable Tool Method of drilling. The collected water samples were analyzed in laboratory. The measured vertical electrical conductivity was correlated with the vertical electrical sections derived through resistivity modeling. As the survey was conducted at 5x5km grid, therefore the resistivity as well as water quality was assumed to be taken from the same area within 25 km^2. If resistivity and water quality varies considerably within this area, there will be an error in hydro-geological mapping.

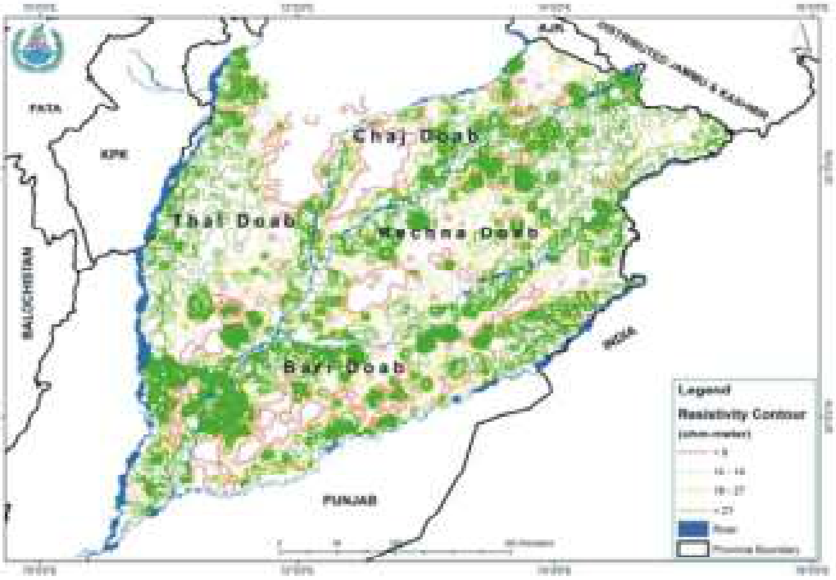

Fig. 3(a): Reistivity Map for 100-150 M Depth

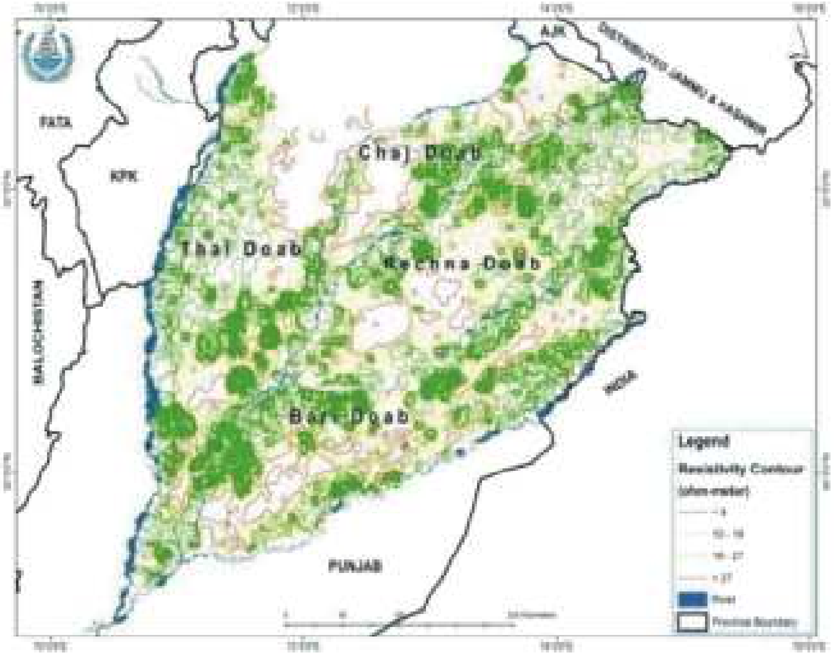

Fig. 3(b): Resistiity Map for 150-200 M Depth

Vertically, the resistivity was correlated with water quality at and below water table. The resistivity above water table has not been interpreted for any conclusion. Below water table, the resistivity was correlated with water quality at the regular vertical depth interval of 50m (Figure 4). As the depth to water table varies from point to point in the area therefore instead of taking only upper level of the aquifer, the shallow water quality was mapped at the depth of 50m.

The lithology of Thal Doab alluvium is coarser whereas Chaj, Rechna and Bari have identical characteristics, therefore two correlation curves were developed for the conversion of earth resistivity into groundwater conductivity. The Figure 4 indicates that interpreted resistivity of 35 Ohm-m and higher pertains to fresh groundwater with EC of less than 1dS/m in alluvium complex of UIPA.

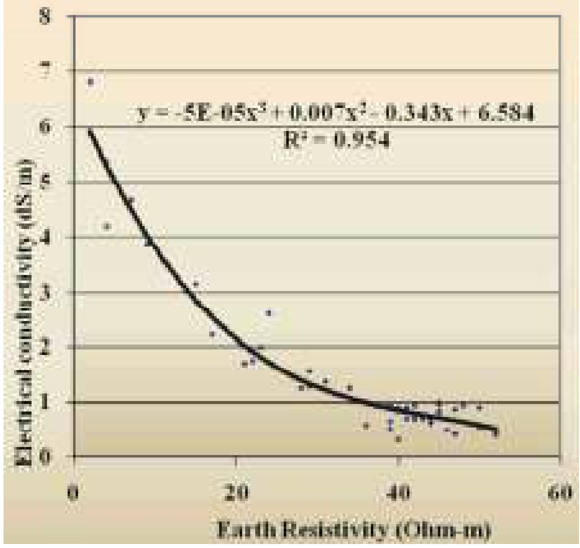

Fig. 4(a): Correlation in Thal Doab

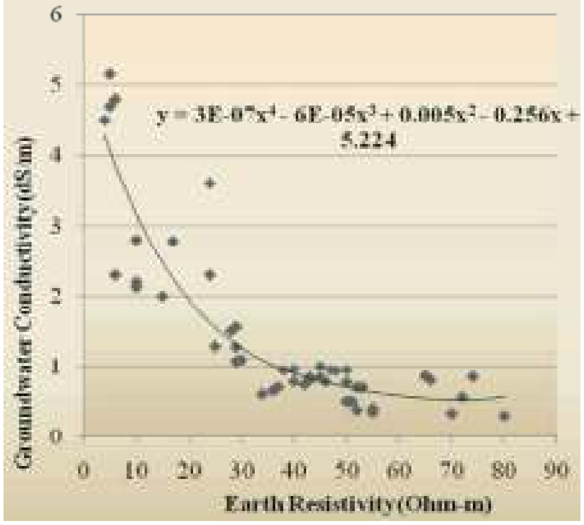

Fig. 4(b): Correlation for Bari Rechan and Chaj Doab

Fig. 4: Correlation between earth resistivity and EC of groundwater

Table 1: Correlation between Water Quality, Lithology and Resistivity

S.No.	Resistivity (Ohm-m)	Water Quality if sandy sediments prevails	Geology if Groundwater is fresh
1	> 27	Fresh	Sand (fine silty)
2	19-27	Fresh, low quality	Sand clay Silt
3	10-18	Marginal water to brackish water	Clayey sand, silty sand
4	< 9	Saline water	Clay, Silt

Groundwater Quality Mapping

Interpretation of Resistivity Data in Terms of Water Quality and Lithology: The earth resistivity is dependent on rock type, voids, fluid content and salt concentration in fluid. The inter-relationship of electrical resistivity, rock formation and type of water in Indus PalinAquifer is summarized in Table 1. It is apparent from Table 1 that low resistivity is either due to fine grained rock or saline water in the coarse grained rock or saline water. The high resistivity value corresponds to freshwater in sandy formation.

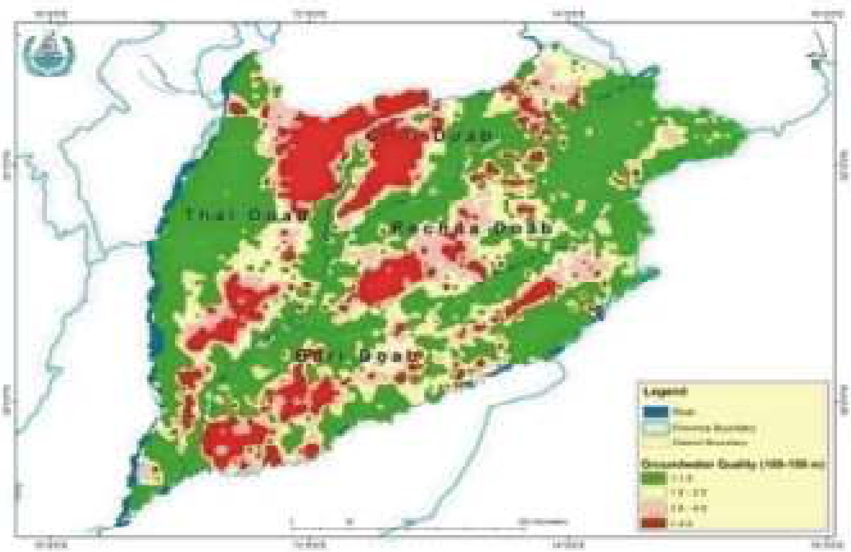

Fig. 5(a): Groundwater Quality Map 100-150 M

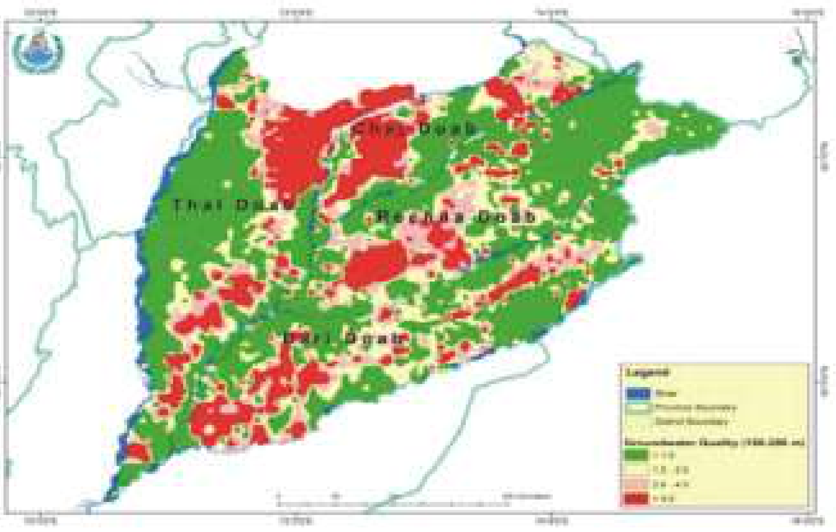

Fig. 5(b): GroundWater Quality Map 150-200 M

Fig. 5: Groundwater Qulaty Maps of UIPA

Water quality maps prepared by integration of geophysical survey, well drilling are given in Figure 5. The mapping is based on four zones depending on electrical conductivity (EC) by considering irrigation water use. These zones are with the EC; < 1.5 dS/m (indicated by green colour pertaining to fresh groundwater), 1.5-2.5 dS/m (indicated by yellow color pertaining to marginal quality groundwater); 2.5-4 dS/m (pink color pertaining to saline groundwater) and >4 dS/m (red color contours pertaining to highly saline water).

Groundwater Quality Map: Figure 5(a and b) show the groundwater quality maps for depths 100 to 150 m and 150 to 200 m. In Thal Doab, thetrend of decrease in area under usable quality groundwater is again observed. The fresh and marginal quality groundwater in this mapping unit is 52.67 percent and 14.13 percent respectively making total of 66.80 percent. The area under saline and highly saline groundwater is increased to 43.20 percent. Still the major part of Thal is under usable water. In Chaj Doab the fresh and marginal quality groundwater

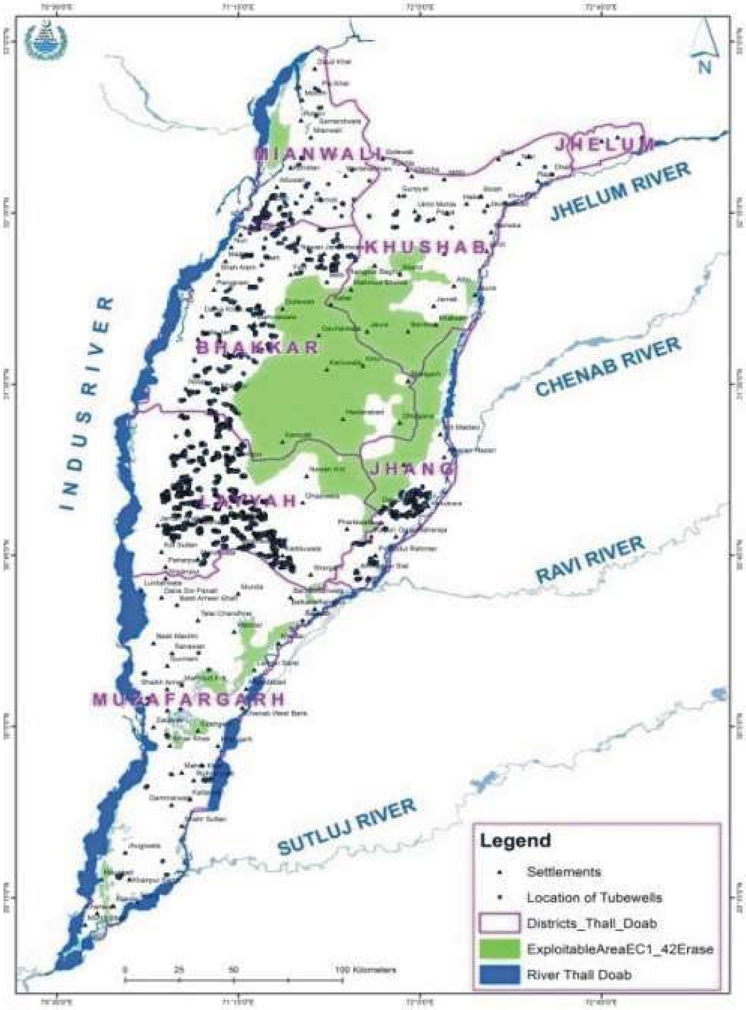

Fig. 6: Discovered Groundwater Body in Thal Doab of UIPA

in this mapping unit is 38.31 percent and 23, 65 percent, respectively, making total of 61.69 percent for usable groundwater quality. The trend of decrease in area under usable quality groundwater is again observed. The area under saline and highly saline groundwater percent is increased to 15.31 and 22.88 percent;totaling 38.31 percent. In spite of increase in area underlain by saline and highly saline groundwater, usable water still occupies major part of Chaj Doab. In Rechan Doab, the fresh and marginal quality groundwater in this mapping unit is 57 percent and 20 percent respectively, making total of 77 percent for usable groundwater quality. The area under saline and highly saline groundwater percent is increased to 14 and 9 percent; totaling 23 percent. The analysis of Figure 5(a, b) indicates that in Rechan Doab the freshwater is also available in deeper horizon. In Bari Doab the fresh and marginal quality groundwater in this mapping unit is 43.14 percent and 23.04 percent respectivelymaking total of 66.18 percent of Doab. The area under saline and highly saline groundwater is increased to 21.78 percent and 9.03 percent totaling 33.78 percent. The analysis indicates that water quality in BariDoab is sensitive with respect to depth.

Discovery of a Fresh Groundwater Body in Northwestern Part of UIPA: Prepared water quality map of Thal Doab based on these investigations indicated that almost 97percent of the area of Bakkhar and Minawlai whereas 45 percent of Khushab Districts falling in Upper Thal Doab are underlain by fresh groundwater as explored by the PCRWR. This area was not mapped in past. The newly delineated freshwater body is spreading over an area of 0.81 million hectares. The explored groundwater is shown in Figure 6 with green color.It is estimated that the newly discovered fresh groundwater body can directly irrigated more than two hundred thousand acres for agriculture production which is presently underlain by sand-dunes and conventional cropping is not under practices even now.

Evaluation of Groundwater Reserve of UIPA: The calculated groundwater reserve in all four units of UIPA is discussed in this section of the paper. The reserve is calculated for usable groundwater whereas saline and highly salinegroundwater is not quantified in the evaluation. The fresh groundwater prevails upto greater depths in Thal Doab. Therefore the reserve of Thal doab is evaluated to the depth of 400 meters and is described below. Other information can be provided on demand of any reader.

Groundwater Reserve of Thal Doab: Mainfreshwater in Thal Doab aquifer is upto the maximum depth of 400m. After this depth the bedrock extent to the regional scale, therefore groundwater estimation was taken upto the depth of 400m. It is estimated that area under freshwater of EC less than 1.5dS/m is about 16331Km^2 whereas the area under marginal quality groundwater which is usable for irrigation (EC of range; 1.6-2.5 dS/m) is about 5601km^2. Therefore the total area under usable water for irrigation, industrial and drinking purposes adds upto about 21933 km^2. The total volume of water in alluvium with EC less than 1.5 dS/m is about 2138 BCM whereas the volume of water in alluvium with EC range; 1.6-2.5 is about 528 BCM. In this way total usable water for irrigation, drinking and industrial use comes about; 2666 BCM. The active aquifer storage for water less than 1.5 dS/ is about 800 BCM whereas the storage for water of EC range; 1.5-2.5 dS/m is about 159 BCM. The total useable water which can be pumped from Thal Aquifers for drinking, irrigation and industrial use is about 958 BCM.

Assessment of Recharge Source and Groundwater Resident Time

Isotopic Study in Thal Doab

Isotopes in Groundwater: Spatial distribution of δ18O of shallow and deep groundwater in Thal Doab can be divided into three main categories depending upon their isotopic composition viz. Category-1 with enriched isotopic values (δ18O > -5.5‰), Category-2 with intermediate isotopic values (-7.5 to -5.5‰) and the Category-3 with depleted isotope values (δ18O < -7.5‰). Geographical distribution of these categories in shallow groundwater is depicted in Figure 7(a) Category-1 waters are found in a narrow zone in the upper eastern part of the Thal Doab between Grot, Distt. Khushab and Hyderabad Thal, Disttrict. Bhakar. Their isotopic composition reflects that shallow groundwater in this zone is recharged by the rain and there is no contribution of river water at these stations. As we move vertically and laterally away from the rain fed area, isotropic values go on depleting suggesting the decreasing role of rain and increasing role of surface waters in groundwater recharge. Shallow groundwater at sampling points surrounding the rain-fed area show intermediate isotopic values (Category-2 waters) suggesting mixing of varying fractions of rain water and river water. At sampling points immediately below the rain-fed area, shallow groundwater has δ18O composition in between -5.5 and -6.5‰. These values reveal that rain is the dominant source of recharge at these locations and contribution of surface water is very low. In the area shown in light green colour in Figure 7(a) (mixed recharge zone), groundwater isotopic composition is relatively depleted (between -6.5 and -7.5‰) reflecting more contribution of surface water as compared to the rain. All the sampling points located along the Indus River right from the start of the doab to the very end show highly negative δ18O values (< -9‰), which signify that these sites are fed by isotopically depleted river / canal water. Most of the points located along the Chenab River have δ18O from -9 to -8‰ reflecting the major input from this river.

Geographical distribution of various categories of deep groundwater is depicted in Figure 7 (b). Unfortunately, deep groundwater samples from the upper part of the study area were not available because the tube wells were either not existing or not in operation during the field sampling period. Two sites near Hyderabad Thal in District Bhakar were sampled which have δ^{18}O values -4.8‰ and -5‰ indicating that deep groundwater in this area falls in Category-1 like the shallow groundwater. As in shallow groundwater, the area surrounding the rain-fed locations has intermediate isotopic composition (Category-2) reflecting the mixed recharge from both sources. Three samples taken from the points immediately below the rain recharged locations have δ^{18}O values -6.1, -6.3 and -6.4‰ meaning that rain is the dominant contributor as compared to surface water. Contribution of surface water is more at other locations in mixed recharge zone. All the points located along the Chenab River and Indus River (depleted isotopic values) indicates major contribution from the river/canal system (Category-3).

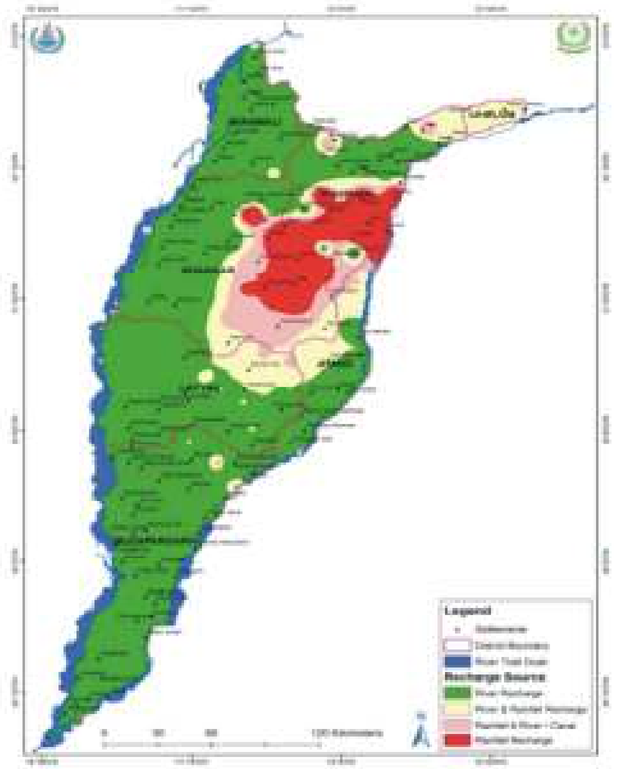

Fig. 7(a): Recharge Source in Shallow Groundwater in Tha Doab

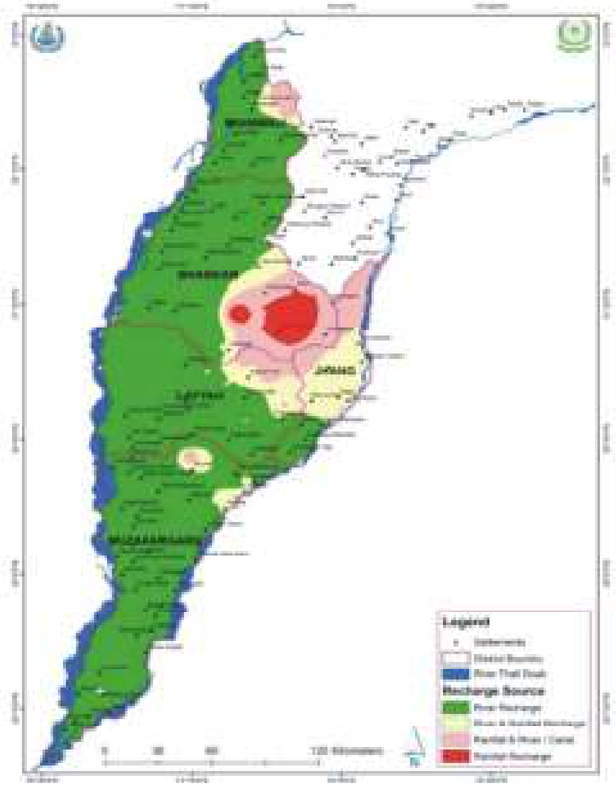

Fig. 7(b): Recharge Source inDeep Groundwater in Thal Doab

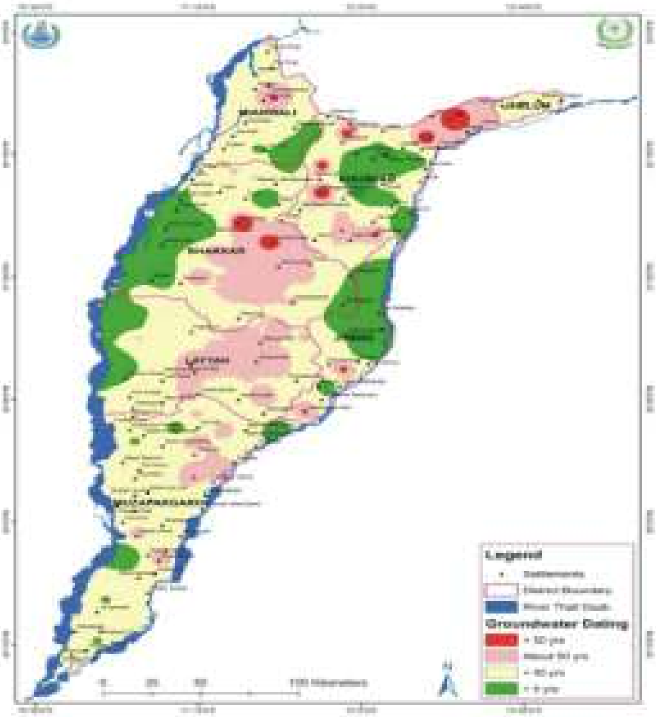

Fig. 8(a): Shallow Groundwater resident time in Thal Doab

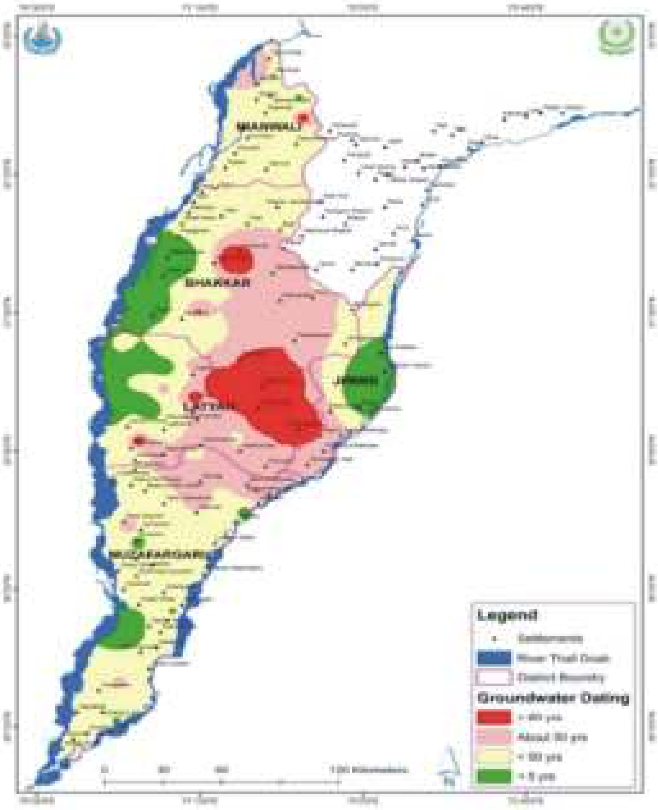

Fig. 8(b): Deep groundwater resident time in Thal Aquifer δ18O values in shallow and deep groundwater show similar geographical distribution pattern proving that they are interconnected and influenced by the same recharge mechanism.

Groundwater Residence Time: Tritium values of rivers range from 10 to 12. TU which could be considered as the present day tritium content in precipitation in the study area. Tritium values in groundwater range from 0 to 21.2 TU. Tritium activity is found in most of the analyzed samples, which indicates that aquifers are nourished by fresh recharge over most of the Doab. In general, groundwater can be divided into following main categories depending upon the tritium values.

0 to 2 TU; Areas having tritium content in the range of 0 to 2 TU were recharged before 1950s when thermonuclear tests were made in the northern hemisphere releasing a large quantity of tritium into the atmosphere. This is old water having residence time of more than 60 years [6].

2 to 4 TU tritium content of 2 to 4 TU suggests that less modern tritiated water has infiltrated at these locations and hence the average residence time of groundwater at these locations is likely to have been longer (about 50 years).

4 to 8 TU; Groundwater having tritium in the range of 4 to 8 TU is relatively young and contains significant fraction of post-1960s water. Areas with groundwater having tritium in this range are related to modern recharge.

> 8 TU; Areas where groundwater tritium values are more than 8 TU are associated with recent recharge and groundwater is recent in origin. Residence time of such waters is only few years. i.e. and groundwater is recent in origin. Residence time of such waters is only few years.

Geographical distribution of above mentioned four categories of water are depicted in Figure 8(a, b). These Figures show that sampling locations along the river Indus and in the confluence area generally contain modern to recent groundwater indicating quick recharge. Groundwater in upper middle part of the doab (Thal Deseret) has no or very little tritium. The reason might be the long travel time from a distant area or very slow movement in the unsaturated zone resulting in the loss of tritium activity due to radioactive decay before recharging the aquifer. Hence, groundwater in this zone is old (residence time more than 50 years).

RegionalGroundwater Flow Modeling

Simulated Groundwater Flow Pattern: To summaries the regional flow the output of all the four Daobs(subsystems) was merged into single system as shown in Figure 9. The figure depicts that; in Thal Doab; the regional flow direction is from northeast to south west. The equi-potential lines indicate several local flow and distortion in pattern of equi-potential lines along River Indus in west because of several hydraulic structures; barrages dams and weirs on mighty Indus River. The density of equi-potential line is low in lower Indus because of low land slope and velocity of groundwater flow.

In Chaj Doab, thedirection of regional groundwater flow is parallel to the bounding rivers. The flow direction in upper Chaj Doab is mainly westward along both rivers. However the flow is influenced by the Rasul Barrage on River Jhelum in Upper Chaj Doab. Equi-potential lines in Lower Chaj Doab indicate change in direction of flow from westward to southward with the change in direction of boundary conditions.

In Rechna Doab the simulated eqi-potential lines indicate groundwater flow in south-west direction parallel to bounding Ravi and Chenab Rivers. However the velocity of flow varies in upper, middle and lower part of the Doab. The velocity is high in upper and middle of Rechna but low in Lower Rechna due to change in slope

In Bari Doab The simulated groundwater flow indicate that regional flow is in south-west along the flow direction of bounding Rvai and Sutlej River. However the influence of these rivers is low because of absence of perennial flow. Locally in upper part of Bari Doab the sink in Lahore city has distorted regional flow direction. In this area the flow is toward Lahore city because of development of hydraulic gradient due to extensive pumping.

Simulated Hydraulic Heads: The hydraulic heads are most important output of any groundwater model. It is key determinant for assessment of system behavior and performance. The sustainability of a groundwater system is dependent on dynamics of this parameter as it is direct indicator of change in reserve of groundwater in an aquifer. Therefore extensive discussion is mad on this parameter; as the models are regional therefore hydraulic heads are disused on zonal bases and each Doab is divided into Upper, Central and Lower Zones. The simulatedhydraulic heads in UIPA are discussed in following this section;

Simulated Hydraulic Heads in Thal Doab: The average of simulated heads in Upper Thal varies from 193 m to 191.21 m, in predevelopment to 2009, with net fall of about 1.8m with13 fold increase in pumping. The simulated hydraulic heads were found to beincreasing to 192.2 m for the

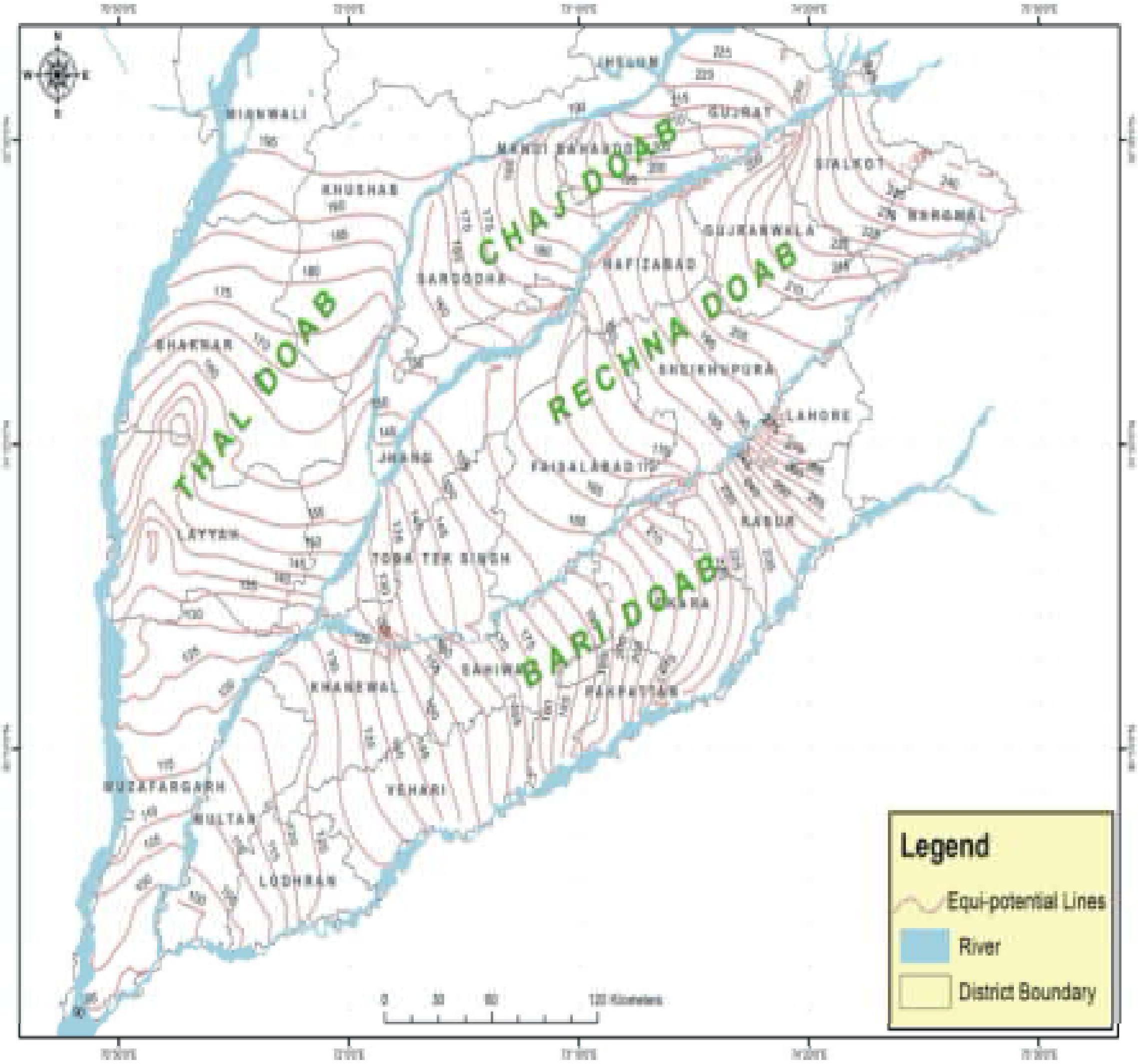

Fig. 9: Simulated Regional Groundwater Flow in UIPA

Table 2: Safe Yield of Different Zone of UIPA Ascertained During Modeling (BCM/Mha)

Zone	Thal Doab
Upper	8
Central	9
Lower	10
Average	9

predictive period simulation of year 2025. This gain in groundwater is because of repeated flood in Indus Basin. The average of simulated hydraulic heads in Central Thal has maximum value of 164.79 m at pre-development to the lowered value of164.0 mduring 2009 with the net fall of 0.79 m. The average value of simulated hydraulic heads for predictive simulation of year 2025 is 163.3 m with the expected decline of 0.7m. The aquifer exploitation will need care after the year 2020. The pre-development average heads in Lower Thal was 114.77 m which was reduced to 112.50 m in 2009 with the net decline of 1.17 m in 25 years of pumping. The average of simulated hydraulic heads for predictive scenario of year 2025 is 113.25 m with the net gain of 1.32 m. which indicates prevailing of water logging in Lower Thal.

Assessment of Safe Yield: Majority of the model development in UIPA remained inclusive either because of continuedinduced recharge in response to pumping or these have been developed in patches which remained under water logging condition during past fifty years. The regional flow modeling however has been able to ascertain safe yield of 12 zones in UIPA. The ascertained safe yield is given in Table 2. The highest yielding is Thal with safe yield of 9 BCM/ Mha.

CONCLUSIONS

The following conclusions are dawn from the study.

- The overall usable groundwater content in the study area is 8993 BCM with active storage of 2748 BCM.
- Total area under usable water quality is 7.67 Mha which is about 70percent of total area under all four doabs studied
- Output of regional groundwater modeling revealed that rivers are playing important role in UIPA aquifer replenishment.
- The isotopic study yielded that central parts of Doab are mainly recharged by precipitation whereas the areas between central parts and flood plains have mixed source of recharge (precipitation + irrigation network) and flood plains and areas along rivers are recharged mainly by river water.
- The regional groundwater flow modeling revealedthat average safe yield of Indus Plain is 7.5 BCM /Mha. The Thal Doab is highest yielding with average safe yield of 9 BCM/Mha.
- The comprehensive study concluded that Thal and Chaj Doabs has still groundwater potential for development whereas the Rechan and Bari Doabs has already crossed limit of safe yield.

Recommendations: The legislation for groundwater governance is urgently required for Lower Bari and Upper Rechna Doab for sustainability of groundwater and irrigated agriculture in Indus Basin of Pakistan

REFERENCES

1. Kahlown, M.A. and A. Majeed, 2004. Pakistan Water Resources Development and Management. Pakistan Council of Research in Water Resources, Islamabad, Pakistan, pp: 209.
2. Greenman, D.W., W.V. Swarzenski and G.D. Bennet, 1967. The groundwater hydrology of the Punjab, West Pakistan, with emphasis on problems caused by canal irrigation: U.S. Geol. survey water supply paper 1608 –H pp: 66.
3. Wilson, B.H. and N.K. Bose, 1934. A Gravity Survey of Sub- alluvium of Jhelum-Chenab-Ravi –Doabs and its Application to Problem of water logging; Punjab Irrig. Research Inst., Memv 6, 1: 44.
4. Bennet, G., D. Attta-ur-rehman, Ijaz Ahmad Sheikh and Sabir Ali, 1967. Analysis of Aquifer Tests in the Punjab Province of West Pakistan United State Geological Survey Water Supply Paper 1608-G.
5. PARC, 2001. Consumptive Use of Major Crops. Ministry of Food, Agriculture and Livestock, Islamabad.
6. Ahmad, S., 2001. Water Demand Management, Unpublished Paper. FAO, RNE, Cairo Egypt.
7. IWASRI, 2014. International Waterloging and Salinity Research Institute, “Surface Water and Groundwater Nexus: Groundwater Management Options for Indus Basin Irrigation System” Publication No. 299 Lahore, Pakistan.
8. Bogoslovski, V.V. and A.A. Ogilvy, 1973. Deformations of Natural Electric Fields Near Drainage Structures, Geophys. Prospect, 21: 716-72.
9. Issar, A. and A. Levanon, 1974. The use of Geophysical Methods in Hydrogeological Investigations in Israel. Hydrogeological Sciences Journal, 19(2): 199217.
10. Reynolds, J.M., 1987. The role of Surface Geophysics in the Assessment of Regional Groundwater Potential in Northern Nigeria. Planning and Engineering Geology, Geological Society London, Engineering Geology Special Publications, 4: 185-190.
11. Yadav, G. S. and H. Abolfazli, 1998. Geoelectrical Soundings and Their Relationship to Hydraulic Parameters in Semiarid Regions of Jalore, Northwestern India. Journal of Applied Geophysics, 39: 35-51.
12. Zouhri, L., 2001. The aquifer of the Mamora Basin Morocco: Geometry and Groundwater flow. Journal of African Earth Sciences, 32(4): 837-850.
13. Adepelumi, A.A., B.D. Ako and T.R. Ajayi, 2001. Groundwater Contamination in the Basement-Complex Area of Ile-Ife, Southwestern Nigeria. A Case Study Using the Electrical-Resistivity Geophysical Method. Hydrogeology Journal, 9: 611-622.
14. Benkabbour, B., E.A. Toto and Y. Fakir, 2004. Using DC resistivity method to characterize the geometry and the salinity of the Plio-Quaternary consolidated coastal aquifer of the Mamora plain. Environmental Geology, 45: 518-526.
15. Lashkaripour, G.R., H. Sadeghi and Qushaeei, 2005a. Vertical electrical soundings for groundwater assessment in southeastern Iran: A case study. Journal of Applied Science, 5(6): 973-977.
16. Al-Bassam, A.M., 2005. Resistivity method for groundwater exploration in the Cretaceous-Tertiary sedimentary sequence east of Jeddah, Saudi Arabia. Journal of Environmental Hydrology, 13(19): 11.

17. Kouzana, L., A. Ben Mammou and M.S. Felfoul, 2009. Seawater Intrusion and Associated Process: Case of Korba Aquifer (Cap-Bon, Tunisia). Comptes Rendus Geoscience, 341: 21-35.
18. Runnells, D.D., 1993. Inorganic chemical processes and reactions: regional groundwater quality. New York, Van Nostrand Reinhold, pp: 131-153.
19. Herczeg, A.L. and W.M. Edmunds, 1999, Inorganic ions as tracers, in Cook, P.G. and Herczeg, A.L., eds., Environmental tracers in subsurface hydrology: Boston, Kluwer Academic Publishers, pp: 31-77.
20. Clark, I. and P. Fritz, 1997. Environmental Isotopes in Hydrologeology. Lewis, Boca Raton, FL. pp: 328. Coplen, T.B., 1994.
21. Kendall, C. and T.B. Coplen, 2001. Distribution of Oxygen-18 and Deuterium in River Waters Across the United States. Hydrological Processes, 15: 1363-1393.
22. Mccarthy, K.A., D.M. William, W.D.J.M. Wilkinson and L.D. White, 1992. The Dynamic Relationship between Groundwater and the Columbia River: Using Deuterium and Oxygen-18 as Tracers. Journal of Hydrology, 135: 1-12.
23. Hsin-Fu Yeh, Hung-I Lin, Cheng-Haw Lee , Kuo-Chin Hsu and Chi-Shin Wu, 2014. Identifying Seasonal Groundwater Recharge Using Environmental Stable Isotopes. Water 2014, 6: 2849-2861.
24. Dinçer, T., 1968. The use of Oxygen-18 and Deuterium Concentrations in the Water Balance of Lakes. Water Res. Res., pp: 1289-1306.
25. Vandens Chrick, G., B. Van Wesemael, E. Frot, A. Pulido-Bosch, L. Molina, M. Stiévenard and R. Souchez, 2002. Using Stable Isotope Analysis (δD and δ18O) to Characterise the Regional Hydrology of the Sierra de Gador, South East Spain. J. Hydrol., 265: 43-55.
26. Heilweil, V.M., D.K. Solomon, S.B. Gingerich and I.M. Verstraeten, 2009. Oxygen, Hydrogen and Helium Isotopes for Investigating Groundwater Systems of the Cape Verde Islands, West Africa. Hydrogeol. J., 17: 1157-1174.
27. Singh, M., S. Kumar, B. Kumar, S. Singh and I.B. Singh, 2013. Investigation on the hydrodynamics of Ganga Alluvial Plain Using Environmental isotopes: A Case Study of the Gomati River Basin, Northern India. Hydrogeol. J., 21: 687-700.
28. Epstein, S. and T. Mayeda, 1953. Variation of 18O Content of waters from natural sources, Geochem. Comochem. Acta, 4: 213-224.
29. Sajjad, M.I., 1989. Isotope hydrology in Pakistan, instrumentation- methodology- applications, Ph.D. Thesis submitted to University of the Punjab, Lahore.
30. Florkowski, T., 1981. Low-level tritium assay in water samples by electrolytic enrichment and liquid-scintillation counting in the IAEA laboratory. In: Proceedings of the international symposium on methods of low-level counting and spectrometry. International Atomic Energy Agency, Vienna, pp: 558.
31. Toth, J., 1963. A Theoretical Analysis of Groundwater Flow In Small Drainage Basins Journal of Geophysical Research, 68(16): 4795-4812
32. Zhou, Y. and Wenpeng Li, 2011. A Review of Regional Groundwater Flow Modeling, Geoscience Frontier, 2(2): 205-214.
33. Freeze, R.A. and P.A. Witherspoon, 1967. Theoretical analysis of regional groundwater flow: 2. Effect of Water Table Configuration and Subsurface Permeability Variation. Water Resources Research, 3(2): 623e634.
34. Sun, R.J. and R.H. Johnson, 1994. Regional Aquifer System Analysis Program of the U.S. Geological Survey, 1978e1992. U.S. Geological Survey. Circular, pp: 10.
35. D'Agnese, F.A., G.M. O'Brien, C.C. Faunt, W.R. Belcher and C. San Juan, 2002. "A Three-Dimensional Numerical Model of Predevelopment Conditions in the Death Valley Regional Groundwater Flow System, Nevada and California." U.S. Geological Survey Water-Resources Investigations Report 02-4102. pp: 114.
36. Welsh, W.D., 2006. Great Artesian Basin Transient Groundwater Model. Bureau of Rural Sciences, Department of Agriculture, Fisheries and Forestry, Australia.
37. Karanjac J., M. Altunkaynak and G. Ovul, 1977.. Mathematical model of Uluova Plain- a Training and Management tool. Groundwater, 15(5): 348-357.
38. Hawkins, D.B. and D.B. Stephens, 1983. Groundwater Modeling in a South Western Alluvial Basin. Groundwater, 21(6): 733-739.
39. Dufresne, D.P. and C.W. Drake, 1999. Regional Groundwater Flow Codel Construction and Wellfield site selection in a Karst area, Lake City Florida. Engineering Geology, 52: 129-139.
40. Varni, R.M. and E.J. Usunoff, 1999. Simulation of Regional-Scale Groundwater Flow in the Azul River Basin, Buenos Aires Province, Argentina. Hydrogeology Journal, 7: 180-187.

41. Abdulla, F.A., M.A. Al-Khatib and Z.D. Al Ghazzawi, 2000. Development of groundwater modeling for the Azraq basin, Jordan. Environmental Geology, 40: 11-18.
42. Khan, S. Tariq Rana, Kaleem Ullah Evan Christen and Mohammad Nafees, 2003. Investigating Conjunctive Water Management Options Using a Dynamic Surface-Groundwater Modeling Approach: A Case Study of Rechna DoabCSIRO Land and Water Technical Report 35/03, pp: 361.
43. Alam, K., 2010. Evaluation of aquifer system in quetta valley through geophysical methods and groundwater flow modeling. Ph.D thesis University of Punjab Lahore Pakistan, pp: 159.
44. Ashraf, A., 2008. Te conjunctive Use of groundwater modeling and GIS to study the water Resource of Upper Jhelum SCARP Area of Indus Bain. Ph.D thesis Quaid-i-azam Univerity Islamabad Pakistan, pp: 131.