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Groundwater Quality Evaluation in Thal Doab of Indus Basin of Pakistan

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ABSTRACT: *Indus Basin is typical model of conjunctive use of surface and groundwater. A well transmissive continuous and deep alluvium Indus PlainAquifer (IPA)is underlain by world's largest contiguous Indus Basin Irrigation System (IBIS). Currently the overall Indus aquifer is supplementing more than 40 percent in total water resources of Pakistan. Pressure on groundwater is increasing and groundwater withdrawal has crossed the limit of safe yield in many parts of IPA.Groundwater mining is creating detrimental environmental issues like lowering of water table,saline water upconing and intrusion. Management of groundwater through regulation is difficult to implement in the absence of required updated hydrogeologicalinformation about the aquifer.A program ofevaluation of national aquifers is under implementation by Pakistan Council of Research in Water Resource (PCRWR). Investigations program was initiated in Thal Doab of Indus Basinwhere 56 exploratory wells were drilled at a regular grid of 25 Km x25 Km.Water as well as soil samples were collectedandanalyzed for seven important parameters of water quality. The mapping of water qualityindicated large vertical and spatial variations in water qualityofthe study area. Hydrogeological facieswere worked out by developing Piper andDurovDiagrams. The evolution of groundwater quality was worked out in the context of geological framework of the area. The study yielded that most of the groundwater in Thal Doab is fresh because of extensive seepage and recharge of aquifer from rivers, precipitation and irrigation network.*

Keywords: *Groundwater quality, groundwater evolution, Hydrogeological facies, Indus Plain Aquifer, Thal Doab*

I. INTRODUCTION

Groundwater is one of the nation's most valuable natural resource and playing important role in agri-based economy of Pakistan. The sole groundwater potential exists in Upper part of IPA which comprises of four doabs (the land in between two rivers);Thal, Bari, Rechna, Chaj and riverian lands along Indus River.Variation in quality of water in this alluvium aquifer is dependent on the availability of recharge source.The management of this aquifer and associated environmental problems remained challenge since the middle of nineteen century when natural groundwater equilibrium was disturbedwith the onset of canal irrigation system in the Indus Basin.Environmental issues related to groundwater became a serious concern for sustainability of irrigated agriculture in Indus Basin. Research studies for remedial measures were initiated in 1870when observation wells were installed in irrigated areas to monitor environmental hazards of rising water table. Later, in 1933, Taylor, Malhotra and Mehta [1]worked on water logging and salinity and related its cause to the monsoon precipitation. Wilsdon and Bose [2] conducted geophysical survey to assess vertical extent of alluvium aquifer in Upper Indus Plain. Tipton and Kalmbatch[3] prepared feasibility report for Water and Power Development Authority (WAPDA) for implementation of Salinity Control and Reclamation Propjet (SCARP III) in Lower Thal Doab.Greenman etal. [4] described in detail the chemical quality of the native ground water of the Punjab region including Thal Doab through hundreds of exploratory wells. In 1970,Mundorff et al. [5] conducted analog modeling studyto evaluate the aquifer characteristics and remedial measureof water logging and salinity in Thal Doab.In 1999 numerical groundwater simulation was applied as management tool under Punjab Private Sector Development Project of Punjab Irrigation and Power Department[6]to establish groundwater management areas in Lower Thal Doab. Tahir and Hifza[7] worked out distribution of nitrate in the water resources of the area to explore the possible risk of crippling fluorosisin Upper Thal Doab. Shaheen and Baig[8] assessed drought severity in Thal Doab by using Remote Sensing and GIS techniques. They computed Standardized Precipitation Index on six monthly bases.

Exploitation of aquifer at large scale requires proper management based onupdated knowledge of groundwater chemistry. The chemistry of a groundwater sample is signature that reflects main physical processes and chemical reactions in an aquifer. It gives the sum of effects of all processes starting from dilution of precipitation, infiltration to the soil and the water table. Many researchers used hydrochemical characteristics to evaluate the groundwater quality of river basins. Adonis[9]analyzed the hydrochemical characteristics of the groundwater in the Incomati Estuary, Maputo, Mozambiqueto work out the groundwater chemistry. The purpose of study was to assess spatial and temporal variations in water quality and to evaluate the suitability of the groundwater for drinking and irrigation purposes. El-Fiky[10] examined the hydrogeochemical and isotopic data of groundwater of the different aquifers of the RasSudr-Abu Zenima area, southwest Sinai, Egypt to determine the main factors controlling the groundwater chemistry and salinity as well as its hydrogeochemicalprocess. Zhang et al.[11] applied hydrochemical characteristics to assess the water quality of surface water and groundwater in SongnenPlain, Northeast China by using fuzzy membership analysis and multivariate statistics. Hagras[12] assessed the usability of groundwater for drinking and irrigation purpose using hydrochemical characteristics in Punjab, Pakistan. This study aims to investigate the groundwater quality in Thal part of IPA in Pakistan.

II. DESCRIPTION OF STUDY AREA

2.1 Geography

Thal Doab is one of the main parts of IPAwhichoccupies an area of about 3.3 mha,spreading over seven districts of Punjab Province; Mianwali, Khoshab, Sargodha, Jhang/ Bakkhar and Muzaffargarh. The area is a triangular shape with base in north in foothills of the Salt Range Mountains and apex in south and is located between latitudes 28º 57′46.3″ to 32º 58′ 49″ north and longitudes 70° 30′ 04″ to72º 55′ 30″east as shown in the location map given in Fig.1. Thal area is bounded by hills in north, Indus River in west and Jhelum and Chenab Rivers in east. Thisdoab is one of the hottest areas of Pakistan. The mean average annual temperature at Mianwali is 24°C with the maximum value of 30oC during June and average minimum of 4°C during January. The average minimum temperature during the year is 17°C. The average annual maximum rainfall is 500 mm in north which is highest throughout the Thal Doab. The construction of a network of irrigation canals and development of tubewell technology during 20th century has converted a major part of this desert into irrigated land. The southern part of Lower Thal is under extensive agricultural practices where different types of crops and orchards are contributing in national economy and benefiting the Indus Civilization.

2.2 Geology

The major rock units of Thal Doab, which constitutes the aquifer, are Quaternary alluvial and aeolian deposits. The alluvium consists dominantly of unconsolidated fine to coarse sand, with minor, generally localized lenses of clay and silt. The sediments were deposited in a subsidingtrough by Indus River and its tributaries; Jhelum and Chenab Rivers. Surficial aeolian sand forms an extensive deposit over the alluvium in central Thal Doab. The thickness of the alluvium varies widely, with less in marginal areas along hills and greater in central part of Thal Doab. The whole adjacent boundary in north is dominated by Salt Range Mountains. Strata of the Salt Range are composed of highly fractured and folded, fossilferous rocks of Cambrian to Pleistocene age. The Salt Range Formation (SRF) consists of an un-metamorphosed sequence of salt, marl, gypsum and dolomite with dominant red gypsiferousclaystone. The top of the formation is a gypsum layer containing high-grade oil shale or at places a highly altered volcanic rock known as Khewra Trap or Khewrite. Piedmont alluvial deposits flank the Salt Range, foothills [13]. The consolidated rocks on western boundary of Thal Doab are also of sedimentary origin and are extension of Suleman and Kirther Ranges. These rocks are of Carboniferous to Recent age and consist of sandstone, limestone shale and conglomerates [14].

2.3 Hydrology

The groundwater reservoir is available in the form of alluvium; and replenishment is based on hydrology in terms of source and extent of recharge. The Indus River controls hydrology in Upper Thal Doab mainly as it is at higher elevation and its depositions contains coarse grained sediments making it feasible for groundwater recharges. Due to favorable natural gradient several offtakes from mighty Indus with its travel through Thal Doab feed the irrigation network and replenish the underlying alluvium aquifer.

Because of high transmissivity of geological formation of Indus deposits the replenishment of aquifer is rapid along its course. The coefficient of permeability is in the range of 0.05 to 1.2 m/sec. Greenman et al.,[4]. Depth to water table in most of area is shallow and is in the range of 0.5 to 9 m from general ground surface. The groundwater exploitation in this area started in early 1980s and now about 0.18 million shallow tubewells are pumping about 18 BCM of groundwater in ThalDoab[15].

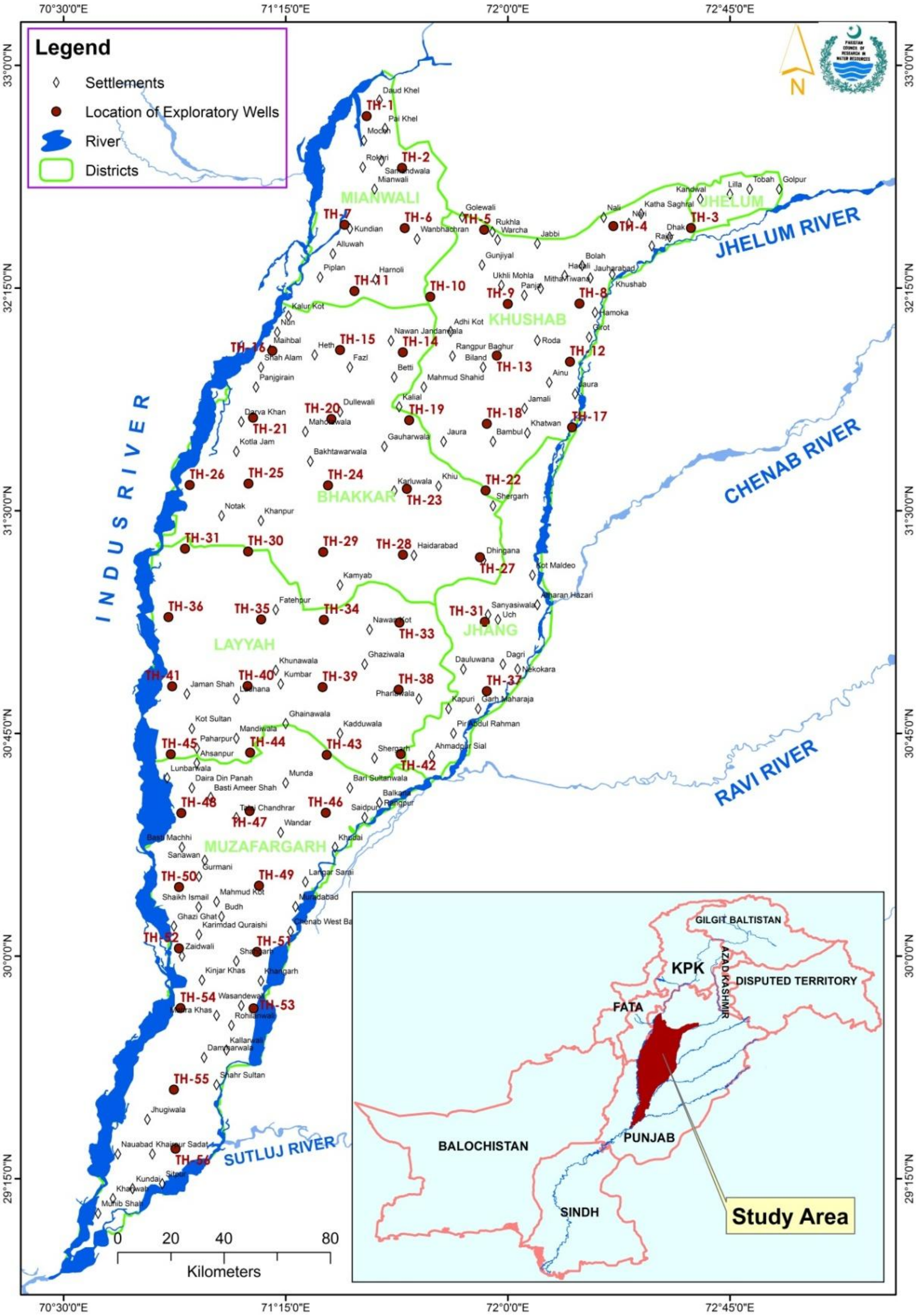


Figure 1: location map showing exploratory wells in Thal Doab

III. MATERIALS AND METHODS

Extensive water quality sampling of aquifer with large spatial and vertical coverage was necessary to understand geochemical process and evaluate water quality for irrigation, drinking and industrial use. The complete procedure consisted of well drilling, sample collection, transportation and analysis and then use of existing graphical techniques and analytical procedures for description of groundwater quality and its evolution in the context of geology and recharge sources.

3.1 Exploratory Well Drilling and Water Quality Sampling

Comprehensive assessment of aquifer required extensive groundwater sampling which could cover spatial and vertical variations in quality. Total 56 exploratory wells (TH-l to TH-56) of 450 mm diameter were drilled at regular grid of 25km x 25km over the area of about 3.3 mha by using Percussion Rigs. The location of exploratory wells is shown in Fig. 1. Percussion is useful for investigation purposes though it takes more time as compare to the rotary method of drilling. It gives accurate water quality and lithological sampling. All these exploratory wells were drilled to the constant depth of 90 meters for uniform vertical coverage. Water samples were collected at regular vertical interval of 3 m starting from watertable. In this way total 1860 water samples were collected and analyzed for evaluation of groundwater in study area. Similarly, the lithological sampling was carried out at 3 m depth interval for information on vertical changes in geological formation.

3.2 Water Samples Preservation and Laboratory Analysis

Collected water samples were analyzed for seven elements which make up nearly 95 percent of all water solutes; calcium, magnesium, sodium, potassium, chloride, sulfate and bicarbonate [16, 17].Electrical conductivity (EC), total dissolved salts (TDS) and pH of these samples were also measured in laboratory at room temperature. Sodium Adsorption Ratio (SAR) and residual sodium carbonate (RSC) of each sample were calculated for assessment of use of water in irrigation. Standard protocols [18] as given in Table 1 were followed for sampling, preservation,transportation,field and laboratory testing of water samples. A blank sample of known standard and previously analyzed was reanalyzed after every ten samples to check the reproducibility of methods for the analyzed parameters and their results were found in the acceptable range of 5 % deviation from the actual samples.

Table1: Methods Used for Water Samples Preservation and Analysis

Sr. #	PARAMETERS	ANALYTICAL METHOD
1.	Bicarbonate(mg/l)	2320, Standard method (1992)
2.	Calcium (mg/l)	3500-Ca-D, Standard Method (1992)
3.	Chloride (mg/l)	Titration (Silver Nitrate), Method 4500- B Standard Method (1992)
4.	Magnesium (mg/l)	2340-C, Standard Method (1992)
5.	Ph	4500-B, Standard Method (1992)
6.	Potassium (mg/l)	3500-B, Standard Method (1992)
7.	Sodium (mg/l)	3500-B, Standard Method (1992)
8.	Sulfate (mg/l)	SulfaVer4 (Hach-8051) by Spectrophotometer Method-4500-B, Standard Method (1992)
9.	TDS (mg/l)	2540C, Standard method (1992)

3.3 Statistical Analysis of Samples

The summary of statistical analysis for water qualityparametersasgenerated in AquChem9.1 is given in Table 2. The table shows minimum, maximum, mean, standard deviation, skewness and t-statistic. All parameters arepositively skeweed with t-statistics in the range of absolute value of 1.7 to 1.8 which is little less than required value of 2.It is acceptable in field study of regional groundwater system. The variance has outcome for Na, Cl, TDS, SO_4 andEC due to large spatialvariation in these parameters representing true extreme values of a distribution.

Table 2: Summary of Statistical Anaylsis of water quality parameters in 56 exploratory wells

Parameter	Minimum	Maximum	Arithmetic Mean	Standard deviation	Skewness	Variance	t-statistics
Ca(meq/l)	0.40	18.00	2.63	2.88	0.0025	8.30	-1.7
Na(meq/l)	0.00	53.60	8.14	10.14	0.0025	102.90	-1.7
K(meq/l)	0.04	4.10	0.53	0.59	0.0025	0.35	-1.7
Mg(meq/l)	0.40	17.00	3.53	3.45	0.0026	11. 92	-1.8
CI(meq/l)	0.00	41.50	3.67	6.36	0.0025	40.40	-1.7

SO_4 (meq/l)	0.00	280.0	8.62	37.90	0.0025	1434	-1.7
HCO_3 (meq/l)	2.20	20.00	6.21	3.27	0.0025	10.70	-1.7
EC(µS/cm)	300.00	7500	1401.60	1456.50	0.0025	2.1E+06	-1.7
TDS(ppm)	213.00	5361	993.90	1047.80	0.0026	1. 1 E+06	-1.8

IV. RESULTS AND DISCUSSIONS

In an alluvium unconfined aquifer the groundwater moves in all directions from recharge zone with the velocity depending upon hydraulic conductivity and hydraulic heads. This movement is expressed by tensor which covers multi-dimensional variations in solute composition; therefore both spatial and vertical components have been mapped for valuable outcome of the current study.

4.1 Vertical Variation in Water Quality

The EC of water samples was plotted against depth in AquaChem for assessment of vertical variation in water qualityas shown in Fig.2. The plot indicates that most of the exploratory wells are falling in freshwater zone with little variations in EC with depth, especially along Indus River. Plot in Fig. 2 indicates that 37 wells are falling in freshwater and show negligible changes in EC with depth. The variation in EC with depth in remaining 19 wells indicates following three trends in water quality with depth;

I. Seven wells indicate decrease in EC with the depth:
(TH-5,TH-l, TH-19, TH21, TH-25,TH-32 TH-37).

II. Ten wells indicate increase in EC with depth:
(TH-9, TH-lO, TH -12, TH-20, TH-21, TH30 TH-41, TH-43, TH-39, TH-40).

III. Two wells are having low EC at top and bottom but high in middle:
(TH-2 and TH-26)

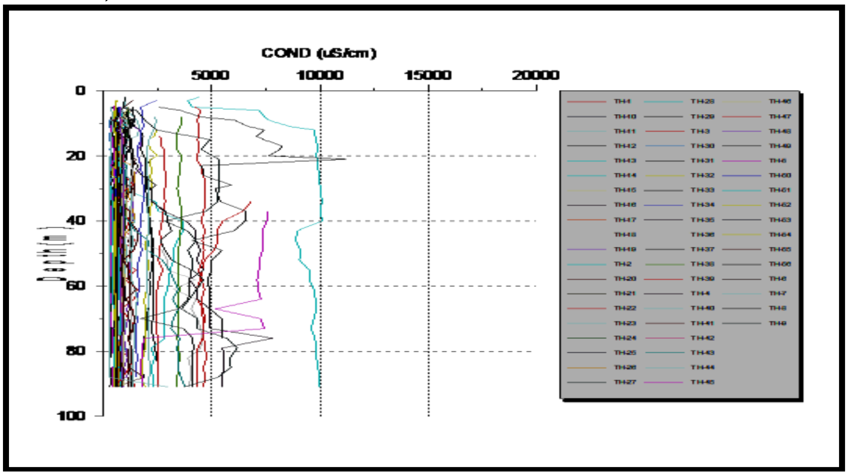


Figure 2: vertical variations in groundwater quality

4.2 Spatial variation in groundwater quality

For assessment of spatial variation in water quality, water sample from the top of aquifer were processed and plotted in ArcGIS 9.1. Separate maps were prepared for cations, anions and EC. Plotted EC in Fig. 3 indicates low values in recharge zones along Indus River in Upper Thal Doab. The area along river Jhelum, near Salt Range is found with highest salt concentration. This is because of the low permeability in formation along JhelumRiver due to higher presence of clay lenses which retard the recharge. The recharge source in eastern side of Lower Thal is Chenab and Indus Rivers and dense irrigation network, therefore the groundwater is mostly fresh in Lower Thal. However a small patch of saline water at confluence of the two rivers is because of deep clay deposits in this area. The variation in cations and anions in the study area is depicted in Fig.4.Generally, the cations and anions variations follow the trend of EC. In anions, the Na varies from nil to 54 meq/l. Ca varies from 0.40 to 18 meq/l and Mg varies from 0.4 to 17 meq/l. In cations the SO_4 varies from 0.0 to 288meq/l, Cl varies from 0 to 51.5 meq/l followed by the bicarbonates which varies from 2.20 to 20 meq/l. SO_4 are high in Upper Thal just below the Salt Range Mountain exposed with gypsum ($CaSO_4H_2O$) and anhydrite ($CaSO_4$).

4.3 HydrogeochemicalFacies and Water Typology

The idea of "hydrogeochemicalfacies" is the classification of waters according to the relative proportions of major ions [19]. Different graphical representation has been developed by researcher to classify water according to percentage of cations and anions in water sample. Most widely graphically methods for determination of water type and hydrogeological facies are Piper and Durov Diagrams. Developed diagrams for classification of groundwater in study area are disused in the following sections.

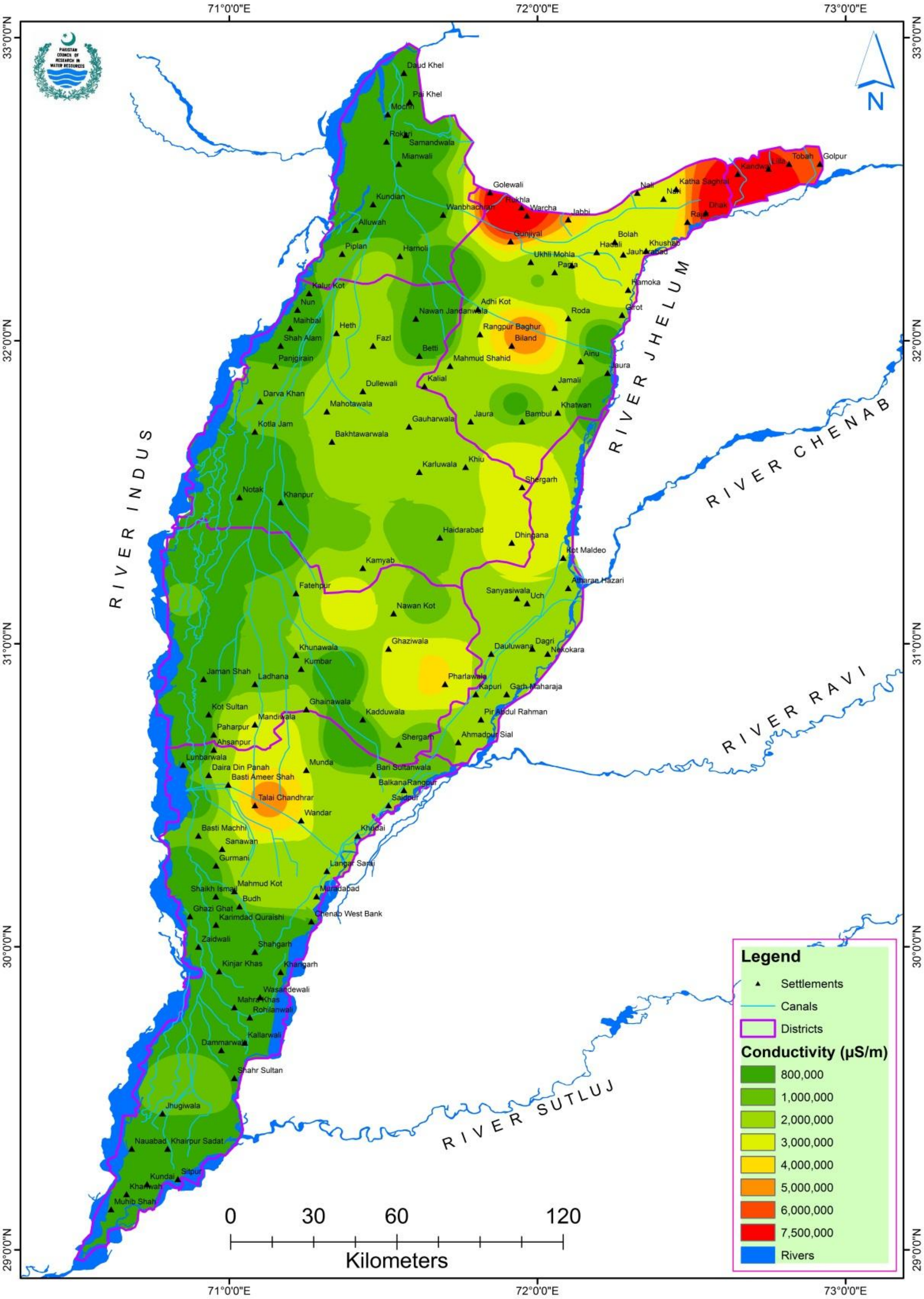
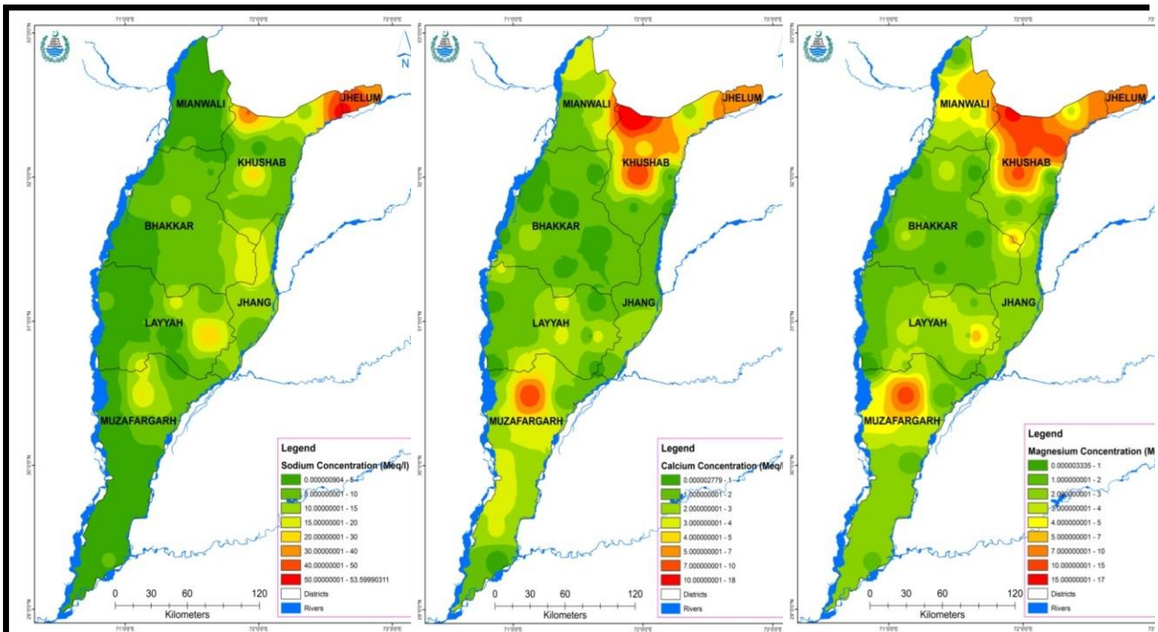


Figure 3: Electrical Conductivity Plot



(a) Na concentration (meq/l) (b) Ca concentration (meq/l) (c) Mg Concentration (meq/l)

(d) HCO_3 Concentration (meq/l) (e) Cl Concentration(meq/l) (f) SO_4 Concentration (meq/l)

Figure 4: Spatial Variation of Major Anions and Cations Concentration in Thal Doab Groundwater

4.3.1 Piper Plot

The most commonly used graphical diagram which helps in classification of "water type" or "hydrochemicalfacies"; and mixing between two types of waters is Piper Diagram. In Piper Diagramthecations, expressed as percentages of total cations in milliequivalents per liter, are plotted as a single point on the left triangle; while anions, similarly expressed as percentages of total anions, appear as a point to the right triangle. These two points are then projected into the central diamond-shaped area parallel to the upper edges of the central area. This single point is thus uniquely related to the total ionic distribution; a circle can be drawn at this point with its area proportional to the total dissolved solids[20]. The trilinear diagram conveniently reveals similarities and differences among groundwater samples because those with similar qualities will tend to plot together as a groups. Further, simple mixtures of two source waters can be identified. The water quality data of Thal Doab was plotted in Piper Diagram by AquaChem to identify hydrogeochemicalfacies and mixing of groundwater.

The output of Piper as shown in Fig.5 and Table 3 indicates that prominent hydrogeological facies in Thal Doab Aquifer are; $CaHCO_3$ type followed by NaCl type whereas the mixing of water forms hydrogeological facies like; Ca Na HCO_3 and Ca Mg Cl, Ca, Mg, and HCO_3 type.

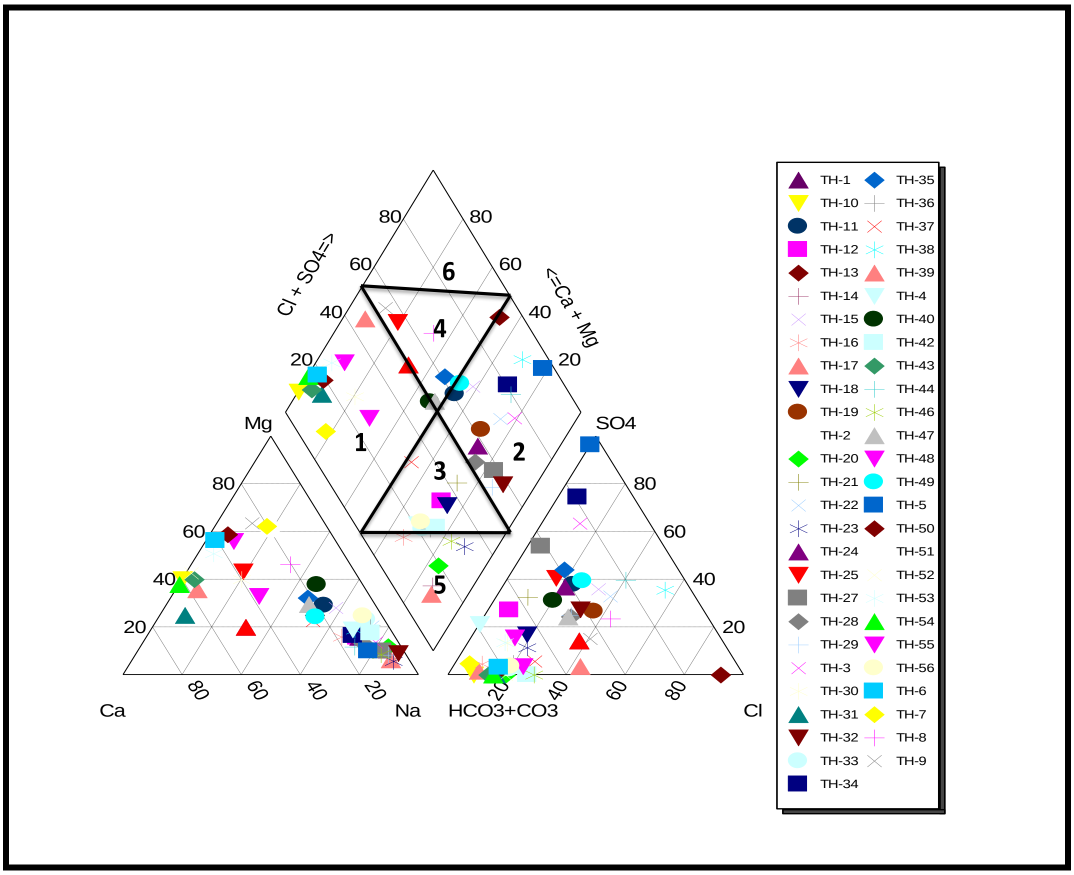


Figure 5: Piper Diagram depicting hydrogeological facies in Thal groundwater

Table 3: hydrogeological Facies as worked out by Piper Diagram

Facies Type	Exploratory Wells No	Number of Samples	Percentage
CaHC03	TH-55,TH-39,TH-46,TH-43, TH-54,TH-6,TH-7,TH-48,TH-18, TH-31	10	22
NaCl	TH-I3, TH-16, TH-34, TH-40, TH-19, TH-24, TH-28, TH-29, TH-II, TH-2, TH-32,TH-3, TH-22, TH-15	14	31
Mixed Ca Na HC03	TH-56, Th-42,TH-18, TH-12, TH-21, TH-22, TH-16	7	16
Mixed Ca Mg Cl	TH-49, TH-47, TH-l, Th-25, TH-35, TH-2, TH-22, TH-29	8	18
CaCl	TH-17, TH-20, TH-46, TH-23, TH-14	6	l3
Na HC03	NILL		
Total		45	100

4.3.2 Durov Diagram

In Piper Diagram some information are lost during transformation from triangular todiamond-shaped part of the diagram. In this plot magnesium and calcium are combined in cations whereas chloride and sulfate are combined in anions. Durov[21] introduced another diagram which provides more information on the hydrochemicalfacies by helping to identify the water types. The advantage of this diagram is that it can display some possible geochemical processes that could help in understanding quality of groundwater and its evolution. In Durov it is possible to depict pH and EC in addition to cations and anions. The Durov Diagram for the major cations and anions was plotted using AquaChem software as given in Fig.6.The description of water quality by marked fields yields that most of the water is along ion- exchange line in zone 3 and along mixing,dissolution line. Few wells are falling along reverse ion exchange and endpoint of aquifer (discharge zone). Durov Diagram indicates that Thal Doab is hydrogeologically active due to extensive pumping for irrigation, rapid replenishment because of transmissive alluvium, source in the form of IBIS and direct precipitation. On pH plot the concentration of wells reveals acidic groundwater as pH of most of the samples is below 7.5.

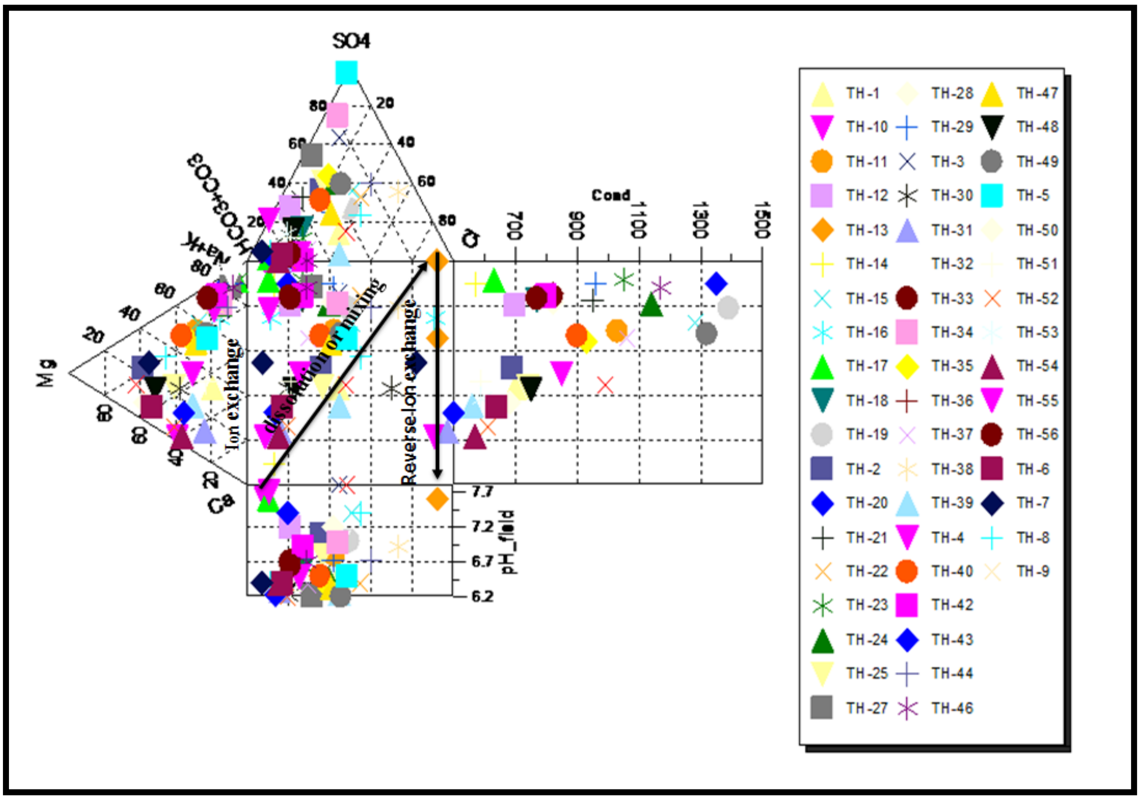


Figure 6: Durov Diagram depicting geochemical processes in Thal groundwater

4.4 Water Quality Assessment for Irrigation

The assessment of the water for irrigation is complex exercise due to interaction of soil-water- crop-climate during plant growth. The salt tolerant crop can give production by using water having 10 years salinity than usual agriculture based on soil and management practices. Soluble salts are present in all natural waters and its concentration and composition determines the suitability for irrigation. The amount of salts in water may be small but may be quite significant to affect yield of crops. Suitability of water for irrigation is based on its salinity, sodicity and toxicity.

The soil salinity problem due to application of water occurs when soluble salts accumulate in the root zone to extent that crops are injured. Salt accumulation increases the osmotic pressure and crop yield are reduced due to effect of osmotic pressure in reducing water uptake by plant.

Another consideration in evaluating irrigation water quality is sodicity (the potential for an excess concentration of sodium) in the soil leading to a deterioration of soil structure. The accumulation of sodium in soils results most often from theuse of high Sodium Absorption Ratio (SAR) irrigation water or water with high level of HCO3 and CO3 ions. When calcium and magnesium are the predominant cations adsorbed on soil, exchange occurs and soil tends to have a granular structure. On the other hand the proportion of sodium tends to deflocculated soil, disperses the clay and may cause reduction of permeability when the amount of adsorbed sodium increases 10 % of the total cations.

There is long list of toxic element in water in which Boron is important in natural water. Though Boron is essential to plant growth but exceedingly toxic at concentration only slightly higher above optimum i.e. > 1 can become Toxic for crops [22]. However the Boron is a seldom problem in Indus Basin, therefore it is not analyzed in present study. The criteria flowed by Provincial Irrigation DrainageAuthority (PIDA) in Indus Basin is given in Table 4.

Table 4: Guideline for Interpretations of Water quality for irrigation adopted by PIDA in Pakistan

Parameter	Units	Usability		
		Usable	Marginal	Hazardous
Salinity	S/cm	<1500	1500-3000	>3000
Sodicity(SAR)	-	<10	10-1	>18
RSC	Meq	<2.5	2.5-5	>5
T oxicity(Boron)	Ppm	<1		

The combination of EC and SAR have also been used to determine the suitability of water for irrigation. Wilcox Diagram [23] was used to classify the groundwater samples for irrigation. In this diagram, EC is taken as salinity hazard and SAR as alkalinity hazard as shown in Fig. 7.The Fig.Indicates that out of 56 wells, five wells fall in the hazardious and thirteen wells fallen in marginal groundwater quality zones. In this way 68 % wells are falling in freshusable groundwater under normal cultural practices. The groundwater in 23 percent wells is indicating marginal groundwater which is being successfully utilized by local population as the soils of the area are sandy. Many farmers are using water of more than 4000µS/cm in areas along Jhelum River. However the groundwater in 9 % of wells is found unusable under conventional irrigation practices.

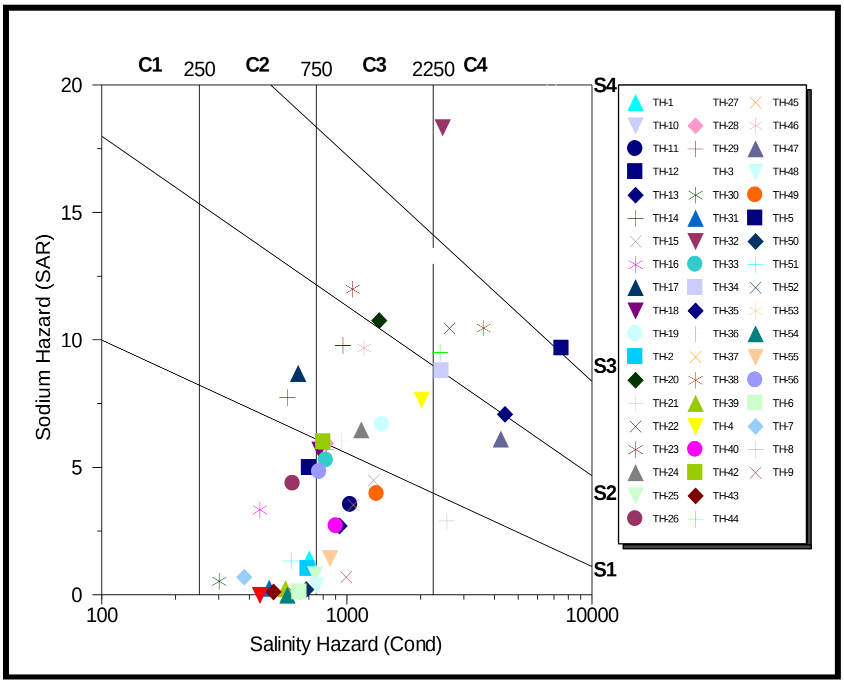


Figure 7: Wilcox diagram illustrating the groundwater quality for irrigation use

V. GROUNDWATER QUALITY EVOLUTION

The source of chemical and reactions that influenced the concentrations of solutes in groundwater of Thal Doab are expected to be: (1) the dissolution of limestone (calcite, $CaCO_3$) and dolomite ($CaMg(CO_3)_2$) for Ca, Mg, and HCO_3, (2) the dissolution of gypsum ($CaSO_4H_2O$) and anhydrite ($CaSO_4$) for Ca and SO_4, (3) the dissolution of halite (NaCl) for Na and Cl in the SRF. The possible source of ion exchange in Lower Thal might be reactions on the surfaces of some clay minerals whereby sodium is released to the water in exchange for calcium or magnesium. Sodium also is derived from the dissolution of silicate minerals such as plagioclase feldspars fills in this part of Doab. Potassium is most probably derived from the dissolution of silicate in some clay minerals However, some minerals, such as calcite CaCO3, are expected to be precipitated from solution to form a solid.

In flood plains of Indus where sub-surface geological formation is transmissive and hydraulic gradient is favorable for groundwater recharge is found with low salt concentration up to entire depth of 90 meters. This is main recharge zone in Thal Doab. Away from the flood plains in eastern part of Upper and Middle Thal where the recharge source is mainly precipitation the salt concentration is low in shallow horizons and high in deep groundwater. Fig. 5 shows that anions are low in therecharge area and increasing towards the discharge area in aquifer. In general the increase in EC and anions dominance evaluation sequence; $HCO_3 \rightarrow SO_4 \rightarrow Cl$ as suggested by Chebotarev[24] holds loosely by reflecting the change from oxidizing to reduction in alluvium aquifer of Thal Doab. This sequence might hold completely for crystalline or pure silicious sedimentary terrain. The cation evaluation sequence in the groundwater system is though difficult to hold, however the zonation identified by Matthess [25]; Ca- Ca+Mg-Na holds good in study area as the freshwater in recharge area has high concentration of Ca as indicted in Fig. 5.

VI. CONCLUSIONS

I. Alluviums of Indus Plains are well tranmissive and replenishment is rapid along rivers as recharge sources is available throughout the year. Water quality mapping reveled that about 1.81 mha constituting about 54percent of Thal Dab is underlain by freshwater of EC less than 1500µS/cm.

II. About 0.45Mha constituting13 percent of study area is underlain by marginal quality water of EC 1500 to 2500µS/cm. This is zone between active flood plains and Bar uplands. Remaining 33 percent area with water relatively higher salt concentration is central part called bar deposits.

III. The area along Indus is with little vertical variation in water quality andgroundwater is fresh upto greater depths(up to 90 meters) which form a huge groundwater reservoir.

IV. The groundwater of Thal Doab is alkaline type with pH above 7 which is often preferred for drinking purpose.

V. Thal Doab is hydrogeologically active as indicated by process like dissolution mixing, and ionic exchange in Duorv Diagram.

VI. Most prominent hydrogeological facies are $CaHCO_3$ type followed by NaCltype.

VII. Ca, Mg, and HCO_3 are produced by dissolution of limestone and dolomite and $SO_4$is from Gypsum and Anhydrite of Khewrite whereas the Na and Cl are produced from dissolution of rock salt(NaCl) of SRF.

VII. RECOMMENDATIONS

I. The monitoring network of SCARP Monitoring Organization (SMO) needs to be expanded to entire Thal Doab area and groundwater monitoring data be maintained in proper database system.

II. Solute transport model should be developed for prediction of saline water intrusions and for different scenarios of pumping of aquifer at different depths

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