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Hypothetical Geological Model Affecting Groundwater Quality in Doabs of Indus Basin, Punjab, Pakistan

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Abstract: The groundwater quality of Indus basin around Sargodha and adjacent areas of Punjab plain is known for its poor-quality in multiple aquifers at different depths. The poor-quality water is being used for domestic and irrigation purposes, causing significant health hazards to communities, ecosystem, livestock and crops. The aquifer water, sediment analysis and surface drainage system, including river beds and dormant meanders have been analyzed during different studies. The subsoil data points had not been concluded or established the geological reason or created a model impacting the quality of groundwater. In the past, limited work has been recognized in multiple source areas and focus remained only on Salt Range outcrops. The geological significance of Kirana-Chiniot hillocks has not been considered. The aquifer solvents support the existence of near to far distance geological formations that are consistently charging the aquifers in Doabs (the area between two rivers). The present study comprises subsurface rock data, composition and geometry below the alluvial cover to speculate geological model, which is contributing to alter groundwater composition after dilution and distribution of aquifers. The east-west trending zone of 200-220 km length stretches from Lahore to Khisor Range, while its width in the north-south direction is about 60-80 km around Sargodha-Chinot-Sangla hillocks. The hypothetical model is based on sub-crop rock distribution drilled wells for oil and gas, 2D-Seismic reflection data, regional gravity mapping and geology of Kirana-Chinot-Sangla hillocks. Cambrian and Precambrian lithologies and associated minerals after dilution with recharging waters are controlling the groundwater quality in Doabs.

Keywords: Hypothetical geological model, groundwater quality, Doab, Indus basin, Punjab.

Introduction

The Punjab plain is covered with alluvial strata and is surrounded by hill ranges including Salt, Surgahr, Marwat and Suleiman Ranges in north and west. This area is intercepted by five rivers; Indus, Jehlum, Chenab, Ravi and Satluj and several canals. It is covered by crop fields and farms among the densely populated cities, towns and villages. The area of alluvial plain between two rivers is also regarded as Doabs and known as Thal, Chaj, Rachna and Bari Doab from west to east (Fig. 1). The cultivation, human and animal life is entirely dependent on the availability of adequate water quality. The available resource of such water depends on the existing river system and groundwater (GW) recharged from seasonal rains in the area. The appropriate quality of water in this region is a major issue. The total dissolved solids (TDS) values are generally high in the area. The rock strata in the outcrops of mountains that surround the Punjab plain are believed to be a source for the solvents (Swarzenski, 1969). In addition, the presence of industrial zones is contributing to serious contamination issues which are injurious to human health and crops and causes the deterioration of the quality of river waters and drainages along with associated GW reservoirs. Subsurface water from fair to poor-quality in this region is being used for drinking and agricultural purposes causing serious health issues. The salinity in GW increases away from the rivers and reaches higher levels of TDS. Drilling of the aquifer at multiple depths represents fair to poor-quality of GW. Surprisingly, decades of recharge from rain and flooding has not refined the GW quality. In this study we have reviewed and analyzed the status of GW with respect to hardness, Ca, Mg, Cl, SO_4, NO_3, F, TDS, EC, pH, alkalinity and its link to the possible source, system and mechanism of GW movement in aquifers at depth.

Geological Setting

The entire Doab areas lie in Indus Basin and are bordered by Kashmir, Salt, Trans Indus and Suleiman Ranges in the east, north and west directions respectively. The Kirana, Chiniot, and Sangla are uplifted hills intercepting Doab area in the middle and aligned in E-W direction (Fig. 1). These uplifted mountains and hilllocks are the key source of Neogene molasses strata and overlying Quaternary alluvial cover which comprise aquifers. Below this molasses strata, the Precambrian Salt Range Formation to Eocene carbonates ranging from evaporites, marl, sandstones, carbonates and shales lie above

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Precambrian meta-sedimentary strata and volcanic layers. The quartzite and phyllite are Precambrian meta-sediments in Kirana hill area along with volcanics and dykes. The Eocene carbonates in the sedimentary sequence are the result of the last marine transgression in this basin (Imran et al., 2016). The lithological units exposed in the bordering vicinity and in situ of Doabs include a wide range of lithofacies. These lithofacies after chemical weathering and dilution are playing a key role in controlling the quality of GW, which has been charged in multiple aquifer levels of Doabs. The presence of salt, gypsum, anhydrite, carbonates, magnesium, laterite, bauxite, hematite, limonite, celestite, sulphur, shales and silicates enriched with minerals at different levels of stratigraphy in the outcrop areas is well known, (Malkani et al., 2017), (Fig. 2). The contact of Quaternary alluvial with underlying Siwalik or any other strata is diffused and has not been resolved by the wells drilled for water and seismic reflection data recorded till date for oil and gas exploration. However, wells drilled for oil and gas in Doabs suggest the presence of contact which is a key factor to understand the thickness of soil, rock types and their ages in the subsurface. Seismic reflection, gravity, and magnetic data integration help to establish the relationship between subsurface of soils in Doabs and foothill areas.

Increased Salinity and TDS in Doabs

The earlier study on fresh and saline GW zones in Punjab, Pakistan conducted by WAPDA and US Agency for International Development (Swarzenski 1969), discussed the following key findings.

1. River water in Punjab is a vital source of GW recharge and is of the calcium-bicarbonate type that contains 90-350 mg/l of TDS (Greenman et al., 1967), (Table 1).

2. Upon GW circulation, it was found that the water of these rivers contains only 13% of dissolved sodium. The calcium in GW is reduced to 40% of total cations due to base exchange in clays and the precipitation of calcium carbonate (Fig. 3).

3. Magnesium is about 25% of total cations and has an excess of calcium and magnesium over sodium in GW containing less than 300 mg/l.

4. The evolution of GW commences from calcium-magnesium-bicarbonate type from recharge and modifies to more mineralized water with an abundance of sodium. GW known for 500 to 1,000 mg/l is of the sodium-bicarbonate type or mixed type. The increase in mineralization from 1,000 to 3,000 mg/l, produces an increase in the relative proportion of chloride and sulfate over the bicarbonate.

5. Highly mineralized waters of the Punjab region are generally of sodium-chloride type, whereas in DI Khan district they are of a sodium-sulfate type. Calcium and magnesium chloride waters having 3,000 to 10,000 mg/l of TDS are not common but reported in all saline GW zones.

6. As the TDS extends between 5,000 to 10,000 mg/l, the quality of water reaches to sodium-chloride type. Locally, the presence of calcium-chloride type water in the lower part of Rechna and Bari Doabs and in Bahawalpur area. Thus Presence of sodium-sulfate waters, with 3,000 to 10,000 mg/l of TDS are believed to be originated from variations in the lithologic environment.

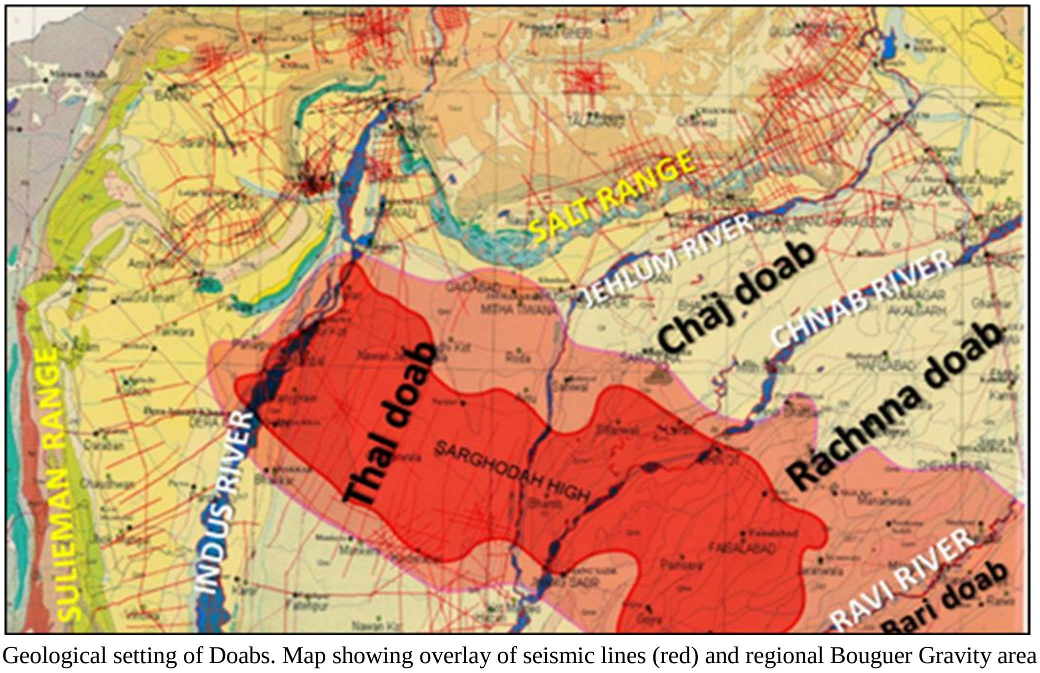

Fig. 1 Geological setting of Doabs. Map showing overlay of seismic lines (red) and regional Bouguer Gravity area of Sargodha High on the geological map of Pakistan (modified after Qureshi et al., 1994).

7. The theories for the origin of saline GW from the Salt Range and other source areas, cyclic windborne salt accumulations and connate seawater were not able to justify the observed distribution of salinity in the remained captured since deposition. The origin of saline GW obtained from such source after dilution or mixing is inadequate.

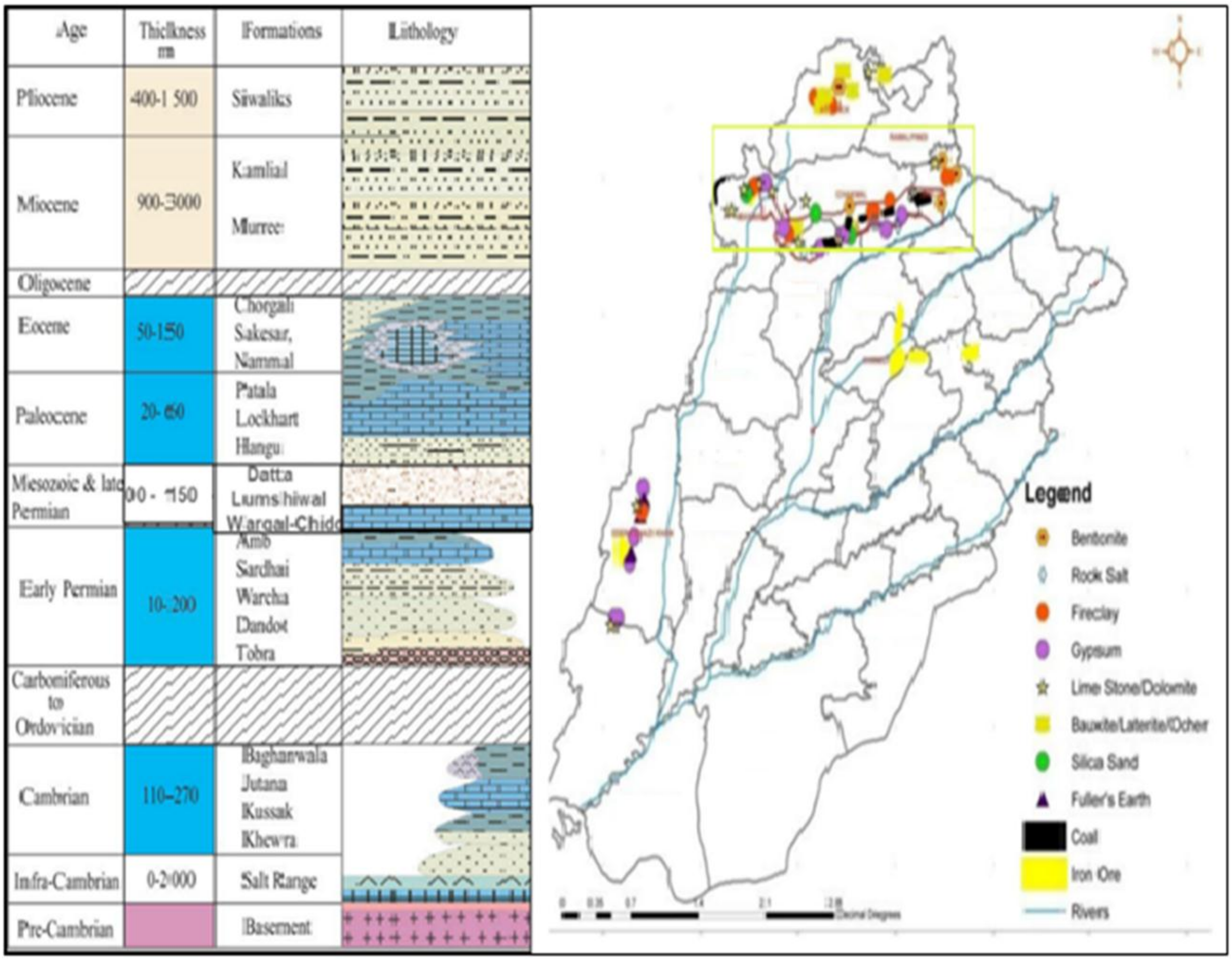

Fig. 2 Rocks and minerals reported in the surrounding hills of Doabs (modified after Malkani et al., 2017) and types of lithologies occurring in Salt and Trans Indus Ranges. Yellow outline area shows location of Salt Range outcrops.

alluvial aquifer.

8. If halite and gypsum deposits in the Salt Range were primary sources of salts in GW of Punjab, increasing mineral concentrations towards the source, reaching maximam near the base of the Salt Range, might be expected, this, however, is not the case. Similarly, observed GW salinities do not point to any other source of surficial salt accumulation.

9. In Punjab, alluvial deposits directly overlie the Precambrian (?) basement rocks. Elsewhere, they may rest on several thousand feet of rocks of the Murree and Siwalik series. These rocks are of fresh-water origin, thus with this understanding of rock distribution, the presence of other source locations was not trusted.

10. No brackish-water or evaporite deposits are known from Early Miocene to younger strata of the shallow marine basin in which saline waters may have

11. The solution-evaporation hypothesis has been considered for a study where combined process of solution and evaporation can explain the observed gradual increase and change in mineralization of GW away from recharge area.

The study conducted by British Geological Survey (Bell et al., 2015) in Indus Ganges Basin (IGB), on GW system considered following assessment for Doabs in Pakistan.

1. The upper 200m of the alluvial cover has been tested for the dwelling of water in IGB (Bell et al., 2015). Distribution of saline water in the top 200m of the IGB aquifer is shown in figure 4.

2. Approximately 20–25% of the aquifer is impacted by the presence of saline water over 1000 mg/l. The basin has not been subjected to widespread marine transgression.

Table 1. Chemical composition of river and GW from shallow and deep sources in Rechna Doab, (modified after Greenman et al., 1967).

TABLE 1- Chemical Composition of River water and Ground water from shallow and deep sources, Rachna Doab																								
Total Dissolved Solid (PPM)	Cations												Anions											
	Calcium (Ca)				Magnesium (Mg)				Sodium (Na) and Potassium (K)				Carbonates (CO2)				Chloride (Cl)				Sulfate (SO4)			
	Percenrtt of total miiliequivavelents per liter																							
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
<300.....	62	42	42	41	25	29	24	26	13	29	34	33	72	71	66	73	11	11	10	5	17	18	24	22
300-500	....	40	25	29	...	25	26	20	...	35	49	51	...	64	66	74	...	8	12	7	...	28	22	19
500-1000	.....	18	15	15	...	21	17	14	...	61	68	71	...	57	50	56	...	15	17	16	...	28	33	28
1000-2000	.....	11	9	...	...	12	13	...	...	77	78	...	...	51	38	...	...	18	27	...	...	31	35	...
A. Average, Indus Jehlum and Chenab River, 1960-64 (153ppm)																								
B. Average, 192 Samples from Shallow wells, Rachna Doab, 1956-59.																								
C. Average, 190 Samples deep test holes, WASID, 1956-63.																								
D. Average, 89 Samples From Tubewells, Shadman Reclamation Scheme, 1963.																								

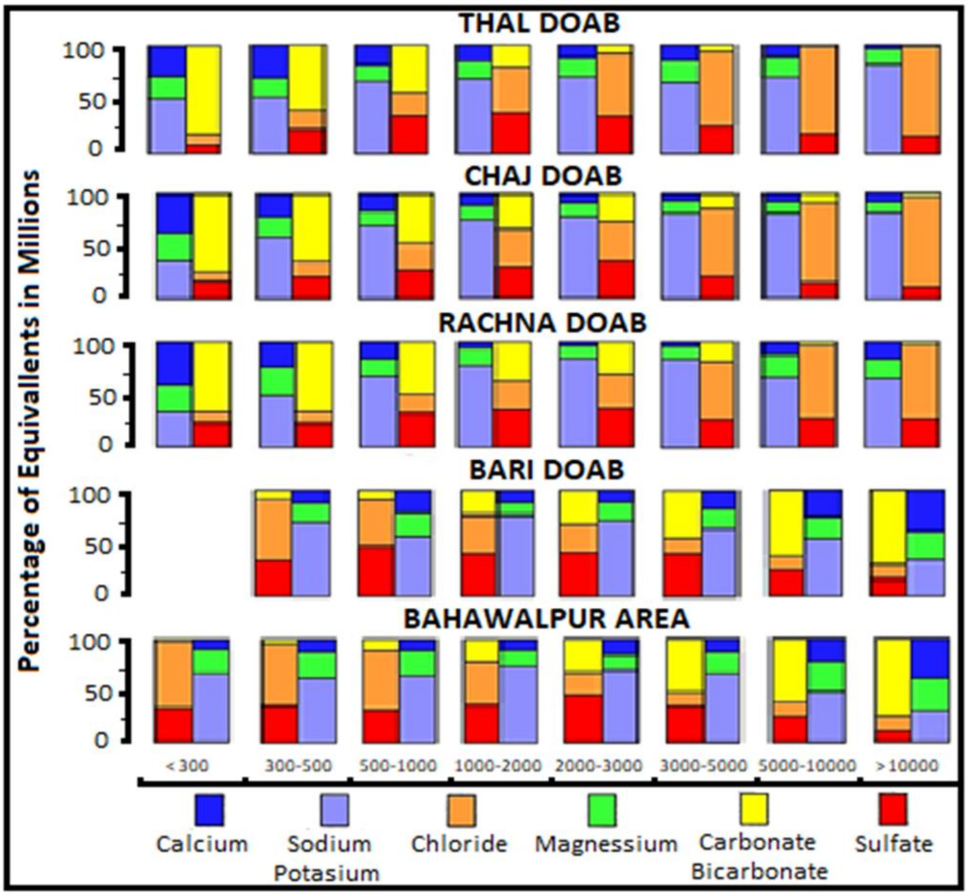

Fig. 3 Classification of GW in the Punjab region shown by bar graphs summarizing analytical data for 953 water samples taken, during WASID's test drilling operations between 1956 and 1963, from Bari, Chaj, Rechna and Thal Doabs and Bahawalpur area. In general, only one water sample from each test site was included in the compilation of chemical data. Thus, figure presents a synopsis of the chemical quality of GW between depths of about 200 to 400 feet at more than 900 test sites, (modified after Greenman et al., 1967).

3. Salinity of GW in Indus Basin is believed to be the consequence of high evaporation after irrigation or flooding relative to rainfall resulting in salinization of soil and GW.

4. The water at a deeper level can be saline due to the presence of evaporite sequences and its longer residence times at that depth. The fresh GW that overlies or is adjacent to saline GW after pumping can mobilize deeper saline water to shallow depth.

5. River water can flush out the saline water to provide fresh GW along banks. The loss of irrigation water from canals develop freshwater lenses in areas of saline GW. This leads to shallow water tables, waterlogging and increased salinization. Over-

irrigation leads to deteriorating quality and the accumulation of soil salts, which are flushed into GW.

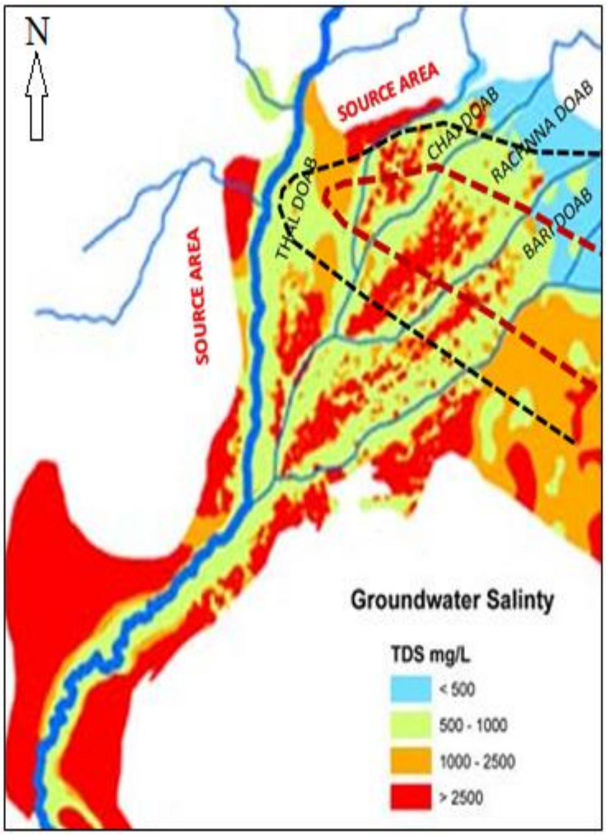

Fig. 4 Modified from map published in the IGB groundwater system report by British Geological Survey on the distribution of saline water in the IGB aquifer, (Bell et al., 2015). The black and red dotted lines are outlines for truncations of Salt Range and Precambrian metasediments respectively around Sargodha High.

Studies conducted at Thal Doab by Khan et al., (2015), after evaluation of 55 wells data concluded as follows.

1. The main recharge zone in Thal Doab is floodplain of Indus river, where sub-surface geological formations are believed to be transmissive and hydraulic gradient is favorable for GW recharge. This zone shows low salt concentration up to the entire depth of 90m.

2. The source of chemical reactions that influence the concentrations of solutes in GW of Thal Doab is likely to be the result of:

   a. Dissolution of limestone (calcite, $CaCO_3$) and dolomite $CaMg(CO_3)_2$ for Ca, Mg, and HCO_3.
   b. Dissolution of gypsum ($CaSO_4 2H_2O$) and anhydrite ($CaSO_4$) for Ca and SO_4.
   c. Dissolution of halite (NaCl) for Na and Cl from Salt Range Formation.

3. The source of ion exchange in lower Thal might be reactions on the surfaces of some clay minerals (Khan et al., 2015). Whereby, sodium is released to the water in exchange for calcium or magnesium. The alluvium of Indus plain is transmissive and refill rapidly from rivers around the year. Water quality mapping represents that about 18,100 km^2 constituting 54% of Thal Doab is underlain by freshwater of EC less than 1500 µS/cm.

4. About 13% of Thal Doab (4,500 km^2) between active floodplains and Bar uplands is underlain by the marginal quality water of EC 1500 to 2500 µS/cm. The remaining 33% area comprises higher salt concentration in the central part called bar deposits. In Thal Doab the most prominent hydrogeological facies are $CaHCO_3$ followed by NaCl type.

5. Ca, Mg, and HCO_3 are produced by dissolution of limestone, dolomite and SO_4 is from gypsum and anhydrite of Khewria. The Na and Cl are produced from the dissolution of rock salt (NaCl) of Salt Range Formation.

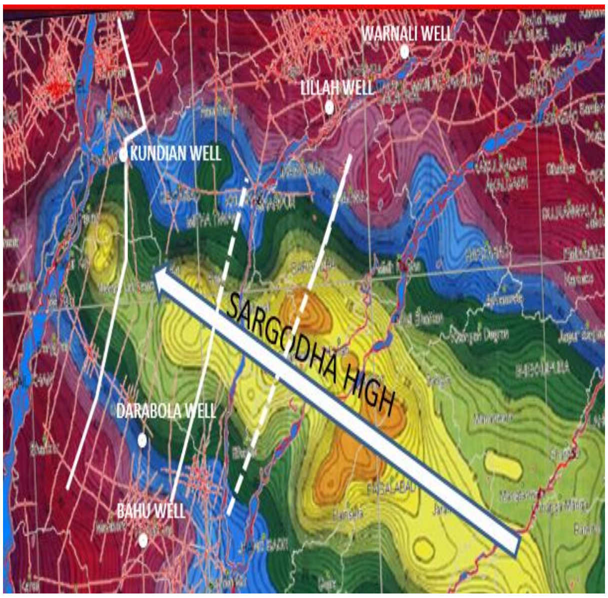

Fig. 5 Gravity map with an overlay of 2D-seismic line location (red and white) showing Sargodha High across Doabs. White lines represent interpreted data set for model building across Sargodha High. Oil and gas wells shown by white circles, 01 (Warnali-1), 02 (Lillah-1), 03 (Kundian-1), 04 (Bahu-1), 05 (Darabola-1). The X-section of well data is shown in Fig. 8. White arrow is plunging of Sargodha High in NE direction, (modified after Philips Petroleum, 1987).

Additional Data: Revised Concepts for Increased Salinity and TDS

The understandings for the source responsible for the quality of existing water in the Doab areas by previous workers require to revisit concepts. Despite well-known geological areas outcropping within and in the peripheries of Doabs, the links with the sodium chloride type and sodium sulfate type is not clear. The link between calcium and magnesium chloride waters have not been well established. However, the relationship has been made in case of a study conducted by Khan et al. (2014) in Thal Doab but still, this area has not been correlated for the source of sediments residing below alluvial cover in the middle around Sargodha High.

Group	Formation	Description
Machh Super Group	Sharaban Formation	Conglomerates with slate intercalations
	Hadda Formation	Calcareous quartzites
	Asianwala Formation	Mainly quartzites with sub ordinate quartz wackes / arenaceous slates, gritty quartzites and slates, often showing cross bedding and ripple marks.
	Tuguwali Formation	Slates, fine grained quartz wackes / arenaceous slates
	Chak 112 Conglomerates	Polymict conglomerate with clasts of dolerite and acid volcanics
UNCONFORMITY		
Hachi Volcanics	Volcanogenic slates	Often interbedded with rhyolite / rhyolitic tuff and dolerite
	Volcanics	Dolerites, andesites, dacites, dacitic tuff, rhyolites and rhyolitic tuff.

Fig. 6 Generalized stratigraphic section of Sargodha High (modified after Chaudhry et al., 2009).

The study conducted by British Geological Survey for Indus Basin (Bell et al., 2015), suggested the presence of Saline Series for effective contribution in mineralization of deeper water but has not illustrated the zone or type and depth of geological feature associated with the system in Doab regions. In the case of a study conducted by WAPDA and US Agency (Swarzenski, 1969), the relationship of impurities or mineralization of subsurface water was not well established with geological destination present in the basin. Also, several other studies concentrating on localized areas from past to recent remain unsuccessful to elaborate the geological relationship with a clear understanding. In present work, this assessment is made after revisiting the scenario to search the source areas and to establish the link and mechanism involved in the mineralization stage during recharging aquifers of Doabs.

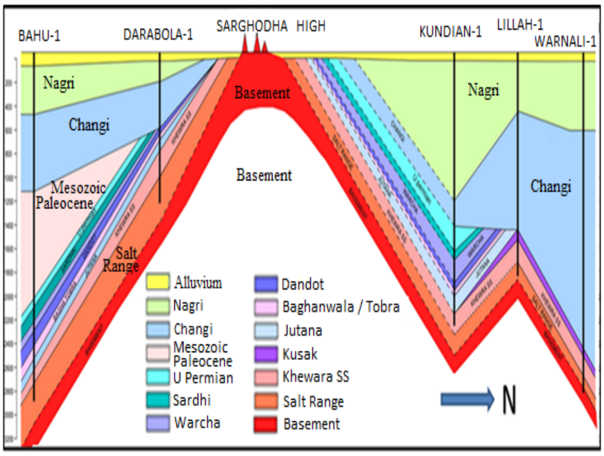

Fig. 7 X-section based on oil and gas wells data across Sargodha High showing truncation of lithological units below alluvial (yellow). Salt Range Formation intercepting alluvium in NS of Sargodha High.

Role of Sargodha High: Kirana-Sangla Hill Zone - Structural and Stratigraphic Imaging Across Doabs

Sargodha High is an uplifted feature dividing the Indus into upper and middle basins. The extent of this High has been mapped by gravity and magnetic and partly by 2D-seismic reflection data. Kirana, Chiniot and Sangla Hills are elevated hilllocks which are surrounded by the alluvial cover in the central part of Chaj and Rachna Doabs. These hills are sparsely aligned along the axis of Sargodha structural uplift formed by Precambrian metasedimentary and volcanics. The gravity and magnetic data show that this structural high is an elongated E-W trending feature. It straddles through Bari, Rachna, Chaj, and Thal Doabs with a clear structural plunge in the west and well-developed flanks dipping in SSW and NNE in directions (Fig. 5). The Precambrian meta-sediments and volcanics of Sargodha High are believed to be intercepting with soil cover and exposed in hilllock area where rock type and their ages have been estimated. Besides, the rock type and its depth forming Sargodha High is known from the well data drilled for dwelling of water. In addition, the rock section exposed in the hillocks (Kirana, Chandra, Shraban, Machh, Tuguwali, Hachhi, Nistarabad, Chiniot, and Sangla) are drilled by the oil and gas exploratory wells (Kundian Lillah, Warnali Baho, Darbola, Saro, Karampur, and Marot), which are located on both the flanks and also provide dip and depth information of the structure of Sargodha High. From the outcrop data of hilllocks and the lithological information provided by water and oil wells, the uppermost part of Sargodha High is composed of meta-sediments and volcanics of Precambrian age intruded by igneous dykes. A generalized stratigraphic section derived mainly from outcrops and the data of water wells drilled along the structural axis of the High show presence of quartzite, phyllite, rhyolite, basalt and dolerites lying below the alluvium in the area (Fig. 6). The stratigraphic data of oil and gas wells drilled on northern and southern flanks of structural high and its correlation with 2D-seismic data towards structural axis suggest variation in the distribution of lithologies across the High below the alluvial cover.

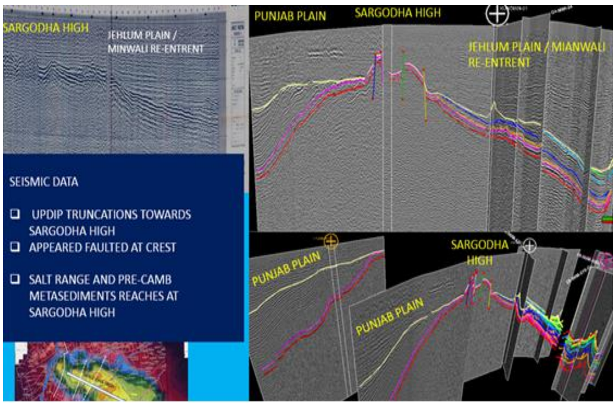

Fig. 8 Interpreted 2D-seismic data and its correlation wells drilled for oil and gas to identify reflectors and age of rocks; white lines are showing locations of 2D data on inset map.

The well data from Kundian-1, Lillah-1, and Warnali-1 drilled to the north of structural axis of High show presence of Platform strata of Salt Range (Pre-Cambrian, Cambrian and Paleogene) above the metasedimentary-volcanic rock unit and are truncating below Siwaliks of Neogene age (Fig. 7). The imaging from 2D-seismic reflection data suggests that these lithologies are successively truncating below Siwalik and show erosional truncation. Salt Range Formation, the truncation extends close to outcrops of Sargodha-Chinot-Sangla hills below alluvial cover (Figs. 8, 9). In the south of Sargodha High, close to structural axis, the 2D-seismic data interpretation suggests presence of Salt Range Formation below alluvium, while truncations of younger platform reflections (drilled wells for Cambrian, Permian, Mesozoic and Paleogene levels) appear erosional and successively stepping away. (Fig. 10).

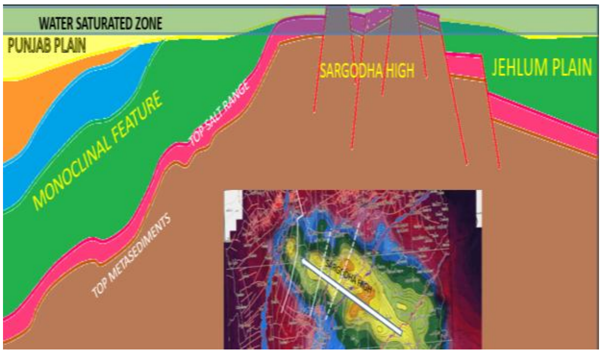

Fig. 9 Subsurface geological model of Doab areas, interpreted from 2D-seismic, well and surface geological data along with expected water saturated zone.

In this scenario of structural and stratigraphic setting, the significance of Salt Range Formation which is in contact with an alluvial cover around Sargodha High cannot be ruled out. The seismic data also demonstrated the presence of extension-related horst and graben structures at the crest of Sargodha High and where the extensional faults are not intercepting Siwalik and alluvial cover (Fig. 8). Towards structural axis across the high, these faults are expected to be buried below alluvial cover. Thus any lateral thickness change of alluvium across horst and graben structures is expected. The seismic data interpretation for the structural evaluation proposed the extension of such structural style across Doabs trending parallel to the structural axis.

It is also interpreted that Salt Range Formation may have been removed after erosion from structural horst preserved in grabens or lows below alluvial cover (Fig. 9). The presence and absence of salt across structurally portioned blocks are possibly controlling the local changes in the quality of GW of Doabs after dilution process. The water may be more saline in a structural low where Salt Range Formation is preserved and here dilution is effectively contributing to enhancing salinity factor. The changes in lateral thickness, variation in depth and quality of water along Sargodha High can be observed from the lithology as revealed from wells drilled at the crest of Sargodha High (Figs. 11, s15). The drilling data provide information of alluvial cover and its reservoirs to a certain depth mainly at shallow levels. So far, no well data show lithologies pertaining to Salt Range Formation along Sargodha High to confirm its presence below alluvial cover as a bedrock. It might have been drilled during a search of water for domestic use and where reporting of lithology was not a priority and lithological observations were not reported by local drillers or hydrogeologists. Few wells in bedrocks of Precambrian, along Sargodha High might have been drilled on horst structures from where Salt Range Formation has been removed by erosion. Present evaluation of proposed structural and stratigraphic setup is based on existing 2D-seismic data recorded mainly in Thal and Chaj Doabs. The lateral continuity of structural style across other Doabs (Chaj, Rachna and Bari) is speculative and is an extrapolation of extensional fault block trend and truncation of seismic events below alluvium. The estimated thickness of alluvium from seismic data at the structural axis in Thal Doab ranges between500-550m. The gravity data suggest the presence of a thick alluvial cover in plunging zone of Sargodha High compared to eastern areas of structural axis intercepted by Chaj, Rachna and Bari Doabs. In the west of Thal Doab, the alluvial cover might be residing above Neogene sediments below which subcrop truncation of Platform rocks has been interpreted at plunging axis (Figs. 9,10). The thickness of alluvial near hilllocks in Chaj and Rachna Doabs depends on the existence of structural horst or graben in a range of 50 to 250m. The previous studies suggested channels among hillocks to justify a change in aquifer character and its thickness above the bedrock.

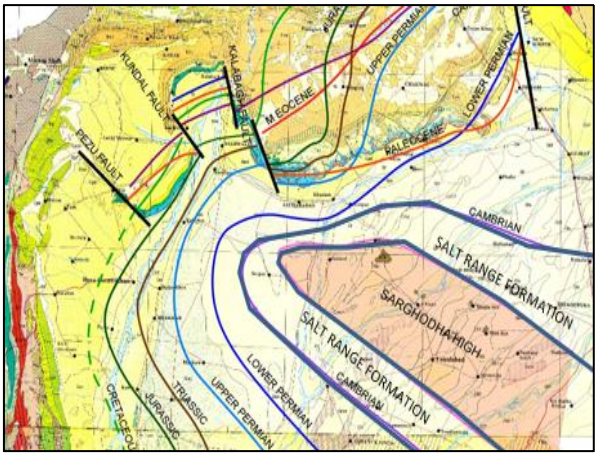

Fig. 10 Geological map with an overlay of sub-crop truncations of Precambrian, Cambrian and Mesozoic in Punjab plain and Potwar basin. Presence and extent of Salt Range Formation around Sargodha High is shown and assumed from oil and gas well data (modified after Qureshi et al., 1994).

Doab Recharging System, Impact of Sargodha High and Chemical Contribution of Rocks

The evolution of GW commences from fresh calcium-magnesium-bicarbonate type entering from recharge area and being modified to more mineralized waters containing a dominant proportion of sodium. GW from

500 to 1,000 mg/l is of sodium-bicarbonate or mixed types, which carries bicarbonate, chloride and sulfate anions in equal proportions. The increase in TDS from 1,000 to 3,000 mg/l produces an increase in chloride and sulfate over the bicarbonate and these waters are of sodium-chloride or sodium-sulfate type. The theory of "solution-evaporation hypothesis has been considered by Greenman et al. (1967). Whereby solution and evaporation can explain the observed gradual increase and change in mineralization of GW away from the sources of recharge. However, the map compiled to represent TDS behavior in Doabs has not demonstrated the gradual change of TDS from river banks to the center of Doabs (MacDonald et al., 2015). The transition zone of water comprising 1000-2500 mg/l of TDS is absent in Chaj, Rachna and Bari Doabs, (Fig. 4). The change is represented by a zone of water having TDS from 500-1000 mg/l to >2500 mg/l. The recharging and dilution close to the near-surface source as multiple bedrocks of Sargodha High to maintain higher TDS solutions across Doabs. The flushing by strongly flowing water currents along rivers is not allowing to accumulate mineralized water along river banks.

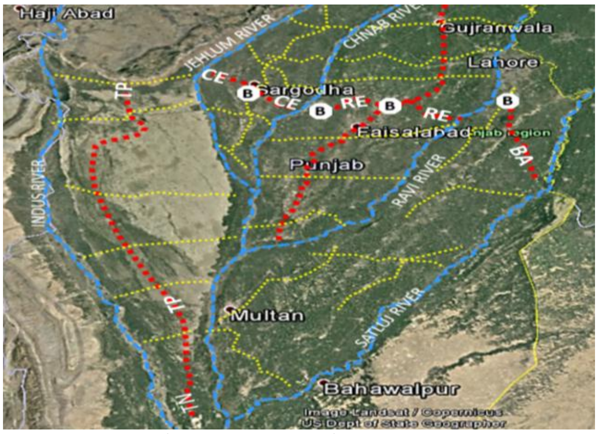

Fig. 11 Location of wells data drilled for groundwater in Doabs used to compile geological cross section. Red are major profiles along with bedrock (Precambrian Basement from Sargodha High) encountered at wells shown in white colors with symbol B. These profiles are shown in figures 14-16 (modified after Greenman et al., 1967).

The flushing of weekly diluted water formed after chemical reaction right below the river bed and its adjacent vicinity from the buried rocks and minerals of Sargodha High is more effective than the dilution process due to limited chemical reaction time. The presence of local source has been inferred from the overlay of TDS map of Doabs on gravity map. The occurrence of the anomalous zone of TDS map of Doabs coincides with the structural trend of gravity high (Fig. 4). The anomalies were seen in north and south of Thal Doab for sodium, calcium, magnesium, carbonate, chloride and sulphate concentrations (Fig. 4) and they suggest a link to the geological source. The anomalies in the north are closely associated with Salt Range outcrop area, while the occurrence of southern anomalies at specified location among the closely spaced Indus and Chenab rivers overlie on the plunging axis of Sargodha High. The flushing ability after recharging of water from both the rivers present on either side has not affected or eliminated this anomalous zone. This suggests dominance and long-term maintenance of in-situ dilution processes occurring along buried rocks of Sargodha High. Its alignment is perpendicular to flowing rivers. Interpretation of geophysical data suggests EW alignment of near-surface bedrock intercepting soil. Dilution and recharging processes along various lithological units of Sargodha High are believed to be actively happening along EW structural trend.

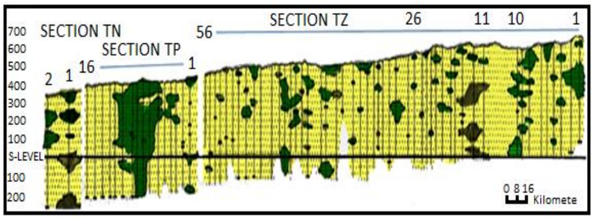

Fig. 12 Geological cross section showing lithology encountered in the alluvial cover of Thal Doab. (Greenman et al., 1967).

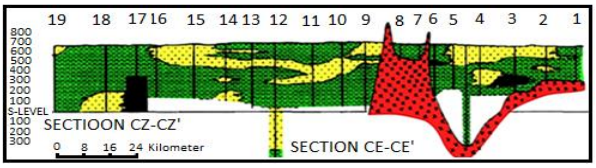

Fig. 13 Geological cross section showing lithology encountered in the alluvial cover of Chaj Doab. (Greenman et al., 1967).

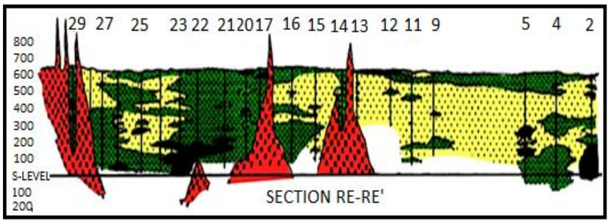

Fig. 14 East west geological cross section showing lithology encountered in the alluvial cover of Rachna Doab. (Greenman et al., 1967).

Hypothetical Groundwater Model

In Doabs the chemical alteration and dilution depend on the depth of penetration of descending water which is in continuous supply by precipitation, rivers and irrigation canal systems. A representative hypothetical GW model is presented in Figure 16. The model represents GW quality of all Doabs from near surface to circulation at depths. The model is based on the secondary data of hydrologic, hydrogeologic, hydrochemical and GW studies. Isotopic and geochemical techniques to assess GW replenishment studies in Doabs were also considered (Ahmad et al., 2002). The model is consistent with the seismic and gravity data of subsurface geological and geophysical investigations. The model represents and may fit an EW cross-section of any Doab at any location. The model is also valid between any two major irrigation canals. The localized variations in GW quality may be observed from place to place at shallow levels. These variations may transpire and emerge because of the impact of irrigation systems, canal seepages, and excessive GW pumping etc. The model simulates fresh GW underneath and along both sides of all the rivers at varying depths.

The chemical quality of fresh GW is dominant in river waters. The mineralized GW perceives in middle and central parts of the Doabs. At the top of the aquifer, a thin layer of rainwater may be observed in central parts of Doabs. River water recharged from flanks of the Doabs is then mixed water and thereafter rainwater dominates. The hydrologic and groundwater management studies of Doabs may enhance understanding of the groundwater circulation systems by comparing numerical groundwater modeling studies directly with measured values.

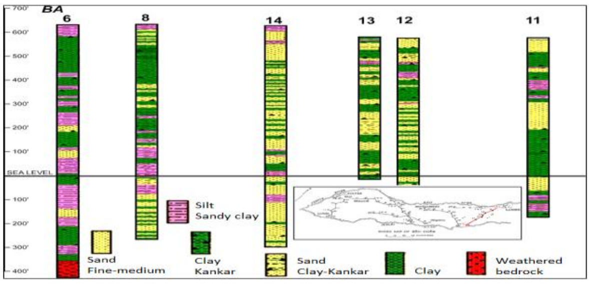

Fig. 15 Wells drilled in Bari Doab. The well located near Lahore encountered bedrock which belongs to Sargodha High (modified after Greenman et al., 1967).

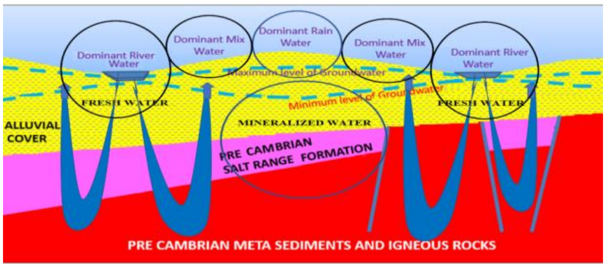

Fig. 16 Hypothetical GW model of Doab representing near surface quality and the flow path of river water (blue arrows) from alluvial cover, underlying Salt Range, meta-sedimentary and igneous rocks.

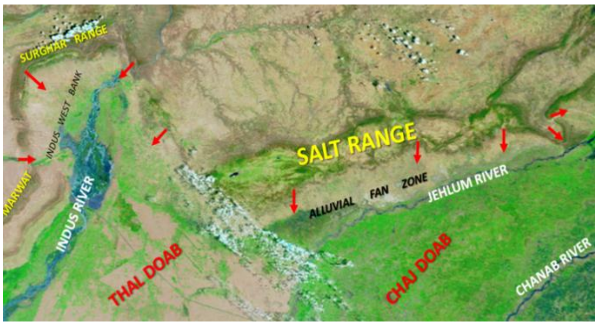

Fig. 17 Drainage zone west of Indus and north of Jhelum rivers supplying sediments and chemically diluted fluids to soil area from Salt, Surghar and Khishore-Marwat Ranges.

It is believed that water has been penetrated beyond the erosional boundary below the alluvial cover to multiple bedrocks present at shallow depths, ranging from igneous (mafic and felsic), metasedimentary (quartzite and phyllites), and sedimentary strata (Salt Range lithologies). In addition to water chemistry, the areas minerals information is known from an outcrop of hilllocks and drilling data along Sargodha High. The water at recharging points of Indus, Jhelum, Chenab, Ravi, and Sutlej rivers is less than 500 mg/l TDS and of calcium, magnesium, bicarbonate in nature and which, after descending to deeper levels intercept and react with silicates, halite, anhydrite, gypsum, and iron-bearing units. The GW alters its characters along its migration path after dilution and reaches to higher TDS between 500 to 2500 mg/l and may be of sodium-chloride or sodium-sulfate type. The sodium recorded in Doabs is also derived from the dissolution of silicate minerals like plagioclase feldspars. Dissolution of silicate minerals present in Sargodha High both in outcrop and subcrop will be a source of potassium in Doabs. Gypsum, anhydrite for Ca and SO_4 and halite for Na and Cl are sourced from salt beds. The SO_4 in GW is most likely derived from gypsum and anhydrite of Khewria deposits of Salt Range Formation.

Role of Salt and Trans Indus Ranges in Groundwater Quality

Salt and Trans Indus Ranges are one of the key sources for the supply of soil material through flooding and in non-flooding time to Doab regions. Erosion of rock strata from these uplifted ranges to Thal, Chaj Doabs and in the zone between Indus river and Surghar-Khisor Range is ongoing through downcutting streams (Fig. 17). This source and supply system under mechanical and chemical weathering conditions is effectively contributing and controlling the formation of regolith and soils. A number of alluvial fans and streams are merging from these Ranges to the soils of Thal and Chaj Doabs and West Bank of Indus river. Dilution process of rock minerals provides solvents enriched in calcium, sodium, chlorite, sulphur and others, which can be linked to the source areas in Salt and Trans-Indus Ranges.

Rock salt and gypsum from salt Range Formation exposed in the uplifted belt are easily dissolvable in water and carried to Doab soils thus enhancing salinity in the GWs. Highly saline water is flowing in downcutting streams carrying this solution to alluvial cover regions. Salt water is originating from Bahadur Khel salt beds exposed in Kohat region along Latember Range, which is carried to Gomal river through down-cutting streams and ultimately off-loaded into aquifers of soil in Bannu basin.

Sulfur spring present in Nammal Gorge and other locations is a direct source of this solvent charging into Thal Doab reservoirs. Numerous carbonates of different age exposed in these ranges are being eroded, diluted and transported to soil areas affecting the water quality in terms of calcium bicarbonate in water of Thal, Chaj Doabs and alluvial cover west of Indus river.

The study conducted on water samples of 55 wells defined the dissolution of limestone and dolomite for Ca, Mg, and HCO_3, gypsum, anhydrite for Ca and SO_4, and halite for Na and Cl sourced from the Salt Range (Khan et al., 2014). The SO_4 in GW is most likely derived from gypsum and anhydrite of Khewra deposits of Salt Range Formation.

Role of Suleiman Range

The Suleiman Range present in the west of Doabs is a bordering elevated mountain range of Middle Indus Basin outcropping sedimentary rock strata from Triassic to Quaternary levels. Lithofacies in the front-line folded strata effectively shedding sediments to Indus basin are shown in the generalized serigraphic column (Fig. 2). These include limestones, stratigraphic and shales at multiple levels as a stratigraphic unit. Numerous down-cutting streams along the gorges recorded mechanical erosional processes along with chemical weathering. Alluvial fans present along the rim of fold belt at the border of Punjab plain and Suleiman hills are erosional features driving sediments to adjacent alluvial areas along the west bank of Indus river. The active streams flowing through these fans are finally shedding its load into the Indus river. The most effective contribution is during the monsoon season and other events of heavy rains during the year. The mineral deposits from the rock strata of Suleiman area adjacent to Punjab area includes celestite, gypsum deposits, silica sand, glauconitic and hematitic sandstone (iron and potash), clays, sulfur and radioactive minerals. The sodium chloride and sodium sulfate types water are reported from the west bank of Indus river.

Conclusion

The quality of water in Punjab province is one of the major concerns for agriculture, livestock and human life. The presence of fresh and mineralized GW zones has been confirmed from a few meters to 425m down after drilling of hundreds of wells in Doabs and adjacent areas. The alluvial cover in Doabs has been tested for multiple levels to find appropriate quality water for domestic, agriculture, livestock and commercial utilization. The mineralized GW is available in the middle and central parts of the Doabs. In the top layer of the aquifer, a thin layer of rainwater may be present in the central parts of Doabs.

From the rivers towards the central parts of the Doabs, the source of GW may be classified as dominant river-water, mixed-water, rain-water and mineralized waters in origin. The TDS of water is less than 500 mg/l at recharging points of Indus, Jhelum, Chenab, Ravi, and Sutlej rivers. The water is of calcium, magnesium and bicarbonate in nature and water after descending to deeper levels intercept and react with silicates, halite, anhydrite, gypsum and iron-bearing units. GW alters its characters along its migration path after dilution and reaches to higher TDS between 500 to 2500 mg/l and may be of sodium chloride or sodium sulfate type.

The hypothetical subsurface model for Sargodha High supported by gravity, seismic and well data of oil and gas is believed to be present across all the Doabs and thus playing a key role in affecting the quality of GW. The Precambrian truncation of Salt Range Formation, igneous and metasedimentary rocks along Sargodha High in the Doab areas is expected to extend with its saline and evaporite sequences along with silicate minerals below the alluvial cover and therefore contributing its ingredients in GW after dilution.

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