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Determination of ground water quality associated with lignite mining in arid climate

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Abstract

Ground water and surface water create a range of problems in lignite mining utilizing surface mining methods. In order to create a safe and economic mining environment, it is essential to carry out mining after dewatering the rock mass surrounding the lignite mines by advance dewatering techniques. This paper briefly describes the ground water regimes including pressure gradients associated with various lignite deposits together with the practical examples of some important lignite deposits in the world. An effective method of controlling ground water in multi-aquifer environment in lignite deposits is to carry out rock mass dewatering using borehole pumps. This approach will help reducing the inflow rates of ground water to the mining excavation and also increase the effective strength of the overburden strata, thus, increasing the slope stability of the mining excavations. The main theme of this paper is to present a case history analysis of Thar lignite deposit in Sindh, Pakistan which has lignite reserves of some 193 billion tonnes. The paper presents a proposed method of dewatering the Thar prospect together with an assessment of the quality of aquifer water which can be used to improve the quality of life of people inhabiting in the Thar Desert area of Sindh, Pakistan.

Water samples from three aquifers were collected from nine different locations and were analyzed in the laboratory for evaluating their physical and chemical characteristics. The test results indicated that the aquifer water can be classified as (sodium+ potassium) – chloride type water with a TDS range of 1000 to 20,000 mg/L. Consequently, this ground water is classified as brackish (saline water) requiring treatment before it can be utilised for domestic or industrial consumptions. It should be noted that this ground water does not contain heavy metals and toxic metals including arsenic, mercury and lead or cyanide. However, results indicate that groundwater from a few locations contained traces of silver (<4oppb)Owithozinc0<0.1ppm.

Keywords: *Open cut mining, Hydrogeology, Aquifers, Lignite, Advanced dewatering, Piper diagram.*

1. Introduction

Mining of lignite deposits all over the world are being carried out under complex hydrogeological environments causing a range of water problems affecting the production and utilization costs. This paper presents a case history analysis of Thar lignite deposit in Sindh, Pakistan which has lignite reserves of some 193 billion tons. The geological and hydrogeological scenario of the lignite deposit in Thar district suggests that the most appropriate proposed method of dewatering the mine will be by utilizing an advanced borehole dewatering technique [1]. The paper presents an assessment of the quality of aquifer water which can be used to improve the quality of life of people inhabiting in the Thar Desert area of Sindh, Pakistan. Water samples from these aquifers were collected from nine different locations and were analyzed in the laboratory for evaluating their physical and chemical characteristics. The physical parameters of water were determined by using pH meter, conductivity meter and TDS (total dissolved solids) meter. A spectrophotometer was used to determine the hardness and ions concentration of various elements in mg/L. The test results were assessed by plotting the chemical analysis results on a triangular graph and a piper diagram.

2. Water problems in lignite mining

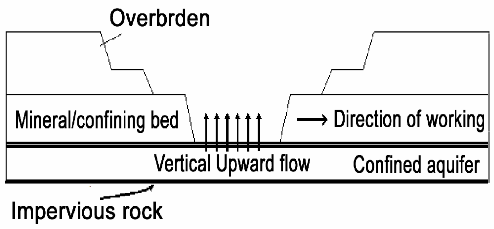
The range of water problems in the surface lignite mining can be grouped as operational problems, stability problems and environmental problems. Operational problems include material handling problems associated with dealing with wet rocks and lignite, blasting issues, machinery efficiency and resource recovery problems. Reduction of soil and rock shear strength due to water saturation causes stability problems which may include stability of high wall, low-wall and spoil slopes. In addition, pit floor heave may initiate catastrophic inflow of water and toe failure of high wall resulting in a major catastrophic high wall slide. Environmental problems include formation of acidic mine water which may generate heavy and toxic metals waste and also promote spontaneous combustion of carboniferous rock materials. In addition, heavy rain and surface water may cause pit slope, haul road and drainage ditch erosion, haul road softening and frost heave in winter, in addition to, water pressure build up in tension cracks and glaciations in winter.

In order to carry out mining of lignite in a complex hydrogeological environment it is necessary to carry out mining in dry conditions using advanced dewatering of rock mass around the lignite open cut by borehole pumping.

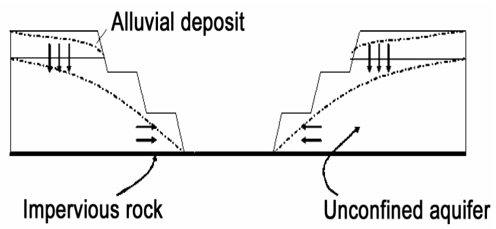
3. Mode of inflow and pressure regimes associated with lignite deposits

The most commonly encountered sources of subsurface water inflow to surface mining are presented in Figure 1 as one-, two-, three- or four regime flows in surface mining respectively [2]. One regime flow can occur where the lignite deposit is located above a confined aquifer. As the overburden materials and the lignite deposit are extracted during the mining operation, the impervious bed may break and water with high pressure flows into the mining excavation. In this case, inflow to the mine generally occurs in the vertical direction (Figure 1.a).

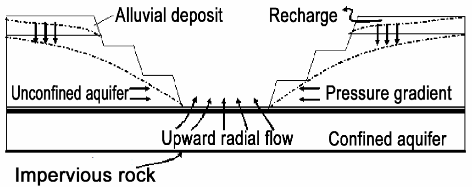
Two-regime flow normally occurs where mining is carried out in an unconfined aquifer overlain by an alluvial deposit that maintains its own water table. Figure 1.b shows this situation. Horizontal inflow to the mining excavation takes place from the unconfined aquifer which in turn receives vertical recharge from the alluvial sediment. The rate of expansion of the cone of depression controls the size of the vertical recharge area in the overlying alluvial series contributing to the groundwater inflow into the mining excavation. In the case of three-regime flow, the process of mining may occur in a water table aquifer overlain by an alluvial sequence and underlain by a confined aquifer as illustrated in Figure 1.c.



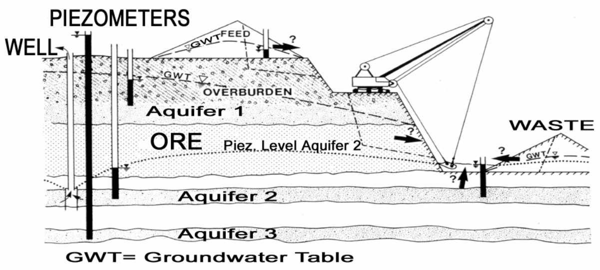
a. One pressure regime flow



b. Two regime flow



c. Three pressure regimes flow



d. Four regimes flow

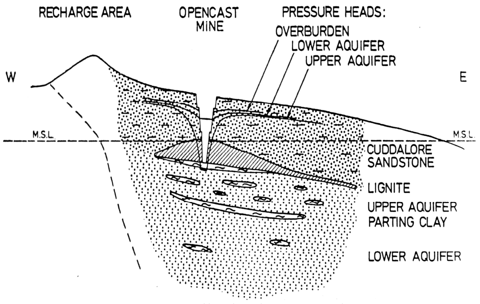
Figure 1. Various pressure and flow regimes of groundwater in surface lignite mining [2]

In such situations the flow regimes can be complicated due to horizontal flows from the alluvial deposit, horizontal flows occurring from the unconfined aquifer as well as vertical downwards recharge from the overlying alluvial aquifer to the unconfined aquifer and vertical upwards flow from the confined aquifer into the mining excavation. In this situation, mine extension will release the pressures of overburden layers on the confined aquifer and the confining layer splits and finally upward inflow from floor beds occurs [2]. Figure 1.d shows a four flow regime where the lignite seam is overlain by an unconfined aquifer and underlain by two confined aquifers separated by impervious shale beds. The spoil tip as well as lignite seam acts an aquifer and change in hydraulic gradient due to the surface mining induces water flow towards the mining excavation.

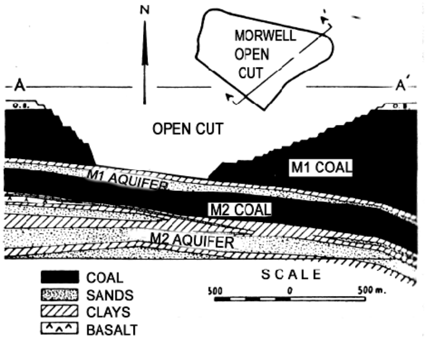
4. Practical examples large lignite deposits

Figure 2 shows the hydrogeological profile and pressure regime of four major lignite or brown coal seams in various part of the world being mined by the surface mining methods. Figure 2a shows the cross-section of lignite seam in Neyveli lignite mine in South India that has been in continuous operation since 1957. The lignite seam is 27m thick and overlaid by an unconfined aquifer comprising 49.5m thick Cuddalore Sandstone which is lateritic (clayey) sandstone. Underlying this lignite seam are two confined aquifers, upper one being 27m thick and the lower one being considerably thicker extending to the bottom of the lignite basin. The intervening stratum between the two confined aquifers is a 2.4 m thick layer of impervious intercalated clay. The original piezometric surface of the aquifers was 48m above the base of the lignite seam, approximately 30 m above MSL. The phreatic surface of the unconfined aquifer is partly above and partly below the piezometric surface of the confined aquifers. Figure 2.b shows the hydrogeological profile of Morwell open cut project in Latrobe Valley, Victoria, Australia producing about 16 mt of brown coal per annum. Two major aquifer systems occur below the open cut, the M$_1$ aquifer is a 15 m thick near continuous sand layer in the inter-seam separating the Morwell 1 and Morwell 2 coal seams. a clay layer separates the M$_1$ aquifer from M$_1$ seam. The deeper M$_2$ aquifer system is comprised as a series of lensoidal sand layers immediately underneath the M$_2$ coal seam. The recharge source to both aquifers is at the western edge of the Latrobe valley. The temperature of water from M$_1$ aquifer is 46^{o}C and that of M$_2$ aquifer is 55^{o}C. The water from both aquifers is of reasonable quality averaging 400 mg/l TDS but they are highly corrosive to mild steel.

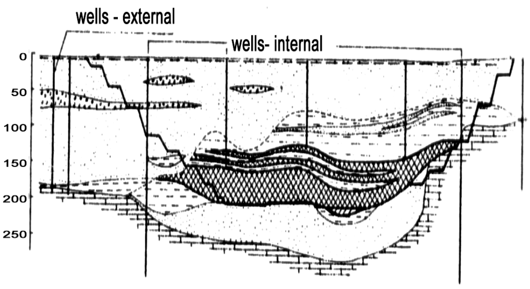
Figure 2.c shows the hydrogeological profile of Belchatow lignite basin in Poland, consisting of a multi-seam basin where the overlying, underlying and intercalating beds consisting of 70-80% clay and 20-30% sand in the form of closed lenses. The sand lenses contain static water under hydraulic head. Thickness of lignite seam reaches 5-40m and overall depth of mine reaching up to 160m. The ground water inflow to this mine is around 30 to 40 M^3/ minute.



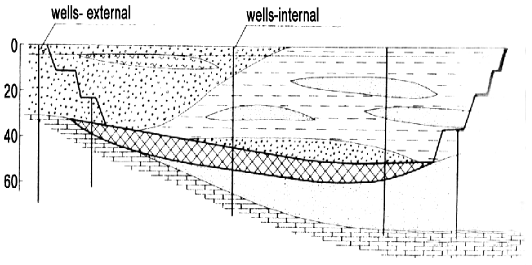
a. Neyveli Lignite Deposit



b. Morewell Brown Coal, Australia



c. Belchatow Lignite Deposit , Poland



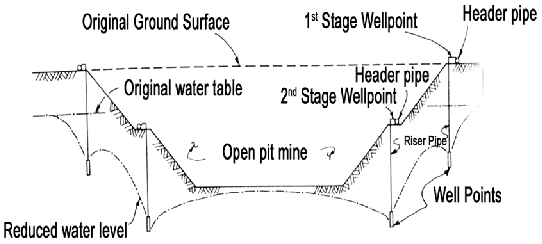
d. Adamano Lignite Deposit

Figure 2. Eexamples of Working Lignite deposits [3]

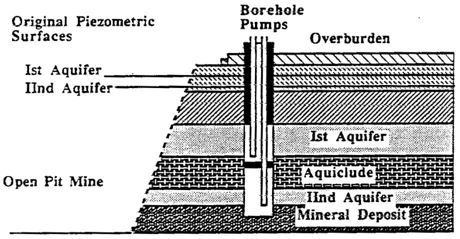
Adamow lignite seam in Poland Figure 2.d, consists of one impermeable flat seam with a variable thickness of 6 to 15m, overlain by 25-75m of overburden consisting of 70-80% Tertiary or Quaternary clays and 20-30% sand of the same age. The lignite seam is underlain by 20-50m thick saturated sand containing sub-artesian water under pressure of 0.3 to 0.8 MPa and having permeability co-efficient of 3-5 m/day. The ground water inflow to this mine varies between 30- 100 m^3/min.

5. Rock mass dewatering methods for lignite seams

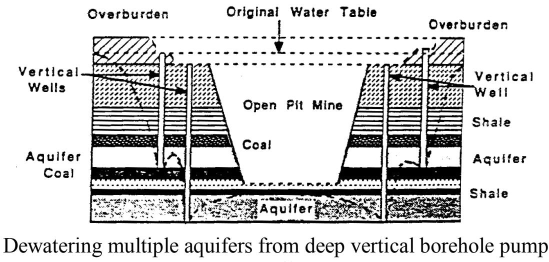
Advanced dewatering of rock mass around the surface lignite mines can be carried out by well point system for unconsolidated sediments and by vertical dewatering wells for unconfined, confined and leaky aquifers (Figure 3) [4]. Conventional and vacuum well point systems are used to dewater unconsolidated sediments which comprises 37-50mm diameter, 0.6 to 1.5m long riser pipes (Figure 3.a). These riser pipes are connected to a common header and pumped by a single or multiple well point pumps which are combination of centrifugal and vacuum pumps being capable of lowering the water levels by 5-6m. For greater lifts, multistage well points, jet ejector or deep well system are more effective.



a. Two stage well point system



b. Dewatering several aquifers from one gravity flow vertical well



c. Dewatering multiple aquifers from deep vertical borehole pumping wells

Figure 3. Dewatering systems for lignite mines [3]

In confined aquifers, a gravity flow well or an artesian flow well can be used Figure 3b and 3c whereas for unconfined and leaky aquifers the dewatering boreholes are equipped with the submersible types of pumps. Both internal borehole wells and external wells surrounding a mining excavation can be used. External borehole pumps are installed just outside the final periphery of open cut excavation. The borehole method of groundwater control offers the possibility of dewatering the rock mass surrounding the mining excavation with the advantages of stability, safety, operational and environmental recompenses of mining under dry conditions. However, advanced dewatering by borehole pumps are expensive in terms of maintenance and refurbishing cost of borehole pumps and it takes a long time to dewater a mine, in some cases several years.

6. Case history analysis of Thar Lignite deposit in Thar Desert

Pakistan has the seventh largest deposits of lignite/brown coal in the world with total lignite reserves of 193 bnt. Thar lignite/ coal deposit is located in the eastern part of Sindh Province about 400 Km east of Karachi as shown in Figure 4. Thar coalfield covers an area of approximately 9000 Km^2 and lignite beds lie at the depths between 130 and 250m. Cumulative seam thickness varies between 7.5m to 36m and the maximum thickness of an individual seam is 23m. Geological Survey of Pakistan (GSP) and United States Geological Survey under Coal Resources Exploration & Assessment Program (COALREAP) first discovered this lignite field in 1994. Total reserves in the four blocks already investigated over an area of 40 Km^2, are more than 9 bnt.

6.2. Stratigraphy and lithology of Thar lignite field

Lignite seams in the Thar area, are found in Bara formation of Palaeocene/Eocene age. The Bara formation is some 95m thick consisting of sandy/silty claystone and sandstone formation overlying the basement granite lying at a depth of 100m to 220m. The basement rock is very light grey weathered, medium compacted-granite containing fine to coarse quartz grains. The overlying Bara formation consists of layers of carbonaceous clay stone, sandy clay stone and silty clay stone. The carbonaceous clay stone is medium light grey to brown in colour containing carboniferous petrified roots, carbonaceous materials and rare sandy resin globules. The olive grey to dark-grey claystone containing petrified

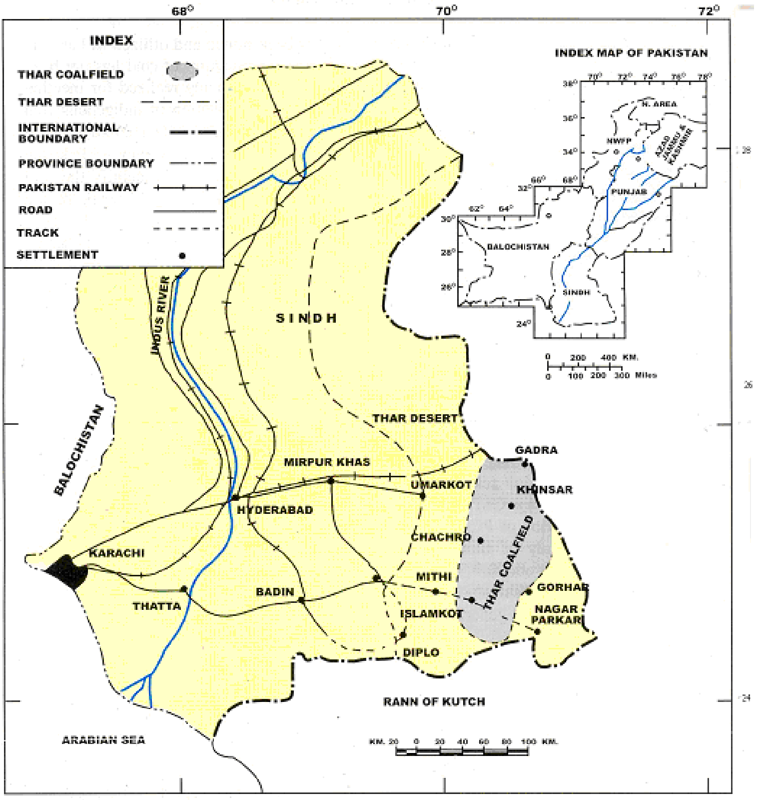
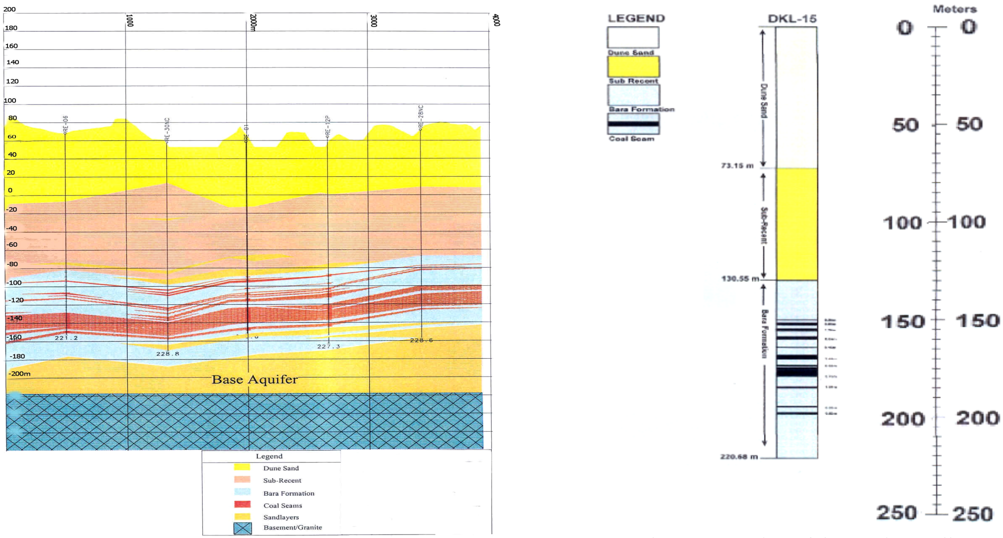


Figure 4. Location of Thar lignite prospect, Sindh, Pakistan[5]



a. Borehole cross section of Thar Aquifers

b. Cross-section of dewatering well

Figure 5. Ground water regimes in Thar Lignite Prospect [6]

roots, carbonaceous materials and rare sandy resin globules. The olive grey to dark-grey claystone containing petrified coal roots and pyretic resin globules overlies this sediment.

There are number of coal seams of varying thickness ranging from 3m to 21m at an average depth of 170m. Bara formation is overlaid by the sub-recent formation comprising inter-bedded carbonaceous sandstone, siltstone and clay stone up to 65m thick, at the depth of 52 – 125m. The recent formation overlying the sub-recent formation consists of some 50m thick dune sand. This sand is fine to medium grained, yellowish grey in colour containing sub-rounded and moderately sorted grains of ferromagnesian minerals. Figure 5 shows the stratigraphic section and lithology of the Thar coalfield.

6.3. Ground water regime in Thar lignite prospect

There are three aquifers present in the Thar area as follows:

a) Top aquifer

It is located at the base of dune sand and stretches out all over the Thar Desert. In the mining area, this aquifer shows a water column of up to 5 meters. The water table is about 10 to 12m above sea level. Permeability is around $3x10^{-7}$m/s.

b) Intermediate aquifer

This aquifer scattered as lenses in sub-recent and Bara formation. Permeability varies between 10^{-5} to 10^{-7} m/s. Ground water in this aquifer is about 10-20m above sea level.

c) Bottom aquifer

This aquifer is located beneath the coal formation down to the granite base. This is the most dominant aquifer in terms of thickness, lateral extension and permeability. The top of this aquifer starts some meters below the coal sequence, the grain size of the sand varies from fine to coarse. Thickness of this aquifer in the mining area is around 50 – 60m that becomes larger in the West compared to that in the East as the granite basement is submerging to the West. This aquifer is under high pressure and the pressure head is around 25m above sea level. This aquifer is of special importance when opening the mine, as it has to be de-pressurized in advance of reaching the mining depth of about 100m. Otherwise, floor rupture would occur followed by flooding of the mine and collapse of the high wall slopes. Therefore, it is necessary to know the horizontal extent of this aquifer and the thickness as well as transmissibility. This aquifer covers an area of about 15,000 km^2. The aquifer is not homogenous with respect to permeability.

Mine dewatering arrangements comprise of the following main elements (Figure 6).

1. Surface dewatering ditches to divert water from the surface hydrological cycle.
2. First stage well points to dewater unconfined aquifer
3. Second stage well points to depressurize intermediate aquifer
4. Third stage pumping wells to depressurize the base aquifer.

6.4. Design of surface drainage ditch

A review of the rainfall data from Mithi district indicates that a daily maximum precipitation of around 100mm/day is expected during the months of July and August. This will lead to a certain flooding of the lower most mine bench without hampering the mining operations on the upper benches. It is expected that during unexpected rainfall the entire operations of mine may close down for a period of two day. The peak flow to the surface drainage system can be calculated, using the rational formula, as follows [8]:

$$Q = 2.78 \text{ K A I} = 2.78 \times 463.77 \times 0.58 \times 100 = 7.5 \times 10^4 \text{ litres/s}$$

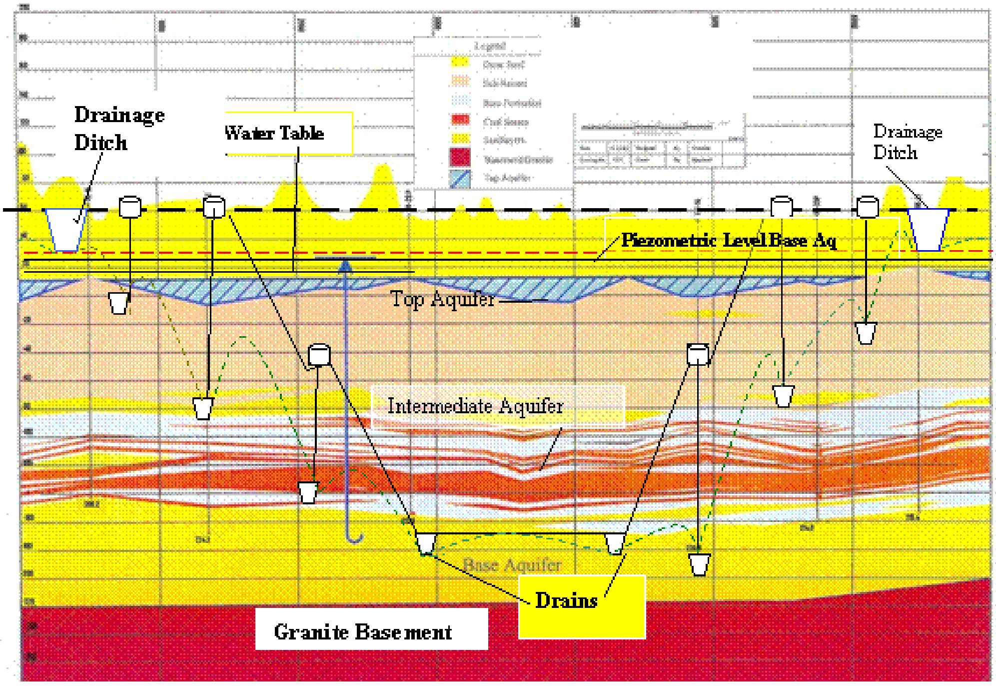


Figure 6. Ground water regime and dewatering arrangement of Thar Lignite prospects [7]

Where
Q = Peak flow in litres/s
A= Catchment area in hectares= 463.77 hectares
K= run-off co-efficient in decimal=0.58
I= rainfall intensity in mm/h=100mm/h

6.5. Prediction of aquifers pumping rates

Pumping rates of various aquifers for the Thar prospect have been calculated using the equivalent well approach by [9] as summarized in Table 1.

In order to lower the water table of the top aquifer 77 wells are being operated. The borehole pumps have working life of 10 years after which time each have to be replaced. The Pump specifications for the top aquifer are 15mm submersible motor pumps type, Grudfos SP 30 pump with capacity 14 litres at about 40 m delivery height. For lower unconfined or leaky aquifers high head borehole pumps are required.

6.6. Water quality assessment of Thar aquifers

Samples from top aquifer were collected from shallow water wells where as two bore holes, RE-51 and RE-52 were drilled to the depth of bottom aquifer and water samples were collected. Water samples were analysed in the local GSP laboratory which has a well established expertise in analysing and interpreting water quality results. PH value was determined using a PH meter. Conductivity + TDS meter was used to determine total dissolved solids and conductivity of the water sample. A spectrophotometer was used to determine the hardness and ions of various elements.

6.5.1. Presentation of water analysis results

The water quality results of Thar Aquifers include pH values, Conductivity in µs/com, total dissolved solids in ppm, total hardness (calcite hardness) and concentration of anions and cations in mg/l. Altogether, samples from Base and Top Aquifers and Indus River at Naukot are taken for analysis. The ion concentrations of various water samples in meq/I can be calculated from mg/l values by using the following equation:

Table 1. Dewatering predictions of Thar Aquifersusing equivalent well approach [9]

Aquifer Characteristics	Pumping calculations	Results
Top aquifer Aquifer thickness L= 5m Drawdown D = 20m Drawdown radius r = 1100m Radius of influence R = 1300m k= 3 x10 $^{-7}$ m/s = 0.0259 m/d T = 0.0259 x5 = 0.13m ^{2}/d h= 12m H=20	Unconfined steady state linear aquifer Modified Dupuit (1863) Equation [10]: $Q=\frac{\pi k\left(H^2-h^2\right)}{\ln\left\{\frac{R}{r}\right\}}$ $=\frac{3.14\,x\,0.0259\,x\left(20^2-12^2\right)}{\ln\left\{\frac{1300}{1100}\right\}}=\frac{21}{0.18}$	=120 m^3/d
Intermediate aquifer Scattered lenses K= 10^{-6} m/s = 0.086 m/d Draw down required D = 80+20 = 100m Thickness of aquifer L= 10m Radius at draw down r = 1050m Radius of influence R= 2500m	$Q=\frac{2\pi kLD}{\ln\left\{\frac{R}{r}\right\}-\frac{n}{2}}$ Peterson Equation $=\frac{2\,x\,\pi\,x\,0.86\,x\,10\,x\,100}{\ln\left\{\frac{2500}{1050}\right\}-\frac{0.5}{2}}$ [11]	=5.4x100/0.37 =1469 m^3/d =0.1 m^3/min =17 l/min
Base Aquifers k=1.3 x10 $^{-4}$m/s=0.00013m/s =11.23m/d Draw down =205+55=260m Aquifer thickness L=55m Radius of draw down r=750m Radius of influence R= 2050m (assumed) n=0.5	$Q=\frac{2\pi kLD}{l_n\left\{\frac{R}{r}\right\}-\frac{n}{2}}$ Peterson Equation (1954) $\frac{2\,x\,3.14\,x\,0.0029\ x\,60\,x\,60\,x\,24\,x\,55\,x\,260}{\ln\left\{\frac{2050}{750}\right\}-\frac{0.5}{2}}$ $=\frac{1.7\,x\,10^7}{1.005-0.25}$	=2.2 x10 ^{7} m^3/day

$$meq/l = \frac{mg/l \ x \ valency}{Formula weight} = \frac{mg/l}{Equivalent \ weight}$$

Atomic weight, molecular weight, valency, and equivalent weights of the most common ions are presented in Table 2.

Water analyses results of 10 aquifer samples and one discharge point samples are shown in Table 3 to 5.

Water analyses results of 10 aquifer samples and one discharge point samples are shown in Table 3 to 5.

The results of water quality of 9 aquifer samples in meq/litre are given in Table 3. The cat ions of water samples determined were sodium, potassium, magnesium and calcium along with soluble iron and manganese. The anion evaluated were chlorides, bi-carbonates, nitrates and suphates. The accuracy of many water samples is readily checked as the solution must be electrically neutral. Thus, the sum of cat ions in meq/l should be equal to sum of anions in meq/l expressed as a percentage. If the balance is < 5% the analysis is determined to be good. The results in Table 4 indicate that 4 samples have a desirable degree of accuracy while 3 samples have an accuracy of 5 to 10%, one between 10-20% and two between 20-30%. Table 4 also shows the ratio of sodium and total cat ions as 'X' co-ordinate and ratio of magnesium and the sum of (Mg^{+++}+ Ca^{++}) as "Y' co-ordinates.

Figure 6 shows the plot of (X,Y) co-ordinates in a triangular graph which is an equivalent triangle of suitable dimension. The apex of the triangle represents sodium peak and the left of the base of the triangle represents calcium and the right hand corner of the triangle magnesium. The left hand side of the triangle is dividedhinotor10oparts and horizontal lines are drawn from it representing Na/Σ Cat ions plotted in milli-equivalents. The base of the triangle is divided in ten equal parts and labeled 0.1 to 1.0.Lines are drawn from the peak of the triangle to the various points on the base of the triangle, thus forming a triangular graph shown in Figure 6. Additional information regarding pH, Total dissolved solids, the ratio of major ions (Cl-/SO4-2) , percentage error in ionic balance and co-ordinates of cations and anions to be displayed on a Piper diagram for analysis.

The triangular graph method permits to distinguish water from different sources. Dilution of water can also be shown by moving the co-ordinates of first water towards the source of dilution. Table 5 shows the concentration of cations like Mg, Ca and (Na+ K) and anions sulphate, bi-carbonates + carbonates and chloride in percentage milli-equivalents. This table also shows Cl^{-1}/SO_4^{-2} ratio, percentage error in ionic

The results of water quality of 9 aquifer samples in meq/litre are given in Table 3. The cat ions of water samples determined were sodium, potassium, magnesium and calcium along with soluble iron and manganese. The anion evaluated were chlorides, bi-carbonates, nitrates and suphates. The accuracy of many water samples is readily checked as the solution must be electrically neutral. Thus, the sum of cat ions in meq/l should be equal to sum of anions in meq/l expressed as a percentage. If the balance is < 5% t

Table 2. Atomic, Molecular and Equivalent weights and valency

Species	Atomic or Molecular weight	Valency	Equivalent Weight	Partial molar volume
Na	22.99	1	22.99	-1.5
K	39.102	1	39.102	8.7
Li	6.939	1	6.939	-34
Ca	40.08	2	20.04	
Mg	24.13	2	12.156	
Sr	87.62	2	43.81	
Ba	137.32	2	68.67	
Fe^2	55.85	2	27.92	0
Cl	35.45	-1	35.45	18.1
F	19	-1	19	-2.1
NO_2	62	-1	60	29.3
SO_4	96.06	-2	48.03	14.5
HCO_3	61.016	-1	61.016	
CO_3	60.08	-2	30.004	-3.7
SiO_2	60.09	0	0	
N	14.007			
O	16			
$CaCO_3$	100.008		50.044	

Table 3. Water quality results of Thar aquifers in mg/l

Parameters		Base aquifer			Top aquifer						Indus River
		RE51 Well A	RE52 Wel B	RE53 Well C	Varyai 1 D	Varyai 2 E	Tilyai 1 F	Tilyai 2 G	Khario3 H	Khario 4 I	Naukot J
pH value		7.21	7.2	7.51	8.5	8.3	8.32	8.17	8.13	8.22	8.06
Conductivity	µs/com	10930	10860	14750	6180	6840	15700	21200	11990	7680	450
Total Diss. Solids	TDS ppm	7660	7500	10200	4220	4790	11114	14800	8390	4464	310
Total Hardness	CaO_3	860	8201	1640	180	228	344	506	740	175	130
Ca^{++} mg/l	Mg/l	152	174	206	8	14	40	60	88	10	26
Magnesium	M_g^{++} mg/l	138	112	350	32	68	75	104	151	40	16
Sodium	Na^+ mg/l	1620	1702	2182	1012	1440	2640	3520	1785	11284	26
Potassium	K^+mg/l	26	27	80	40	60	40	70	40	53	6
Soluble Iron	Fe^{++} mg/l	0.5	0.06	0.16	0.1	0.05	0.04	0.04	0.02	0.07	0.14
Manganese	Mn^{++} mg/l	0.35	traces	0.25	0.38	Traces	0.65	1.28	0.12	Traces	0.02
Total cation	**mg/l**	**1936.9**	**2552**		**1233**	**1729**	**2775.69**	**3755.6**	**2064.14**	**1387.07**	**163**
Chloride	cl^{-1} mg/l	2760	2680	3380	1580	2162	3380	4680	2620	2190	18
Bicarbonate	$HCO_{3\ mg/l}$	240	250	348	456	480	580	768	216	444	120
Nitrate	$NO_{3\ mg/l}$	44	54	178	52	52	20	35	155	58	4
Sulphate	SO_4^{--}mg/l	210	180	450	180	278	488	608	430	240	40
Total An ions	**mg/l**	**3262**	**3202**		**2322**	**2995**	**4968**	**6091**	**3421**	**2932**	**182**
Cl^{-1}/ SO_4 ratio		13.1	14.9	7.5	8.8	7.8	6.9	7.7	6.1	9.1	0.45

Table 4. Water Quality results of Thar Aquifers (in meq/l)

Parameters		Base aquifer			Top aquifer						Indus River
		RE51 Well A	RE52 Well B	RE53 Well C	Varvai 1 D	Varvai 2 E	Tilvai 1 F	Tilvai 2 G	Khario3 H	Khario 4 I	Naukot J
pH value		7.21	7.2	7.51	8.5	8.3	8.32	8.17	8.13	8.22	8.06
Conductivity	µs/com	10930	10860	14750	6180	6840	15700	21200	11990	7680	450
Total Diss. Solids	TDS ppm	7660	7500	10200	4220	4790	11114	14800	8390	4464	310
Total Hardness	CaO_3	860	8201	1640	180	228	344	506	740	175	130
Ca^{**} mg/l	%meq/l	7.58	8.7	10.28	0.399	0.69	2.00	2.99	4.39	0.499	1.3
Magnesium	$M_g^{++\%}$meq/l	11.35	8.88	28.79	2.63	55.94	5.97	8.55	12.42	3.29	1.31
Sodium	$Na^{+\%}$meq/l	70.43	74.00	94.87	44.00	65.24	113.9	153.04	77.6	55.82	1.13
Pottasium	$K^{+\%}$meq/l	0.66	0.69	2.05	1.032	1.538	1.02	1.79	1.02	1.35	0.15
Soluble Iron	Fe^{++} % meq/l	0.07	0	0.0086	0.006	0	0.002	0.002	0.00644	0.0037	0.0075
Manganese	$Mn^{++\%}$meq/l	0.012	traces	0.009	0.013	traces	0.0236	0.0046	0.0043	traces	0.00072
Total cation		**90.06**	**92.27**	**136.01**	**48.07**	**123.41**	**122.92**	**166.37**	**95.340**	**60.96**	**3.9**
Chloride	$cl^{-1\%}$meq/l	77.53	75.28	94.94	44.38	61.14	108.99	131.46	73.50	61.58	0.05
Bicarbonate	$HCO_{3\%}$mg/l	4.06	4.09	5.67	7.47	7.87	95.05	12.58	3.54	7.28	1.97
Nitrate	$NO_{3\%}$meq/l	0.73	0.9	2.96	0.87	0.86	0.33	0.58	2.58	0.966	0.07
Sulphate	$SO_4^{--\%}$ meq/l	4.37	3.75	9.37	3.75	5.79	10.16	12.66	8.95	5.0	0.82
Total An ions		**86.69**	**84.02**	**112.95**	**56.47**	**75.66**	**214.53**	**157.28**	**88.57**	**74.83**	**3.36**
Cl^{-1}/SO_4 ratio		13.14	14.88	7.5	11.83	7.787	7.95	7.7	10.88	9.125	0.45
% Error		1.9%	4.7%	9.25%	9.5%	22.9%	27.1%	2.82%	3.73%	10.2%	7.29%
X=		**0.6**	**0.505**	**0.74**	**0.87**	**0.988**	**0.75**	**0.74**	**0.74**	**0.87**	**0.5**
Y=		**0.78**	**0.801**	**0.71**	**0.915**	**0.535**	**0.93**	**0.92**	**0.81**	**0.94**	**0.28**

Table 5. Water Quality results of Thar Aquifers (% meq/l)

Parameters		Base aquifer			Top aquifer						
		RE51 Well A	RE52 Well B	RE53 Well C	Varvai 1 D	Varvai 2 E	Tilvai 1 F	Tilvai 2 G	Khario3 H	Khario4 I	Indus River Naukot J
pH value		7.21	7.2	7.51	8.5	8.3	8.32	8.17	8.13	8.22	8.06
Conductivity	µs/com	10930	10860	14750	6180	6840	15700	21200	11990	7680	450
Total Diss. Solids	TDS ppm	7660	7500	10200	4220	4790	11114	14800	8390	4464	310
Total Hardness	CaO_3	860	8201	1640	180	228	344	506	740	175	130
Ca^{**} mg/l	%meq/l	8.42%	9.42%	7.56%	0.82	0.56	1.67	1.8%	4.6%	0.82%	33.35%
Magnesium	$M_g^{++\%}$meq/l	12.60%	9.62%	21.17%	5.40	45.33	4.86	5.14%	13.02%	5.40%	33.60%
Sodium	$Na^{+\%}$meq/l	78.54%	80.20%	69.75%	90.34	52.88	92.66	91.98%	81.39%	91.56%	28.98%
Pottasium	$K^{+\%}$meq/l	0.73%	0.75%	1.51%	2.09	1.25	0.83	1.07%	1.07%	2.13%	0.19%
Soluble Iron	Fe^{++} % meq/l	0.08%	Traces	0.006%	0.01	0	0.0016	0.001%	0.007%	0.006%	0.018%
Manganese	Mn^{++} meq/l	0.013%	Traces	0.006%	0.03	0	0.019	0.003	0.005%	0	0%
Total cation		**90.06**	**92.27**	**136.01**	**48.07**	**123.41**	**122.92**	**166.40**	**95.435**	**60.96**	**3.9**
Chloride	$cl^{-1\%}$meq/l	89.43%	89.6%	83.22%	78.53%	80.7%	50.80%	83.58%	82.98%	82.29%	14.88%
Bicarbonate	$HCO_{3\,\%}$mg/l	4.68%	4.87%	5.02%	13.23%	10.4%	44.31%	8.0%	9.73%	9.73%	58.63%
Nitrate	$NO_{3\,\%}$meq/l	0.84%	1.07%	2.62%	1.54%	1.14%	0.15%	0.37%	1.25%	1.25%	2.08%
Sulphate	SO_4^{--} meq/l	5.04%	4.46%	8.3	6.64%	7.65%	4.74%	8.04%	6.68%	6.68%	24.40%
Total An ions		**86.69**	**84.02**	**112.95**	**56.47**	**75.66**	**214.53**	**157.28**	**88.57**	**74.83**	**3.34**
Cl^{-1}/ SO_4 ratio		13.14	14.88	7.5	11.83	7.787	7.95	7.7	10.88	9.125	0.45
% error in Bal		1.9%	4.7%	9.26%	8.04%	23.99%	27.1%	2.82%	3.73%	10.2%	7.29%
CO-ordinates	Ca,Mg,Na	8, 13, 79	8, 8, 74	8, 21, 71	1, 6, 93	1, 45, 54	1, 5, 94	2, 5, 93	5,13,82	1, 6, 93	33,34,33
	Cl^{-1}, HCO_3, SO_4	89, 6, 5	90, 5,5	84, 8, 8	78,15,7	81,11, 8	51, 44,5	84, 8, 8	83,10,7	83, 10, 7	15, 60,25
			Saline Water				Saline Water				Per. Hard Water

The results of water quality of 9 aquifer samples in meq/litre are given in Table 3. The cat ions of water samples determined were sodium, potassium, magnesium and calcium along with soluble iron and manganese. The anion evaluated were chlorides, bi-carbonates, nitrates and suphates. The accuracy of many water samples is readily checked as the solution must be electrically neutral. Thus, the sum of cat ions in meq/l should be equal to sum of anions in meq/l expressed as a percentage. If the balance is < 5% the analysis is determined to be good. The results in Table 4 indicate that 4 samples have a desirable degree of accuracy while 3 samples have an accuracy of 5 to 10%, one between 10-20% and two between 20-30%. Table 4 also shows the ratio of sodium and total cat ions as 'X' co-ordinate and ratio of magnesium and the sum of (Mg^{+++}+ Ca^{++}) as "Y' co-ordinates.

Figure 6 shows the plot of (X,Y) co-ordinates in a triangular graph which is an equivalent triangle of suitable dimension. The apex of the triangle represents sodium peak and the left of the base of the triangle represents calcium and the right hand corner of the triangle magnesium. The left hand side of the triangle is dividedhinotor10oparts and horizontal lines are drawn from it representing Na/Σ Cat ions plotted in milli-equivalents. The base of the triangle is divided in ten equal parts and labeled 0.1 to 1.0.Lines are drawn from the peak of the triangle to the various points on the base of the triangle, thus forming a triangular graph shown in Figure 6. Additional information regarding pH, Total dissolved solids, the ratio of major ions (Cl-/SO4-2) , percentage error in ionic balance and co-ordinates of cations and anions to be displayed on a Piper diagram for analysis

The triangular graph method permits to distinguish water from different sources. Dilution of water can also be shown by moving the co-ordinates of first water towards the source of dilution. Table 5 shows the concentration of cations like Mg, Ca and (Na+ K) and anions sulphate, bi-carbonates + carbonates and chloride in percentage milli-equivalents. This table also shows Cl-1/SO4-2 ratio, percentage error in ionic balance and

6.5.2. Triangular graph method

The results of nine aquifer samples and mine water discharge at Sindh river are shown in Figure 7 which indicates three groups of water. It can be seen that the water from top aquifer is grouped near the peak of Figure 7 whereas from base aquifer are grouped near middle of the graph. It can be clearly observed that the sample H from top aquifer at Khario 3 is being diluted by the Base aquifer which is a confined aquifer with a high hydraulic head indicated by the pizometric surface. Water from Sindh river, which is receiver of mine water discharge, is shown near the centre of the graph.

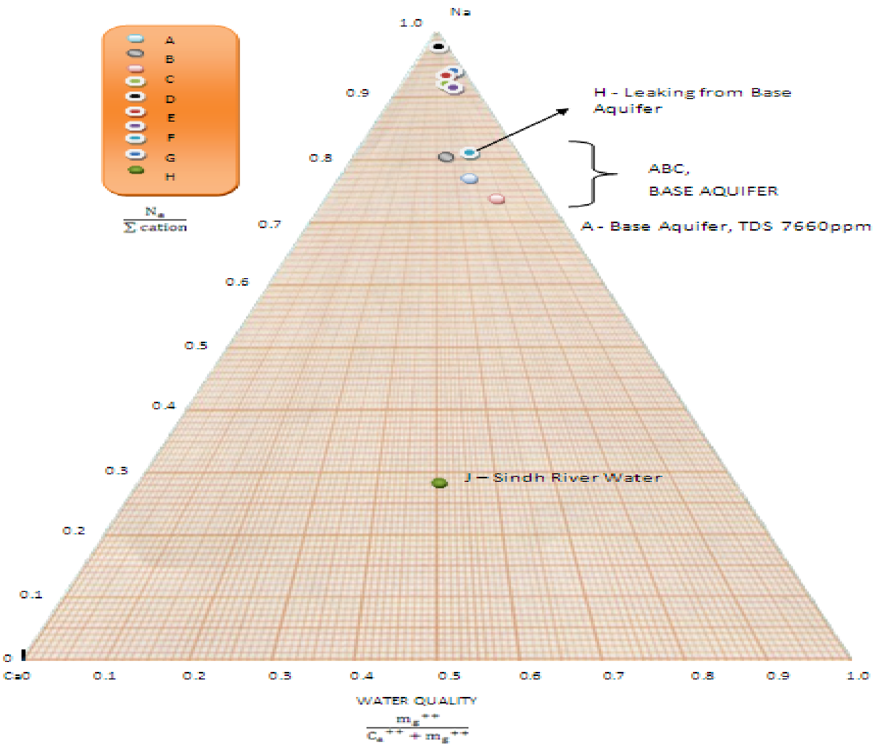


Figure 7. Characterization of aquifer and mine water discharge in Thar Lignite Prospect

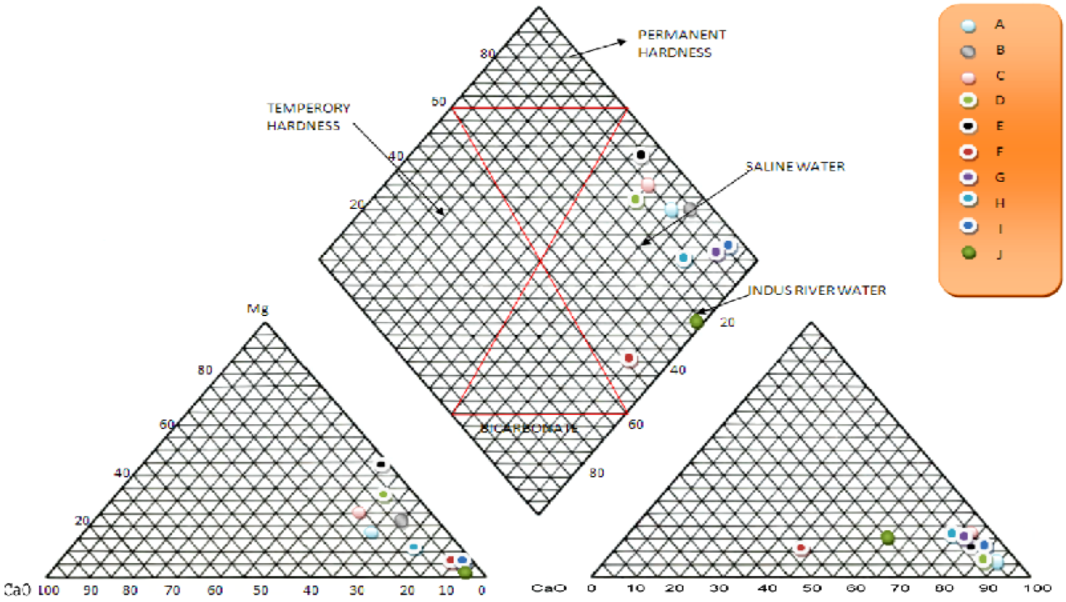


Figure 8. Classification of aquifer water in Thar Lignite Prospect

6.5.3- Piper Diagram

Figure 8 shows the water quality results on a Piper diagram [12], which comprises three separate diagrams arranged in a group. Two triangular diagrams are used to plot cat ions and anions concentrations in meq/l separately and a quardrilateral field defines the quality specifying the chemical nature of the water. It can be appreciated that cation triangle plots the concentration of Mg, Ca and (Na+K) in meq/litre: Mg being on the apex, Ca on the left hand corner and (Na + K) on the right hand corner of the triangle in milli-equivalents/litre. Similarly, in the anion triangle sulphate, (bicarbonate+carbonates) and chlorides co-ordinates are plotted. The anions or cations plotted in the Piper diagrams are assumed to be 100% in the three corners of the traingles. An inter-section of two stright lines projecting from the cation and a anion of a chemical on the quality quadrilateral field defines the chemical nature of water. A water can also be defined as a temporary or permanently hard water or saline or carbonate/ bicarbonate water of sodium or calcium. The Piper diagram can be used to plot chemical abundance of cations and anions, can classify water, define path way of chemical evolution of ground water and can indicate dilution of water from stream or river.

Figure 8 shows the plot of water samples A, B and C from the base aquifer and D to I from the top aquifer that are classifies as saline water. Water sample J fom Sindh river discharge point is also a saline water with more (carbonate and bicarbonate) + sulphate. Table 5 indicates that water “A’ from RE51 well, water “B” from RE 52 well, water sample ‘G’ from Tilvai 2 and water “H” from Khario3 are to be accepted for their accuracy <5%. The accuracy in chemical analyses of other water samples vary between 7.3% to 23.99% and consequently, are unacceptable.

6.6. Suggestions for water treatment

Ground water analyses results show that total dissolved solids in the ground water from Thar prospect contains TDS between 4200 and 15000 ppm. and consequently, water is classified as a saline (brackish water). The results in Table 3 also indicate that most water from Thar aquifers is classed as very hard or hard water and it is not suitable for human consumption before treatment. It is suggested that the ground water at the first instance should be treated in a large infiltration pond near the open pit. As soon as a power plant comes into commission, a desalination plant will be necessary to be installed to treat the aquifer water to improve the quality of water to the accepted drinking standards. A detailed study is needed to select an appropriate and cost effective method for water treatment.

7. Conclusions

From the above discussions the following conclusions can be made:

- The aquifer water from the Thar lignite prospect can be classed as sodium+ potassium – chloride water. This water is also grouped as hard to very hard water having the calcite hardness varying between 175 to 8201 mg/L . The ground water is also unsuitable for irrigating crops because of TDS contents exceeding 700 mg/L. Thus, the ground water at Thar needs desalinization to improve its quality to a potable standard.

- Results in the triangular diagram show that Khario 3 water sample is being inadvertently diluted by the base aquifer water.
- The chemical analyses results in Tables 3 and 4 indicate that many analyses do not comply with the charge balance of cat ions with anions concentration and consequently, the results are not acceptable for further considerations.

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