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WATER RESOURCES ASSESSMENT ASSOCIATED WITH LIGNITE OPERATIONS IN THAR, SINDH, PAKISTAN

OCENA ZASOBÓW WODNYCH ZWIĄZANA Z WYDOBYCIEM WĘGLA BRUNATNEGO W THAR, SINDH, PAKISTAN

Major lignite deposits, all over the World are associated with unconfined and confined aquifers. This creates hydrogeological issues with a range of operational, safety and environmental problems associatedb with lignite mining. Ground water and surface water create a range of problems in lignite mining utilizing surface mining methods. The paper discusses a method of ground water control in a multi-aquifer environment in mining lignite using borehole pumps to dewater the mining operations. The technique will increase the slope stability and will present environmentally friendly solutions. The paper describes a proposed solution for the Thar lignite deposit in Sindh, Pakistan that has total reserves of 192 Bt. The water extracted for safe and economic mining operation can be used after treatment to provide a beneficial water regime to support human and agricultural development in an extremely arid climate. The paper also presents a proposed method of dewatering the Thar prospect together with an assessment of the quality of aquifer water.

A series of boreholes were drilled to intersect lignite seams and surrounding aquifers to obtain water samples to determine their physical and chemical characteristics. The ground water assessments indicated that the saline water can be classified as brackish water with total dissolved solids contents ranging from 1000 to 20,000 mg/L, containing sodium and potassium chloride water. This water could be treated for industrial or agricultural purposes and for carrying out mining operations and supporting local inhabitants because it does not contain heavy and toxic metals such as arsenic, lead, mercury, or cyanides. However, results indicate that groundwater from a few locations contained traces of silver <4 ppb and zinc <0.1 ppm.

Keywords: Open cut mining, hydrogeology, aquifers, lignite, advanced dewatering, Piper diagram

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Na całym świecie złożom węgla brunatnego towarzyszą zamknięte lub otwarte formacje wodonośne. Stwarza to szereg problemów hydrogeologicznych, związanych z prowadzeniem działalności górniczej, jej bezpieczeństwem oraz w aspekcie ochrony środowiska. Wody gruntowe i podziemne stwarzają szereg problemów w trakcie prowadzenia wydobycia, zwłaszcza przy stosowaniu metod odkrywkowych. Artykuł ten przedstawia metodę usuwania wód gruntowych w przypadku formacji wodonośnych przy użyciu pomp głębinowych w celu odwodnienia terenu operacji górniczych. Technika ta poprawia także stabilność skarpy, dając rozwiązania przyjazne dla środowiska. Artykuł opisuje proponowane rozwiązanie opracowane dla złoża węgla brunatnego Thar w Sindh, w Pakistanie. Całkowite zasoby złoża to 192 Bt. Woda wypompowana w celu zabezpieczenia operacji górniczych może po oczyszczeniu zostać ponownie wykorzystanie dla potrzeb ludzkich, na przykład w rolnictwie w tym jakże suchym klimacie. Artykuł przedstawia także metodę odwodnienia złoża w Thar, wraz z oceną jakości wody.

Wywiercono szereg otworów przecinających pokłady lignitu i otaczające je pokłady wodonośne dla uzyskania próbek wody, aby określić jakie procesy oczyszczania chemicznego i fizycznego będą niezbędne. Ocena wody gruntowej wykazała, że woda słona może zostać sklasyfikowana jako woda słonawa zawierająca rozpuszczone substancje stałe w ilości od 1000 do 20 000 mg/L, w tym chlorki sodu i potasu. Woda ta może podlec oczyszczeniu i zostać ponownie wykorzystana do celów przemysłowych lub rolniczych oraz do prowadzenia prac wydobywczych a także na użytek lokalnych mieszkańców ponieważ nie zawiera metali ciężkich ani toksycznych, takich jak arsen, ołów, rtęć lub cyjanki. Jednakże wyniki analizy wskazują, że wody gruntowe z niektórych lokalizacji zawierać mogą śladowe ilości srebra <4 ppb oraz cynku <0.1 ppm.

Słowa kluczowe: górnictwo odkrywkowe, hydrogeologia, formacje wodonośne, lignity, odwodnienie, schemat orurowania

1. Introduction

The mining of lignite deposits is normally associated with complex hydrogeological environments resulting in a need for dewatering operations causing a range of water problems reducing production and influencing utilization costs together with slope stability issues. The paper outlines a proposed method to dewater the Thar lignite deposit in Sindh, Pakistan which has lignite reserves of some 192 Billion tons. The paper suggests advance borehole dewatering technique as the most economic solution based on current information on the deposit. It proposes that water control treatment be implemented for use in the mining operations also importantly to help sustain local inhabitants in terms of agricultural in the extreme arid environment in the Thar Desert area of Sindh, Pakistan. A feasibility study has been undertaken and a series of boreholes have been sunk to determine the deposit configurations and appropriate water samples extracted (Pathan et al., 2006). The water samples from these aquifers were laboratory analyzed for evaluating their physical and chemical characteristics including pH value, conductivity and TDS (total dissolved solids). A spectrophotometer was used to determine the hardness and ions concentration of various elements in mg/L. The test results were analysed and interpreted by using Triangular graph and Piper diagram.

2. Water problems in lignite mining

The range of water problems in 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, and/or 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 ensure dry conditions using advanced dewatering of rock mass around the lignite open cut by borehole pumping.

3. Rock mass dewatering methods for lignite seams

Advanced dewatering of rock mass around surface lignite mines can be carried out by the well point system for unconsolidated sediments and by vertical dewatering wells for unconfined, confined and leaky aquifers (Fig. 1). Conventional and vacuum well point systems are used to dewater unconsolidated sediments which comprise of 37-50 mm diameter and 0.6 to 1.5 m long riser pipes (Fig. 1a). These riser pipes are connected to a common header and pumped by a single or multiple well point pumps which are a combination of centrifugal and vacuum pumps being capable of lowering the water levels by 5-6 m. For greater lifts, multistage well points, jet ejector or deep well systems are more effective.

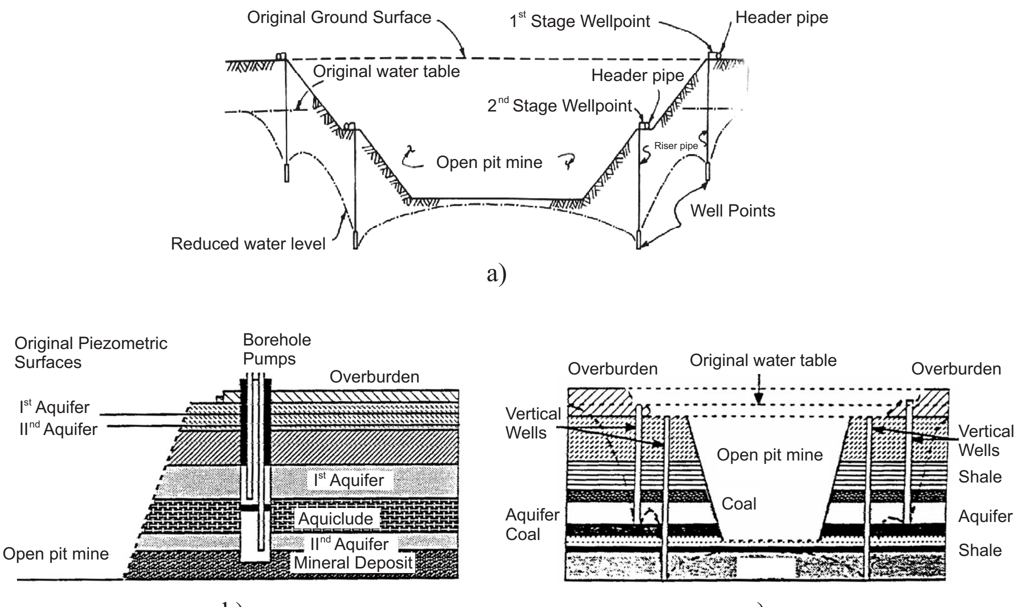


Fig. 1. Rock mass dewatering systems for lignite mines.
a) Two stage well point system; b) Dewatering Several aquifers from one gravity flow vertical well; c) Dewatering multiple aquifers from deep vertical borehole pumping wells

In confined aquifers, a gravity flow well or an artesian flow well can be used (Fig. 1b and Fig. 1c) 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.

4. Case history analysis of Thar lignite deposit in Thar Desert, Pakistan

Pakistan has the seventh largest deposits of lignite/brown coal in the world with total lignite reserves of 192 Bt. Thar lignite/coal deposit is located in the eastern part of Sindh Province about 400 Km east of Karachi as shown in Fig. 2.

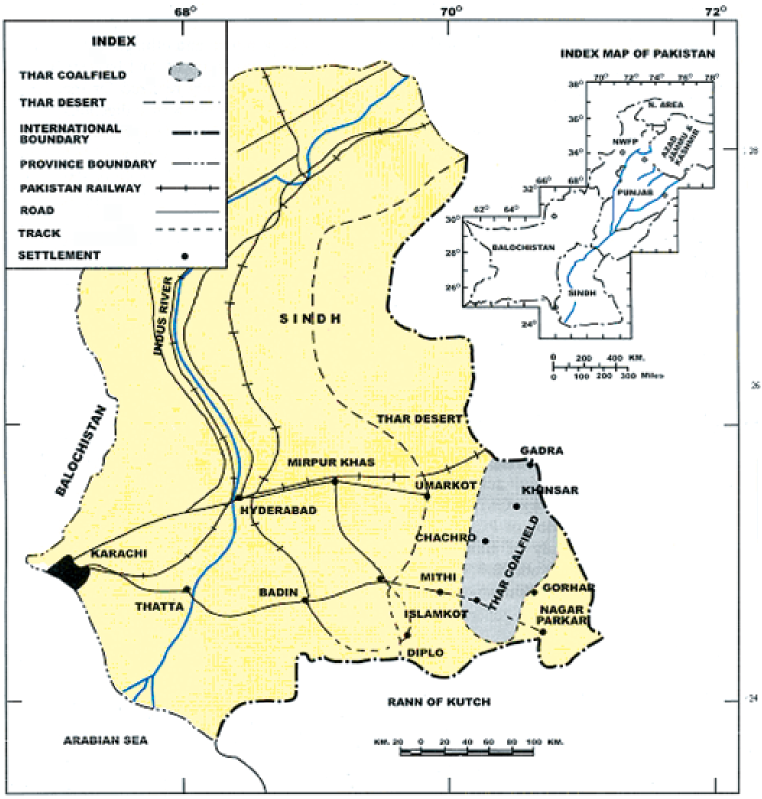


Fig. 2. Location of Thar lignite prospect, Sindh, Pakistan (R.W.E. Power International 2004)

Thar coalfield covers an area of approximately 9000 Km^2 and lignite beds lie at depths between 130 and 250 m. Cumulative seam thickness varies between 7.5 m to 36 m and the maximum thickness of an individual seam is 23 m. Geological Survey of Pakistan (GSP) and United States Geological Survey under the 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 Bt.

4.1. 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 95 m thick consisting of sandy/silty claystone and sandstone formation overlying the basement granite lying at a depth of 100 m to 220 m. 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 coal roots and pyretic resin globules overlies this sediment.

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

4.2. Ground water regime in Thar lignite prospect

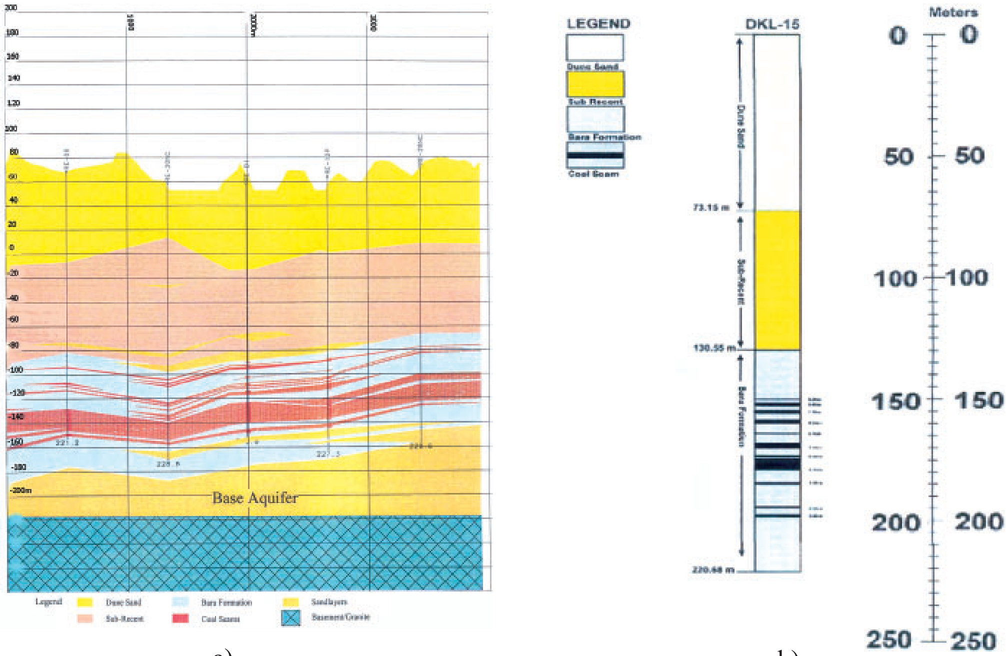
There are three aquifers present in the Thar area as follows:

4.2.1. 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 12 m above sea level. Permeability is around 3×10^{-7}m/s.

4.2.2. Intermediate aquifer

This aquifer is 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 10-20 m above sea level.



a) b)

Fig. 3. Ground water regimes in Thar lignite prospect.
a) Borehole cross section of Thar Aquifers; b) Cross-section of dewatering well

4.2.3. Bottom aquifer

This aquifer is located beneath the coal/lignite 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/lignite sequence; the grain size of the sand varies from fine to coarse. The thickness of this aquifer in the mining area is around 50-60 m and that becomes larger in the West compared to the East as the granite basement is submerging to the West. This aquifer is under high pressure and the pressure head is around 25 m above sea level. This aquifer is of special importance when opening the mine, as it has to be de-pressurized in advance of reaching mining depth of about 100 m, 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 and the aquifer is not homogenous with respect to permeability.

Mine dewatering arrangements comprise of the following main elements (Fig. 4).

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.

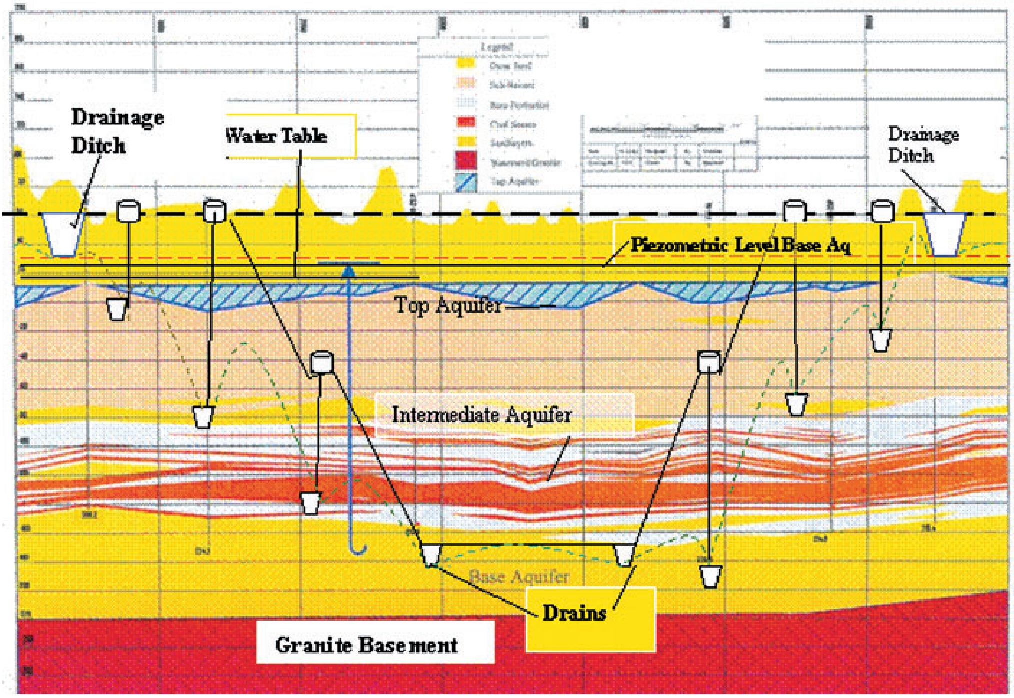


Fig. 4. Ground water regime and dewatering arrangement of Thar Lignite prospects

4.3. Design of surface drainage ditch

A review of the rainfall data from Mithi district indicates that a daily maximum precipitation of around 100 mm /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 days. The peak flow to the surface drainage system can be calculated, using the rational formula, as follows (Singh, 1992):

$$Q = 2.78\, K\, A\, I = 2.78\times463.77\times0.58\times100 = 7.5\times10^{4} \text{ litres/s}$$

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 = 100 mm/h

4.4. Prediction of aquifers pumping rates

Pumping rates of various aquifers for the Thar prospect have been calculated using the equivalent well approach by (Pathan et al., 2007) 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 a working life of 10 years after which time each has to be replaced. The pump specifications for the top aquifer are 15 mm submersible motor pumps type, Grudfos SP 30 pump with capacity 14 litres/min at about 40 m delivery height. In the case of lower unconfined or leaky aquifers high head borehole pumps are required.

TABLE 1

Dewatering predictions of Thar Aquifers using equivalent well approach (based on Pathan et al, 2007)

Aquifer Characteristics	Pumping calculations	Results
Top aquifer Aquifer thickness L = 5 m Drawdown D = 20 m Drawdown radius r = 1100 m Radius of influence R = 1300 m $k = 3\times10^{-7}$ m/s = 0.0259 m/d $T = 0.0259\times5 = 0.13$ m^2/d h = 12 m H =20	**Unconfined steady state linear aquifer** Modified Dupuit (1863) Equation: $Q = \dfrac{\pi k(H^2 - h^2)}{\ln\left\{\dfrac{R}{r}\right\}}$ $= \dfrac{3.14\,x\,0.0259\,x\,(20^2 - 12^2)}{\ln\left\{\dfrac{1300}{1100}\right\}} = \dfrac{21}{0.18}$	= 120 m^3/d
Intermediate aquifer Scattered lenses $K = 10^{-6}$ m/s = 0.086 m/d Draw down required D = 80+20 = 100 m Thickness of aquifer L = 10 m Radius at draw down r = 1050 m Radius of influence R = 2500 m	$Q = \dfrac{2\pi kLD}{\ln\left\{\dfrac{R}{r}\right\} - \dfrac{n}{2}}$ Peterson Equation $= \dfrac{2\,x\,\pi\,x\,0.86\,x\,10\,x\,100}{\ln\left\{\dfrac{2500}{1050}\right\} - \dfrac{0.5}{2}}$	= 5.4×100/0.37 = 1469 m^3/d = 0.1 m^3/min = 17 l/min
Base Aquifers $k = 1.3\times10^{-4}$ m/s = 0.00013 m/s = 11.23 m/d Draw down = 205 + 55 = 260 m Aquifer thickness L = 55 m Radius of draw down r = 750 m Radius of influence R = 2050 m (assumed) n = 0.5	$Q = \dfrac{2\pi kLD}{\ln\left\{\dfrac{R}{r}\right\} - \dfrac{n}{2}}$ Peterson Equation (1954) $\dfrac{2\,x\,3.14\,x\,0.0013\;\;x\,60\,x\,60\,x\,24\,x\,55\,x\,260}{\ln\left\{\dfrac{2050}{750}\right\} - \dfrac{0.5}{2}}$ $= \dfrac{1.008\,x\,10^6}{1.005 - 0.25}$	= 1.3×10^6 m^3/d

4.5. Water Quality Assessment of Thar Aquifers

Samples from the top aquifer were collected from shallow water wells and two bore holes, RE-51 and RE-52 were drilled to the depth of the bottom aquifer and water samples were also 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 (TDS) and conductivity of the water sample. A spectrophotometer was also used to determine the hardness and ions of various elements.

4.5.1. 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 were taken for analysis. The ion concentrations of various water samples in meq/L (mille equivalent per litre) can be calculated from mg/L values by using the following equation:

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

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

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	

Water analyses results of 9 aquifer samples and 1 discharge point sample are shown in Tables 3 to 4.

TABLE 3

Water Quality results of Thar Aquifers in mg/L and meq/L

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Table 3 Water Quality results of Thar Aquifers in mg/L and meq/L

Well System
De-watering Arrangements
Borchole Locations
Well Number
Chemical Analysis
Mining Schedule
Water Quality- Well Number
- Piper Diagram
Related Link Category

Parameters			Base aquifer						Top aquifer												Indus River	
			RE61 Well A		RE62 Well B		RE63 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	Mg/l	% meq/l	152	7.58	174	8.7	206	10.28	8	0.399	14	0.69	40	2.00	60	2.99	88	4.39	10	0.499	26	1.3
Magnesium	M_g^{++} mg/l	% meq/l	138	11.35	112	8.88	350	28.79	32	2.63	68	55.94	75	5.97	104	8.55	151	12.42	40	3.29	16	1.31
Sodium	Na^{+} mg/l	% meq/l	1620	70.43	1702	74.00	2182	94.87	1012	44.00	1440	65.24	2640	113.9	3520	153.04	1785	77.6	11284	55.82	26	1.13
Potassium	K^{+} mg/l	% meq/l	26	0.66	27	0.69	80	2.05	40	1.032	60	1.538	40	1.02	70	1.79	40	1.02	53	1.35	6	0.15
Soluble Iron	Fe^{++} mg/l	% meq/l	0.5	0.07	0.06	0	0.16	0.0086	0.1	0.006	0.05	0	0.04	0.002	0.04	0.002	0.02	0.00644	0.07	0.0037	0.14	0.0075
Manganese	Mn^{++} mg/l	% meq/l	0.35	0.012	traces	traces	0.25	0.009	0.38	0.013	Traces	traces	0.65	0.0236	1.28	0.0046	0.12	0.0043	Traces	traces	0.02	0.00072
Total cation			1938.9	90.06	2552	92.27		136.81	1233	45.87	1729	123.41	2775.89	122.92	3755.8	166.37	2064.14	95.340	1387.07	60.96	163	3.8
Chloride	cl^{-} mg/l	% meq/l	2760	77.53	2680	75.28	3380	94.94	1580	44.38	2162	61.14	3380	108.99	4680	131.46	2620	73.50	2190	61.58	18	0.05
Bicarbonate	HCO_3 mg/l	% meq/l	240	4.06	250	4.09	348	5.67	456	7.47	480	7.87	580	95.05	768	12.58	216	3.54	444	7.28	120	1.97
Nitrate	NO_3 mg/l	% meq/l	44	0.73	54	0.9	178	2.96	52	0.87	52	0.86	20	0.33	35	0.58	155	2.58	58	0.966	4	0.07
Sulphate	SO_4^{--} mg/l	% meq/l	210	4.37	180	3.75	450	9.37	180	3.75	278	5.79	488	10.16	608	12.66	430	8.95	240	5.0	40	0.82
Total An ions			3262	86.69	3202	84.02		112.95	2322	56.47	2995	75.66	4968	214.53	6091	157.28	3421	88.57	2932	74.83	182	3.36
Cl^{-}/SO_4 ratio			13.1	13.14	14.9	14.88	7.5	7.5	8.8	11.83	7.8	7.787	6.9	7.95	7.7	7.7	6.1	10.88	9.1	9.125	0.45	0.45
% Error				1.9%		4.7%		9.25%		9.5%		22.9%		27.1%		2.82%		3.73%		10.2%		7.29%
X= Y=				0.6 0.78		0.505 0.805		0.74 0.71		0.87 0.915		0.948 0.535		0.75 0.93		0.74 0.92		0.74 0.81		0.87 0.94		0.5 0.28

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TABLE 4

Water Quality results of Thar Aquifers (% meq/L)

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Table 4 Water Quality results of Thar Aquifers (% meq/L)

Well System

De-watering Arrangements

Borchole Locations

Well Number

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Water Quality- Well Number

- Piper Diagram

Related Link Category

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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%
Potassium	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 Cl^{-1}, HCO_3, SO_4	8, 13, 79 89, 6, 5	8, 8, 74 90, 5,5	8, 21, 71 84, 8, 8	1, 6, 93 78,15,7	1, 45, 54 81,11, 8	1, 5, 94 51, 44,5	2, 5, 93 84, 8, 8	5,13,82 83,10,7	1, 6, 93 83, 10, 7	33,34,33 15, 60,25
		Saline Water			Saline Water						Per Hard Water

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The results of water quality of 9 aquifer samples and 1 river sample are in mg/L and meq/L is given in Table 3. The cations 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 sulphates. The accuracy of many water samples is readily checked as the solution must be electrically neutral. Thus, the sum of cations 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 3 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 cations as the 'X' co-ordinate and ratio of magnesium and the sum of ($Mg^{+++} + Ca^{++}$) as "Y' co-ordinates.

Fig. 5 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 divided into 10 parts and horizontal lines are drawn from it representing Na/Σ cations plotted in milli-equivalents. The base of the triangle is divided into 10 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 Fig. 5. Additional information regarding pH, total dissolved solids, the ratio of major ions (Cl^{-}/SO_4^{-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 us 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 4 shows the concentration of cations like Mg, Ca and (Na + K) and anions sulphates bi-carbonates + carbonates and chloride in percentage milli-equivalents. This table also shows Cl^{-1}/SO_4^{-2} ratio, percentage error in ionic balance and co-ordinates of anions and cations to be plotted on a Piper diagram. The water quality results of Thar aquifer are discussed by using Triangular graph method and Piper diagram method in the following sub-sections.

4.5.2. Triangular graph method

The results of nine aquifer samples and mine water discharge at Sindh river are shown in Fig. 5 which indicates three groups of water. It can be seen that the water from top aquifer is grouped near the peak of Fig. 5 whereas those from the base aquifer are grouped near the 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.

4.5.3. Piper Diagram

Fig. 6 shows the water quality results on a Piper diagram (Piper, 1944), which comprises three separate diagrams arranged in a group. Two triangular diagrams are used to plot cations 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

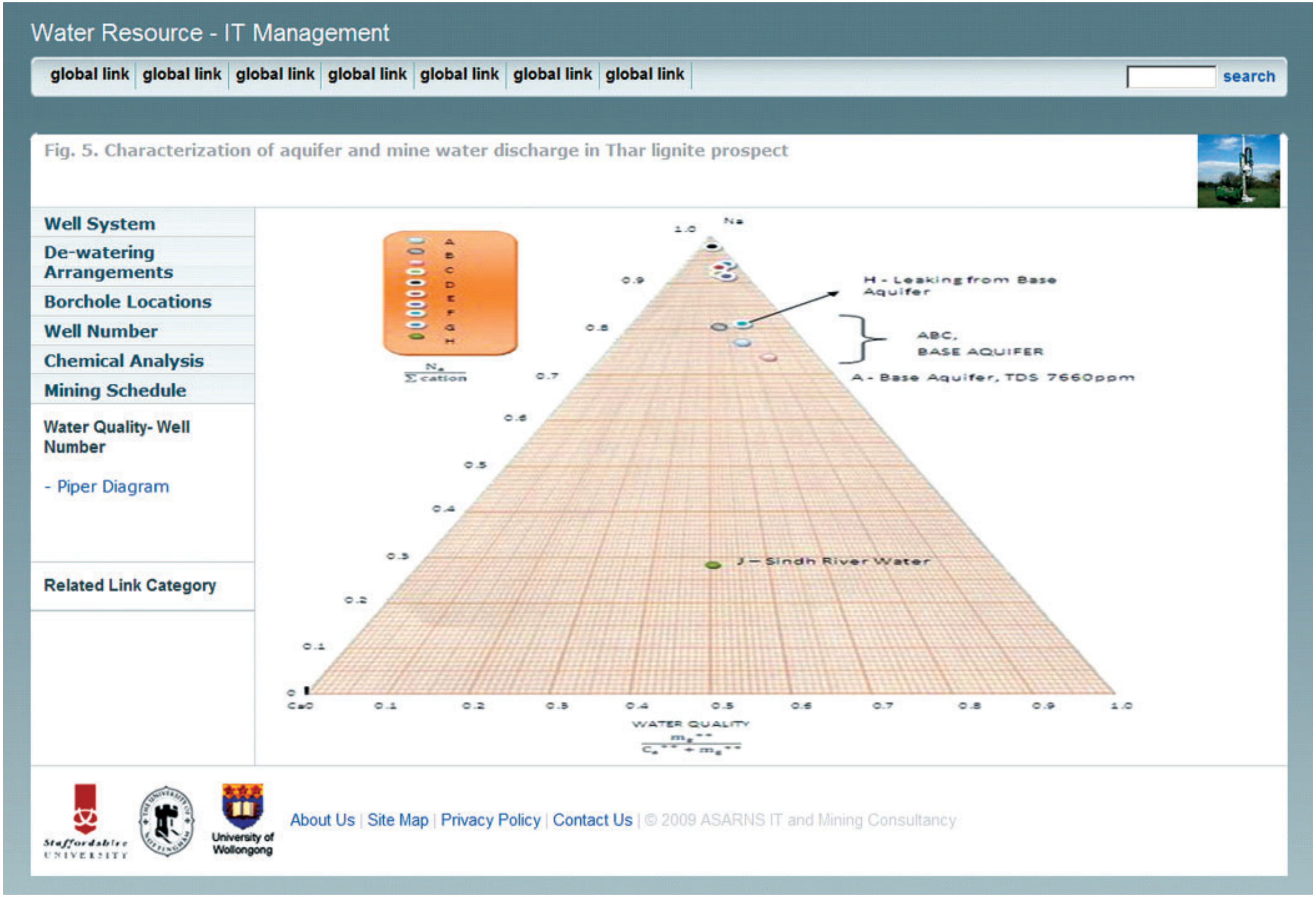

Fig. 5. Characterization of aquifer and mine water discharge in Thar lignite prospect

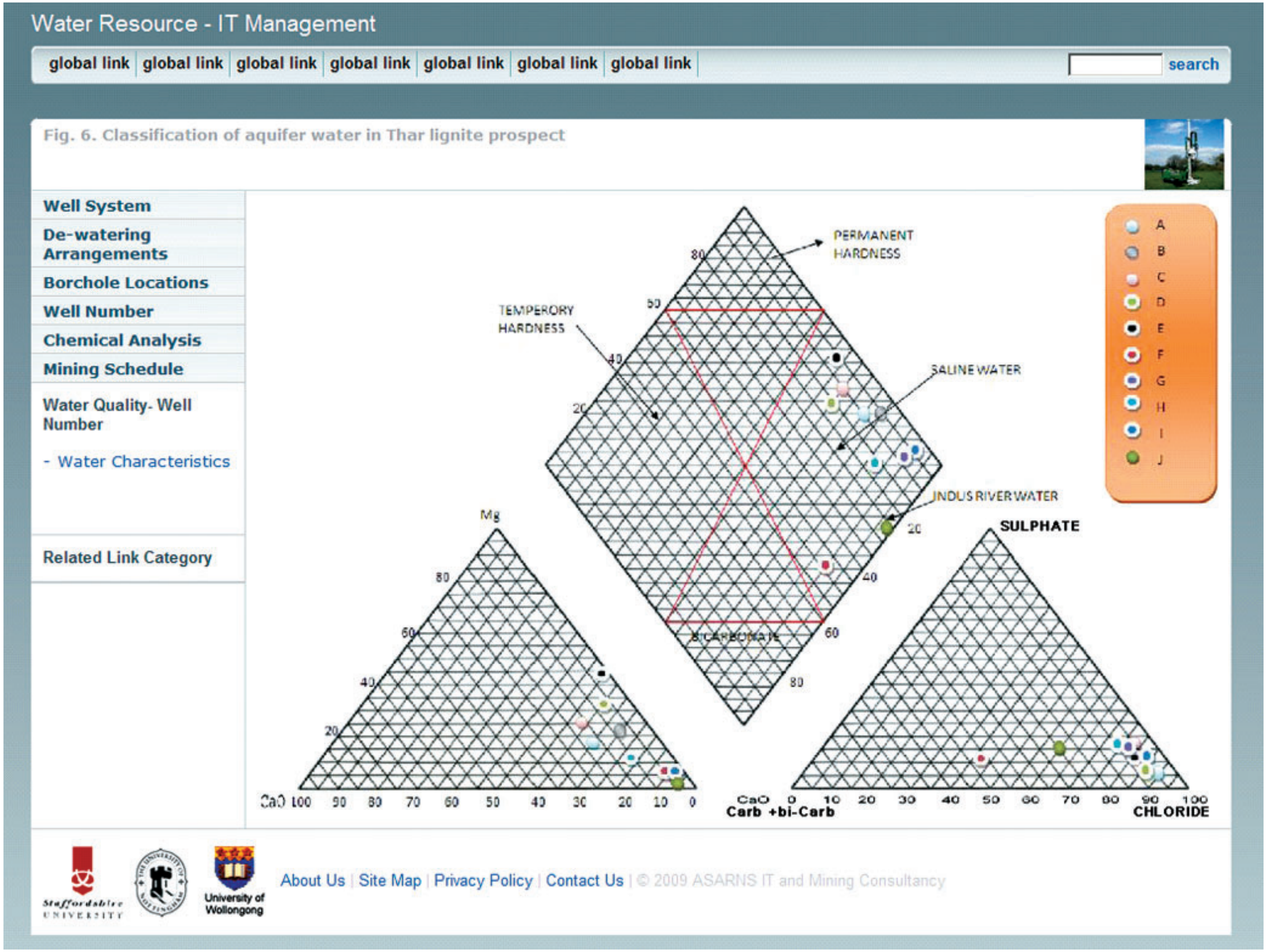

Fig. 6. Classification of aquifer water in Thar lignite prospect

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 abundunce of cations and anions, to classify water, define the path way of chemical evolution of ground water and can indicate dilution of water from stream or river.

Fig. 6 shows the plot of water samples A, B and C from the base aquifer and D to I from the top aquifer that are classified as saline water. Water sample J fom Sindh river discharge point is also a saline water with more (carbonate and bicarbonate) + sulphate. Table 4 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.

4.6. 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. 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.

5. Conclusions

The main conclusion from this study is that the aquifer water from the Thar lignite prospect can be classified as sodium + potassium chloride water. This water is grouped as hard to very hard water having calcite hardness varying between 175-8201 mg/L. The ground water is considered unsuitable for irrigating crops because of TDS contents exceeding 700 mg/L. Thus, the ground water at Thar needs to be desalinated to improve its quality to 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 result in Table 3 indicates that many analyses do not comply with the charge balance of cations with anions concentration and consequently, the results are not acceptable for further considerations.

6. Suggestions for Further Research

The water quality would require improvements to enable the water to be used for irrigation purpose because of the saline nature results for chloride ions. Recent developments in solar technology should be investigated to develop a viable desalination process to assist in improving the water quality for agricultural and human consumption.

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References

Dupuit., 1863. *Etudes theoriques et pratiques sur le mouvment des eaux dams les canaux decouverts et a travers les terrains permeables.* 2eme edition, Dunot, Paris, p. 304.

Fernandez-Rubio R., Sastre J.L., Casas J., Fernandez Lorca S., Singh R.N., 1985. *Mine dewatering design in surface mining to improve the quality of ground water. Mine Water,* Granada, Spain, Vol. 2, p. 931-952.

Norton P., 1982. *Advanced dewatering and control of ground water in surface coal mining*. First International Mine Water Congress of IMWA, Budapest, Hungary, 19-24 April, pp. 517- 530.

Pathan A.G., Halepota G.R., Shah M.A., Singh R.N., 2009. *Geotechnical assessment of the Thar Coalfield, Pakistan.* Journal of Mines, Metals and Fuels, Calcutta, India, p. 19 (to be published).

Pathan A.G., Singh R.N., 2008. *Report on the visit of Professor A.G. Pathan of Mehran University of Engineering and Technology to NCG, the University of Nottingham*, 6-29 July, p. 26.

Pathan A.G., Halepota G.R., Shah M.A., Singh R.N., 2007. *Stability analysis and dewatering scheme for the proposed open cut lignite mine at Thar Coalfield, Pakistan*. International Coal Conference, Karachi, 30-31 October, p. 19.

Pathan A.G., Singh R.N., Shah A.A., 2006. *Hydrogeological studies and the design of mine dewatering system for the proposed open cut lignite mine at Thar, Sindh, Pakistan.* International Conference on "New technology for surface and underground Mining", Kolkata, India, 15-17 December, Journal of Mines, Metals and Fuels, Special Issue, II ISSN 0022-2755, pp. 362-369.

Pathan A.G., 2007. *Report on the Visit of Professor A.G. Pathan of Mehran University of Engineering and Technology to NCG*, University of Nottingham, 6 July-7th August, p.26.

Piper A.M., 1944. *A graphic procedure in the geochemical interpretation of water analyses*. Transaction Amer. Geophysics. Union, 25, p. 914-923.

Reed S.M., Singh R.N., 1987. *A geochemical survey of open cast mine water in the United Kingdom. Hydrology of coal basin,* International Symposium of IMWA, Krakow, Poland, September, p.147-154.

RWE Power International. 2004. *Thar mining project, bankable feasibility study and site assessment report*. Sindh Coal Authority, Province Sindh, Pakistan, Vol. 1, p. 58-130.

Singh R.N., Ngah S.A., Atkins A.S., 1985. *Applicability of current groundwater theories for the prediction of water inflows to surface mining excavations*. 2nd International Mine Water Congress of IMWA, Mine Water, Granada Spain, Vol. 1, p. 553- 569.

Singh R.N., Reed R.M., 1987. *Spatial displacements of opencast mine backfill associated with groundwater recovery.* Hydrology of coal basin, International Symposium of IMWA, Krakow, Poland, September, p. 575-586.

Singh R.N., 1992. *Mine water quality and presentation of mine water chemical analysis results.* Mine water notes, Chapter 13A, University of Wollongong, M.Eng Course in Mine Water, NSW 2522, Australia, p. 13-15.

Singh R.N., 2007. *Report on the visit of Professor R. N. Singh from 18th February 2007 to 18th March 2007 on HEC-BC Higher Education Links Program between Department of Mining Engineering and Nottingham Centre for Geomechanics, School of Civil Engineering*., The University of Nottingham, March 2007, p. 8.

Tylcer J., 1987. *Coexistence of the coal mining and the mineral water exploitation in the Ostrava-Karvina Mining District*. Hydrogeology of coal basins, International Symposium of IMWA, Katowice, Poland, September, p. 587-593.

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