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Provenance of groundwater in the crystalline aquifer of Johannesburg area, South Africa

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Recharge dynamics, possible flow path and human impact within the crystalline aquifer of the Johannesburg area have been described based on the hydrogeochemical characteristics and environmental isotopes. The dominant circulation zone has also been identified in the study. Understanding of the groundwater dynamics is very important for strategic management of the resource as the country is dependent on groundwater for its different activities. It has also been observed that mixing of fresh and polluted groundwater takes place at shallow zones within the weathered crystalline rocks and dissolution cavities in dolomites where the rocks are characterized by the lithological and structural complexities. From the compositional features of the groundwater in the Johannesburg area, it follows that the solute composition of the water basically results from two basic contributions: The reaction of meteoric water with weathered zone in the near surface area and direct infiltration through dolomite dissolution cavities. The results further indicate that the main constituent movement mechanism within the crystalline aquifer is through a diffusive process, which could be due to few fractures with depth and possible sealing by calcite precipitation. Therefore, the provenance of groundwater circulation is limited to the depth of 40 m. The natural water quality is found to be highly impacted by acid mine drainage that is derived from gold mining centers distributed in the upper Witwatersrand basin.

Key words: Crystalline aquifer, diffusive circulation, dissolution cavities, Johannesburg, water supply.

INTRODUCTION

Countries that are located within the arid and semi arid regions like that of South Africa depend on groundwater for various developmental activities. Due to large water usage, the main water supply for big cities like Johannesburg and Pretoria is derived primarily from surface water. However, many communities rely on groundwater for domestic supply, which is obtained from shallow aquifer mainly made of alluvials and weathered crystalline rocks. Groundwater also plays significant role in supplying water for large irrigation fields across the country which is extracted from deep wells located within the dolomitic aquifer. Therefore, understanding the nature of groundwater circulation and hydrogeochemical characteristics of the aquifers is crucial for sustainable development of the country's water resources in particular and the region in general. The prior knowledge on the groundwater circulation media, natural quality of water could give insight on the pollution control, which

could be potentially generated from urban, irrigation and industrial activities.

The study area (Figure 1) is characterized by semi arid environment where annual rainfall (mean value of 700 mm/year) which is highly variable with a distribution biased to summer months (January-March). The summer rainfall in the area is extremely important in its contribution for groundwater recharge.

The elevation in the area ranges from 1365 m a.s.l at Pretoria to 1753 m a.s.l. at Johannesburg (with an elevation difference of 388 m) in the south. Due to the presence of complex and heterogeneous crystalline aquifer in the Johannesburg area, the location of productive aquifers has become problematic as water fluxes are small. Furthermore, because of the spatial variability in the degree of fracturing and weathering, the development of water bearing horizon is limited to shallow weathering zones and fracture media. On the

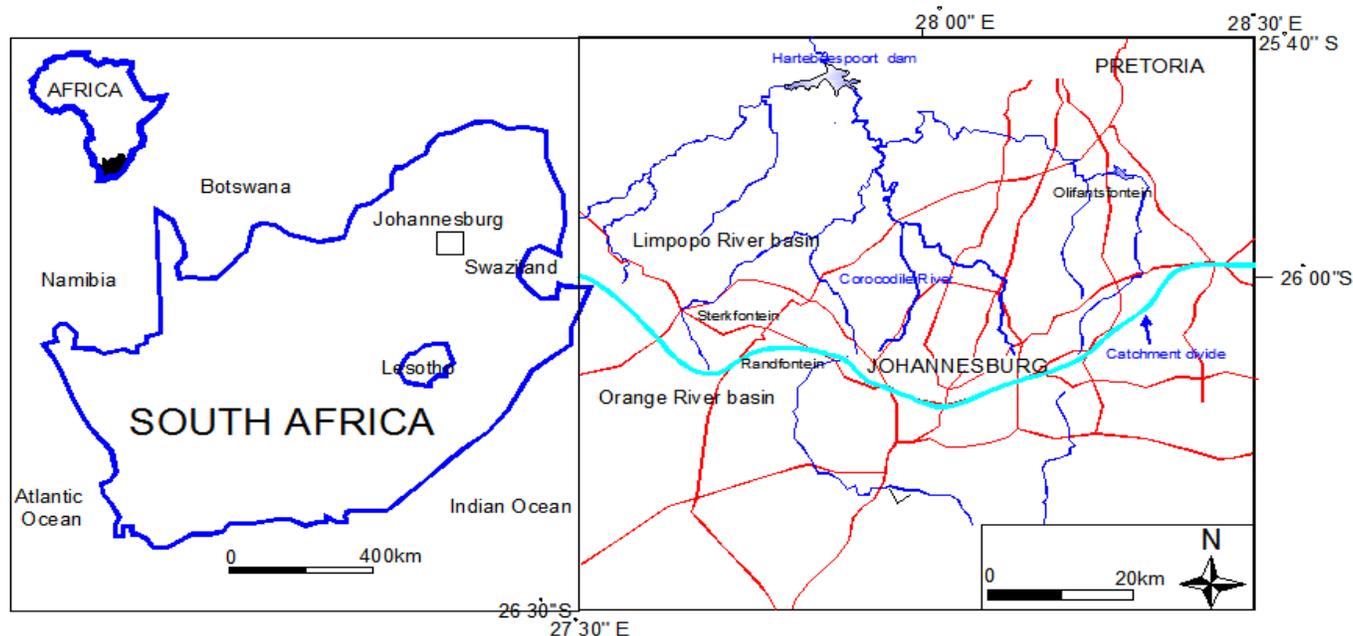


Figure 1. Location map of the study area, Johannesburg at the center (east-west solid line is water divide between Limpopo and Orange Rivers, blue lines represent streams and red lines represent roads).

other hand, the dolomitic aquifers are identified as highly productive aquifers in the region (Barnard, 2000). Chemical and isotopic tracer methods are, therefore, preferable in determining the provenance of groundwater and the status of water-rock interaction. The combined application of isotopes and geochemical parameters, have also been successfully used in the study of the geochemical evolution in granitic batholiths in Canada and other parts of the world (Stober and Bucher, 1999; Gascoyne, 2004; Cook et al., 2005).

The study area is well known for its large-scale urbanization and industrial activities that require huge volume of water. In this area, groundwater is used locally as supplementary source for domestic and industrial uses. However, several wells are pumping water for various activities in the area. With growing fresh water scarcity, groundwater resource assumes increasing importance and needs to be developed and protected according to best management practice. Hence, it is important to understand the groundwater recharge and circulation mechanisms in the weathered profile and fractured zones, which could help for proper management of the resource. The proper understanding of the geochemical process will further help in managing the groundwater quality in the region.

MATERIALS AND METHODS

The main purpose of this work is to understand the geoenvironmental setting based on the groundwater circulation and hydrogeochemical characteristics within the basement rocks of

Johannesburg area. In order to understand the groundwater dynamics in the area, groundwater database from the Department of Water and Environmental Affairs, Pretoria, has been utilized with field verification on accessible water points for physical parameters such as pH, electrical conductivity and total dissolved solids. Numerous variation diagrams have been engaged besides principal component analysis to identify major hydrogeochemical characteristics in the area.

Geological framework

The Johannesburg area is composed of basement crystalline rocks of Archean age. They are broadly classified as granitic rocks, meta-sedimentary and meta-volcanics (Figure 2). The Johannesburg dome consists of Archean greenstones remnants (Ga et al., 2001) and intruded by tonalite, granodiorite, granite and migmatites, unconformably overlain by meta-sedimentary rocks of < 3000 Ma (Barton et al., 1989; Armstrong et al., 1991; Barton et al., 1999). The dome is unconformably overlain by the sedimentary successions of the Witwatersrand Supergroup and is one of the few mid-Archean granite-greenstone inliers exposed in the central part of the Kaapvaal Craton (Poujol and Anhaeusser, 2001). The tonalites are the oldest rock types, migmatites are intermediate in age and granodiorite and granite are the youngest (Barton et al., 1999). The oldest granitic rocks comprise a suite of tonalitic and trondjemitic gneisses and migmatites that occupy most of the northern half of the dome. Exposure of similar rocks also occurs on the southern edge of the dome and unconformably underlies the Witwatersrand Supergroup (Meyers et al., 1990; Barton et al., 1999). The Witwatersrand basin is an arcuate structural basin lying within the Kaapvaal Craton. The Witwatersrand Supergroup is divided into the Lower West Rand Group and the upper Central Rand Group. The former conformably overlies volcanics of the Dominion Group and non-conformably overlaps Archean basement rocks of the Kaapvaal Craton. The south-central portion consists mainly of a variety of homogeneous, medium grained granodioritic

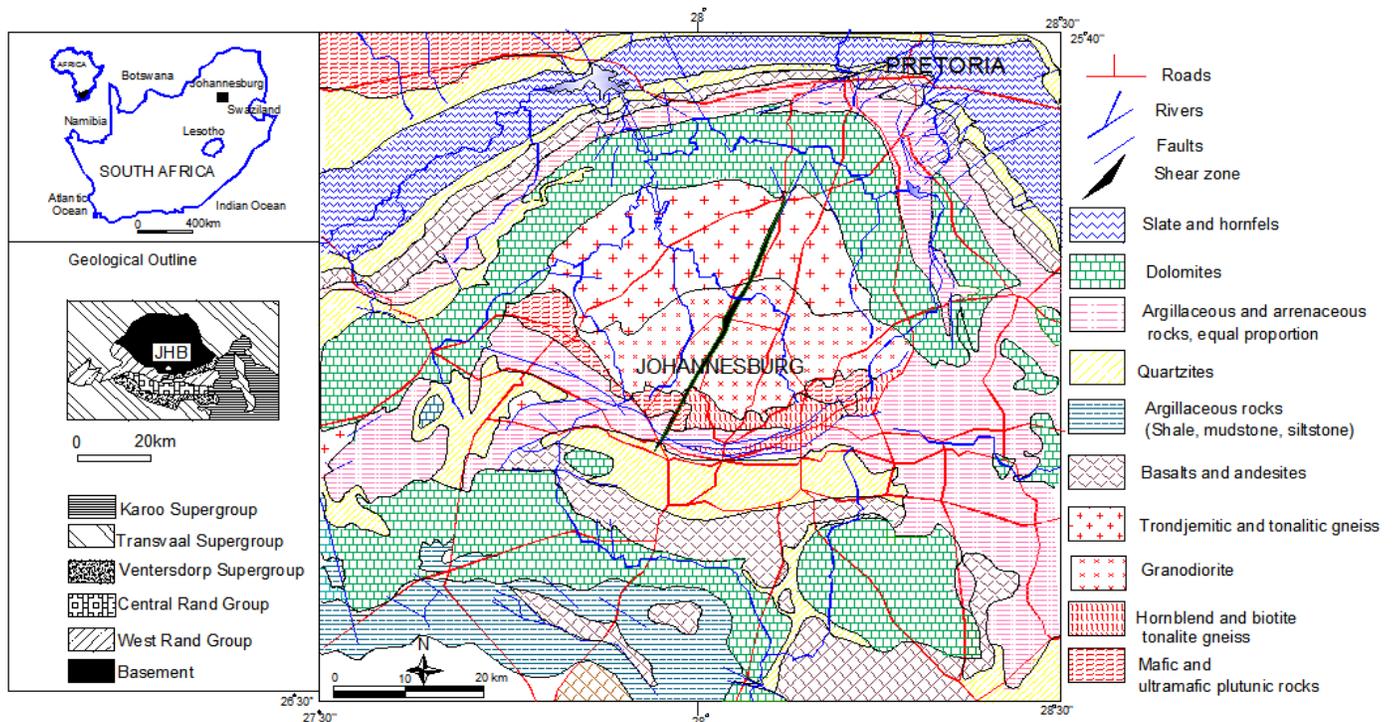


Figure 2. Simplified geological map of the Johannesburg area (Barnard, 1999; Barton et al., 1999; Anhaeusser, 2006).

rocks. Locally, all rocks contain a gneissic fabric and is less developed in the granodiorite and the tonalitic and trondjemitic group includes dioritic, tonalitic and trondjemitic gneiss and migmatites. The Witwatersrand supergroup unconformably overlies basement granitoids and greenstones, as well as sedimentary and volcanic rocks of the Dominion Group. It is made of thick terrigenous sequence comprising arenaceous and argillaceous sedimentary rocks. The deposition took place between 3074 and 2714 Ma (Robb and Meyer, 1995). The part of Witwatersrand basin that lies close to Johannesburg dome is grouped under west rand, central rand and east rand groups. The west rand group consists primarily of quartzites and shales. The central rand group consists of different proportion of quartzites and shales where the sequence consists mainly of quartzites and conglomerates (McCarthy, 2006). The Early Proterozoic Transvaal sequence comprises of relatively undeformed, unmetamorphosed volcanic rocks, quartzites, shales, dolomites iron formations, conglomerates and diamictites (Eriksson and Clendenin, 1990). The Transvaal sequence is made of relatively undeformed, unmetamorphosed volcanic rocks, quartzites, shales, dolomites, iron formations, conglomerates and diamictites (Eriksson and Clendenin, 1990). The Supergroup includes dolomites and iron formations of Chuniespoort group (Eriksson and Clendenin, 1990) which is overlain by Pretoria Group that comprises of predominant mud rocks alternating with quartzitic sandstones, significant interbedded basaltic-andesitic lavas and subordinate conglomerates, diamictites and carbonate rocks all of which have been subjected to low grade metamorphism (Eriksson et al., 2006).

Hydrogeological setting

The present landscape of the study area which is marked by elongated ridges, rolling topography and wide plain areas is a clear

reflection of the old geological activity (intrusion, sedimentation, metamorphism, ductile and brittle tectonics) and subsequent erosion process. These activities have tremendous impact on hydrogeological condition of the rocks primarily by regulating recharge. The Johannesburg dome having a circular outline form sloping relief terrain whereas the enclosing younger rocks form relatively high ground. Fractures of all orientation and weathering zones exist in all rocks. From hydrogeological point of view, the rocks that outcrop in the study area fall under hardrock category with low groundwater productivity except dolomites that contain dissolution cavities and consequently host huge quantity of groundwater.

According to the Johannesburg hydrogeological map of 1: 500 000 scale (Barnard, 1999), and explanatory note (Barnard, 2000); four aquifer types have been identified in the area.

1. An intergranular aquifer in the alluvial covered zones.
2. Fractured aquifer in the Witwatersrand Supergroup associated with fractures, fissures and joints.
3. The karstic aquifer in the dolomites.
4. The intergranular and fractured aquifer in the crystalline rocks.

However, from repeated and detailed field surveys, it is noted that groundwater occurrence in the area can be categorized into three groups: Near surface occurrence within the weathering profile; occurrence within fractures, dykes and shear zones; and occurrence within dissolution cavities in the dolomites. The main characteristic features of groundwater occurrence in the highly productive dolomitic aquifer are pockets of conduits which are compartmentalized primarily by structural discontinuities such as strike slip faults. However, locally dikes, sills and quartz veins generate perched system. The presence of recharging meteoric water through dykes and faults and the influx of thermal water along fractures within the deep gold mines in the Witwatersrand basin

have been documented by Duane et al. (1997). Therefore, occasionally the dykes and faults play important role in regulating recharges in the area. Consequently, it is very frequent to observe perched springs which flow only after heavy rain in the area.

The semicircular deformation of the Witwatersrand and Transvaal Supergroup rocks around Archean granitic pluton could play substantial role in delaying groundwater circulation in the area. However, the randomly oriented left lateral strike slip faults with minor occurrence of right lateral strike slip faults can potentially act as a conduit for accelerated groundwater flow. The area is intensively deformed, fractured and dissected by dikes. Since dikes constitute an important structural set up of the crystalline rocks, they act as conduits for groundwater circulation besides compartmentalizing role in some instances. Owing to the fact that the area is made of deformed crystalline rocks, the main hydrostructures are represented primarily by fractures and weathered zones. The fractured quartzites that form the water divide between the northern Limpopo River basin and the southern Orange River basin are intensively fractured, which provide suitable media for vertical recharge. Granitic gneisses and quartzites, instead, are characterized by massive structures with wide fracture network while shales contain very tight fractures along inclined beds to the south. Dissolution structures are peculiar features of dolomites which are identified as productive aquifers in South Africa.

The alluvials which are found along stream valleys are highly productive in areas such as the lower Crocodile River valley (downstream of Hartebeespoort dam, Figure 1). Such aquifers produce as much as 16 l/s (Barnard, 2000). In the dolomitic aquifer, the occurrence of cavities varies from place to place which is based on the intercalation found in dolomites. Such variability depends on different generation of dolomite (dolomite containing chert layers and those without chert), the availability of acidic infiltrating water, the amount of groundwater moving through the system and the degree of saturation with respect to calcite and dolomite. In large part of the area, dolomites have notorious reputation due to the occurrence of sinkholes due to the formation of dissolution cavities (Buttrick et al., 1993). The presence of acid mine drainage which is generated from the slime dams and abandoned gold mines have a potential to dissolve carbonate rocks such as dolomites. The occurrence of a series of dissolution cavities along preferential groundwater flow direction is a characteristic feature in the dolomites. Appearance and disappearance of springs is also a common feature in the area, which is controlled by availability of the karst structures. One of highly productive springs in the Sterkfontein area within the cradle of human kind World heritage site, is known as Ngosi spring, and emerges as a group of springs from dissolution structures. For this particular spring, the measured $\delta^{18}\text{O}$, $\delta^2\text{H}$ and ^3H values are -5.42‰, -31.0‰, 0.6 ± 0.2 TU respectively. The data show that the spring is categorized as old water with more than five decades in circulation which indicates low permeability of dolomitic aquifer.

RESULTS AND DISCUSSION

Hydrogeochemical and isotope variables give important indications regarding the geoenvironmental history of the enclosing rocks, the velocity and direction of movement and the mechanism of flow in the aquifers. The spatial variation in the concentration of dissolved substances determines the chemical properties and evolution of water along a flow path. In the study area, which is covered with large variety of basement lithologies, the large variation in water chemistry reflects the degree of

fracturing and weathering of the host rocks. In different aquifers, groundwater contains high salinity due to leaching from weathering profile and pollution from gold mines.

For the study area, different combinations of parameters have been plotted from the data presented in Tables 1 and 2, to get information on the water quality characteristics of the crystalline aquifer. The sampling points have been presented in Figure 3. The plots have generated one prominent cluster which represents dominant aquifer in the area and dispersed data points with high salinity that are related to pollution from gold mining activities. For the selected boreholes, the distribution of ions with depth has been presented in Figure 4 and the plots portrays a relatively decreasing pattern with depth, which, instead, suggests diffusive circulation process due to calcite precipitation within fractures (Figure 4a). It is supported by the increasing pH (Figure 4b).

The increase in pH with depth facilitates loss of calcium through precipitation process (Gascoyne, 2004) and possible cation exchange process with sodium. The diffusive circulation is attributed to fracture sealing by calcite that reduces the available pore space at depth. At shallow depth, the presence of relatively less alkaline water is due to the influence of atmospheric and biogenic carbon dioxide through open fractures and dissolution cavities. The decrease in the concentration of magnesium with depth (Figure 4c) reflects less soluble nature of dolomite with chert intercalation that results diffusive movement of ions in the dolomitic aquifer. In low or no flow condition, dissolved salts move mainly by diffusive rather than advective processes. Figures 4d and e depict high concentration of chloride and sulphate, respectively, up to the depth of 60 m, which is considered due to the pollution impact from mines. Chloride could be added to the aquifer from soluble salts within the weathered profile, rock water interaction (including reaction with matrix minerals, fracture-filling minerals) and the presence of soluble salts.

To evaluate the control pattern of various ions on electrical conductivity and indirectly on TDS (salinity), 2D variation diagrams were prepared (Figures 5a to d). In general, the plots show the presence of one dominant water cluster (left lower corner) that has low salinity and mineral content with highly conductive polluted water from gold mining areas. The fast enrichment of ions could be related to rock dominance phase with additional source from multilayer aquifer system or mineral leaching. The fast increase in silica could be related to silicate dissolution from cherty dolomites and granites in more acidic and an oxic condition, which could be assisted by widespread acid mine drainage (AMD) process in the area. The pattern on Figure 5, in general, indicates similar source through weathering of different rock types and mixing of different water types is also a possible controlling process for linear behavior of

Table 1. The variation in ion concentration with depth in some water supply wells.

Code	Latitude	Longitude	Eleve. m.a.s.l	SWL (m)	Well depth (m)	pH	EC (mS/cm)	K (mg/L)	Na (mg/L)	Ca (mg/L)	Mg (mg/L)	Cl (mg/L)	TAL (mg/L)	SO4 (mg/L)
Well_1	-26.03612	27.70000	1520.00	7.92	9.14	7.7	112.5	1.36	62.5	93.3	53.3	94.3	97.6	227.1
Well_2	-25.85639	28.16695	1430.00	15.00	31.00	7.6	66	1.63	6.8	69.6	38.9	15.4	263.3	20.4
Well_3	-25.89639	28.31250	1487.83	22.00	38.00	7.7	53.9	0.54	16.1	45.4	31.1	20	172.4	32.1
Well_4	-25.92750	28.21945	1480.00	30.00	45.00	7.28	87.6	1.76	61.3	63.6	30.1	78.2	209.7	59.1
Well_5	-26.01740	27.71136	1463.52	30.00	56.00	7.2	98	1.51	46.1	87.8	49.1	70.2	119.8	229.7
Well_6	-26.08056	27.57639	1545.22	53.00	60.00	6.8	83	0.7	1	7.1	4	1.5	42.4	9.9
Well_7	-25.89862	28.30278	1519.46	67.00	69.00	7.4	37.1	1.38	5.8	35.2	20.6	6.6	121.3	21.6
Well_8	-25.96945	28.28056	1586.23	76.00	83.00	7.75	40.1	0.43	4.9	39.4	23.9	6.4	168.8	11.4
Well_9	-25.91689	28.33856	1500.00	10.00	87.00	7.85	24.6	0.15	1	23.8	12.8	1.5	118.7	5.5
Well_10	-25.88916	28.20888	1460.00	40.00	89.00	7.4	56	0.92	9.3	46	37.7	18.1	224.2	7
Well_11	-25.89222	28.32195	1524.21	63.00	92.00	7.58	255	0.62	5.6	24.2	15	4.6	92.3	8.1
Well_12	-26.06825	27.64736	1573.01	92.00	98.00	7.64	373	0.54	14.2	30.5	19.8	26	115.2	15.8
Well_13	-26.05080	27.67248	1546.77	74.00	108.50	7.66	34.4	1.6	7.6	35.1	21.2	39	98.5	47.3
Well_13	-25.88222	28.25666	1460.00	107.00	114.00	7.2	44.8	0.65	11	41.4	25.9	11	192.5	12.6
Well_14	-26.01667	28.28555	1570.00	116.00	117.00	7.47	50.2	1.28	12.7	39.8	31.4	28.5	158.6	33
Well_15	-25.90861	28.31695	1501.21	134.00	135.00	7.8	64	0.86	51	39.9	24.1	41.3	153.2	76.1
Well_16	-26.04625	27.67872	1543.61	132.00	135.00	7.82	31.6	0.4	3.2	30.8	19.3	10.9	125.8	8.3
Well_17	-25.85694	28.23333	1490.00	148.00	158.00	7.65	60.4	2.73	6.4	62.3	35	3	265.9	15.6
Well_18	-25.94961	28.34194	1580.00	19.00	164.00	7.48	20.4	0.38	1	21.3	11	1.5	106	6
Well_19	-25.95000	28.26806	1559.77	169.00	176.00	7.7	36.0	0.79	5.4	36.1	21.6	4.2	157.3	9.8

different water types. The distribution of points on the variation diagrams indicates the importance of all ions at low EC condition (lower left part). The points that lie in right top part of Figure 5 are related to AMD impact, which is generated from gold mining industries across the region.

Total alkalinity increases rapidly (Figure 5c) at an initial stage indicating the presence of additional source. The influence of atmospheric and soil CO₂ probably accounts for increase in TAL values in shallow aquifer. Due to calcite precipitation with depth TAL is expected to decrease further below 200 m depth. Similar

enrichment patterns of ions indicate mixing of different water can be considered as an important process to generate these ions.

In order to evaluate the extent of AMD in the area, total iron and sulphate ions have been plotted (Figure 6), and the data are presented in Table 3, where large concentration is observed which justifies the presence of AMD within the groundwater system.

High AMD decant (Figure 7) is a characteristic feature of gold mines in different areas in the upper Witwatersrand basin (Figure 6a), while boreholes located on dolomites have relatively low

iron and sulphate concentration (Figure 6b and c). It is found out that in many areas of the Johannesburg neighborhood, groundwater in the fractured and karstified system located close to gold mines contains high iron and sulphate, which could be the dispersion of the contaminated groundwater flow.

Environmental isotopes such as $\delta^{18}\text{O}$, $\delta^2\text{H}$ and ^3H are widely used to gain some insight into the subsurface flow and recharge condition. These isotopes have been used to study the recharge condition in the sedimentary sequence in South Africa (Sami, 1992; Adams et al., 2001) to

Table 2. Major ion composition of groundwater in the crystalline aquifer.

Sample code	Latitude	Longitude	pH	EC (mS/cm)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Cl (mg/L)	SO ₄ (mg/L)	TAL (mg/L)
BH1	-26.22972	28.04278	7.80	156.00	196.00	61.00	48.00	17.30	50.00	511.00	267.00
BH2	-25.99250	28.11750	6.70	237.00	14.80	7.30	17.70	1.33	9.70	5.90	71.20
SP1	-25.98500	28.33167	7.49	23.80	17.30	15.10	2.10	0.70	1.50	2.00	117.40
SP2	-26.02167	27.56472	7.40	27.00	25.70	16.50	5.90	0.46	5.20	2.00	128.70
SP3	-25.87444	27.78222	7.46	25.50	21.50	14.90	1.00	0.50	4.40	4.50	113.90
BH3	-26.24667	27.71694	6.74	20.20	20.20	8.10	4.80	0.70	1.50	41.60	37.60
BH4	-26.23389	27.80306	7.34	27.10	26.00	15.80	6.30	1.37	1.50	9.00	125.40
BH5	-26.23472	27.72528	6.97	12.40	11.70	6.40	2.60	0.94	1.50	8.20	56.60
BH6	-26.23306	27.78333	7.02	14.20	14.20	8.00	3.70	0.32	1.50	7.60	64.50
BH7	-26.23528	27.74944	7.00	13.50	12.70	7.70	2.60	0.56	3.50	9.10	55.00
BH8	-26.23667	27.79667	7.37	26.50	27.50	16.00	5.20	0.85	1.50	8.00	123.10
BH9	-26.24722	27.74972	6.54	10.70	12.80	2.90	3.30	2.67	1.50	6.20	48.20
BH10	-26.24333	27.79639	7.45	40.40	44.40	25.50	5.90	1.55	3.80	8.40	185.50
BH11	-26.24583	27.68361	6.22	5.20	4.20	1.70	2.60	0.46	1.50	8.40	18.80
BH12	-26.22833	27.73444	7.42	27.70	27.30	15.20	7.10	0.44	1.50	38.10	83.20
BH13	-26.24556	27.68361	6.59	10.50	9.50	2.00	4.80	0.50	1.50	11.40	35.60
BH14	-26.24556	27.72111	6.18	21.90	8.00	5.30	13.70	7.47	21.20	13.00	21.70
BH15	-26.22111	27.77528	5.77	55.30	17.20	22.90	45.50	2.15	105.50	13.70	5.40
BH15	-26.24028	27.80417	7.64	26.50	25.00	15.80	4.80	0.77	1.50	13.20	121.00
BH16	-25.81028	28.14861	6.74	40.10	34.90	23.10	9.80	0.69	18.80	20.40	141.90
BH17	-25.88333	28.31667	7.49	49.60	38.60	22.60	37.90	1.31	29.20	56.40	136.00
BH18	-25.90000	28.31667	7.60	45.40	41.50	26.70	12.30	0.84	19.00	37.00	139.30
BH19	-25.89361	28.30694	7.90	60.20	39.10	24.30	43.10	1.50	36.20	69.90	140.90
BH20	-25.81667	28.10000	7.47	36.70	29.00	18.40	7.30	1.25	5.70	6.80	121.60
BH21	-25.82500	28.12222	8.09	60.80	38.10	37.90	25.60	0.15	58.90	55.30	130.60
BH22	-25.82083	28.12222	7.90	57.60	39.10	34.60	17.90	0.15	49.00	58.20	132.70
BH23	-25.78333	28.18750	8.04	42.90	38.10	25.20	8.80	0.15	21.00	29.00	128.50
BH24	-25.81250	28.15278	7.60	47.40	46.60	28.80	7.90	0.15	18.70	41.90	153.50
BH25	-25.82917	28.17500	7.70	67.20	60.80	38.20	25.90	0.57	56.60	70.40	179.60
BH26	-25.82778	28.16944	7.70	70.00	63.70	40.50	26.60	0.85	60.20	82.30	185.30
BH27	-25.79167	28.20833	7.60	29.80	28.80	19.90	3.20	0.15	1.50	5.80	121.80
BH28	-25.82778	28.11667	7.50	71.00	63.40	40.40	26.30	0.71	56.80	70.20	188.20
BH29	-25.78472	28.20556	7.50	27.70	25.70	18.50	3.20	0.15	1.50	8.20	106.90
BH30	-26.03333	28.46667	7.80	23.60	33.00	9.20	3.20	0.58	1.50	7.20	107.30
BH31	-26.11667	28.43333	8.00	28.80	19.20	9.20	28.00	1.95	9.00	9.60	119.80
BH32	-26.08333	28.50000	7.50	17.10	15.70	9.20	2.90	1.15	3.00	6.50	74.00
BH33	-26.01667	28.45000	7.60	14.80	15.00	6.80	2.00	1.27	1.50	5.90	66.30
BH34	-25.89639	28.31250	7.70	53.90	45.40	31.10	16.10	0.54	20.00	32.10	172.40
BH35	-25.90250	28.31722	7.67	36.00	32.20	21.80	4.50	0.44	7.20	9.50	131.00
BH36	-26.01611	27.70806	7.64	102.30	91.70	53.90	39.10	0.15	61.80	266.90	86.20
BH37	-26.10444	27.60028	7.87	33.00	33.60	21.40	2.40	0.15	11.00	9.50	116.50
BH38	-26.09361	27.62222	6.06	3.60	1.20	1.80	2.60	0.15	1.50	7.70	9.90
BH39	-26.04706	27.70942	7.75	137.80	101.30	55.70	97.50	1.67	138.00	203.30	130.80
BH40	-26.05361	27.62750	7.40	57.50	22.50	26.60	37.10	5.78	132.50	12.00	31.40
BH41	-26.05194	27.65444	7.55	22.30	15.20	16.50	5.90	0.79	8.30	27.10	66.40
BH42	-26.09139	27.59250	7.78	21.80	17.00	13.70	1.00	0.15	6.80	21.90	70.30
BH43	-26.04556	27.64944	7.75	71.30	32.30	32.30	60.10	2.93	37.70	80.20	185.60
BH44	-26.05000	27.69444	7.67	37.50	33.40	22.30	8.60	1.27	19.60	61.00	77.60
BH45	-26.03389	27.68167	7.64	17.60	13.20	12.20	6.50	1.07	3.10	11.20	63.60
BH46	-26.05083	27.67250	7.66	34.40	35.10	21.20	7.60	1.60	39.00	47.30	98.50

Table 2. Contd.

BH47	-26.07917	27.66639	6.07	3.50	2.60	1.70	2.80	0.71	1.50	4.10	12.00
BH48	-26.09417	27.66556	7.69	18.00	21.50	7.20	5.10	0.39	1.50	7.20	61.60
BH49	-26.08889	27.69611	7.34	15.40	14.70	9.20	1.00	0.66	1.50	5.00	48.40
BH50	-26.09500	27.59861	7.26	15.70	15.60	9.60	1.00	0.35	1.50	6.90	56.70
BH51	-26.07722	27.60167	7.67	21.80	10.90	8.90	3.90	0.41	1.50	12.70	77.40
BH52	-26.00583	28.42333	8.05	31.30	28.28	18.75	4.66	1.16	2.00	6.37	138.83
BH53	-26.10806	27.72278	3.72	307.00	480.14	122.59	73.10	4.68	25.58	1892.62	77.60
BH54	-26.11361	27.72278	3.12	574.00	473.14	223.92	97.40	12.43	21.07	4466.80	63.60
BH55	-26.11333	27.72278	2.98	538.00	472.43	199.93	102.49	11.22	17.52	4144.95	98.50
BH56	-25.89528	28.30722	8.30	18.20	12.10	11.70	5.00	1.84	8.40	2.00	84.80
BH57	-25.88917	28.31472	8.05	6.50	2.20	2.00	1.00	1.17	1.50	2.00	26.90
BH58	-25.89722	28.30417	9.43	29.80	2.30	6.70	51.30	1.12	43.50	2.00	88.10
BH59	-26.24861	27.74389	8.84	102.40	4.80	0.50	105.00	163.02	83.60	117.20	206.30
BH60	-25.83333	28.16667	10.20	25.60	0.50	1.00	55.10	0.15	7.20	12.50	109.00
BH61	-25.97167	27.79306	8.30	48.00	53.00	31.50	5.10	0.87	16.90	15.20	209.20
BH62	-26.05833	27.58611	5.99	4.40	4.60	2.40	2.50	0.59	1.50	6.90	17.70
BH63	-26.14028	27.63056	5.62	4.10	2.00	0.50	1.00	0.34	1.50	7.20	9.80
BH64	-26.14306	27.61528	5.31	4.00	1.50	1.60	1.00	0.33	1.50	10.60	8.20
BH65	-26.13333	27.66389	6.68	57.60	16.80	11.50	74.30	2.27	108.30	36.70	39.20
BH66	-26.12778	27.59444	8.09	42.20	41.40	28.50	3.30	0.82	4.40	7.40	208.00
BH67	-26.07222	27.62639	5.99	4.50	4.70	1.10	3.00	0.38	1.50	11.10	19.00
BH68	-25.88889	27.51389	8.19	67.80	46.30	20.20	41.40	6.25	85.50	46.10	61.50
BH69	-25.80833	28.15417	8.24	30.10	23.20	22.10	6.50	0.43	9.00	30.40	115.80
BH70	-26.22417	28.33472	8.21	56.70	33.70	41.20	7.90	0.79	3.70	15.00	200.00
BH71	-26.05361	27.70583	8.12	121.20	87.50	47.50	88.40	3.57	106.00	165.80	217.20
BH72	-26.07725	27.69912	8.27	21.80	19.72	11.34	2.74	0.42	2.50	16.29	79.36
BH73	-26.01039	28.41358	8.15	32.80	28.20	17.93	8.37	2.61	6.84	6.91	135.37

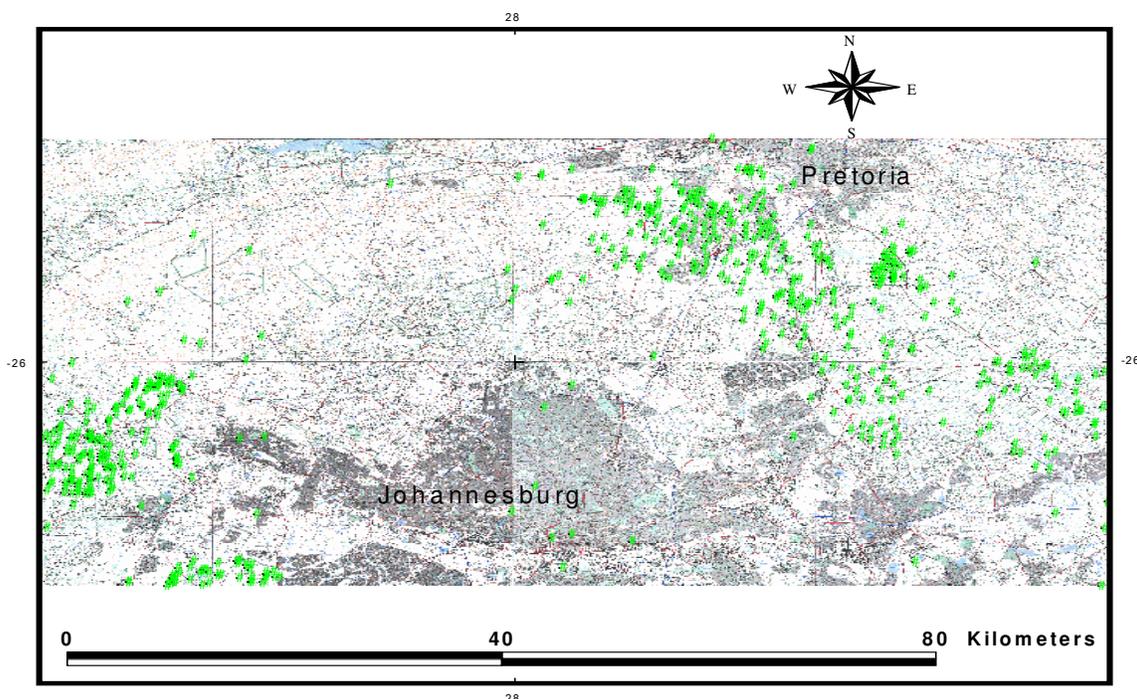


Figure 3. Location map for the groundwater sample points.

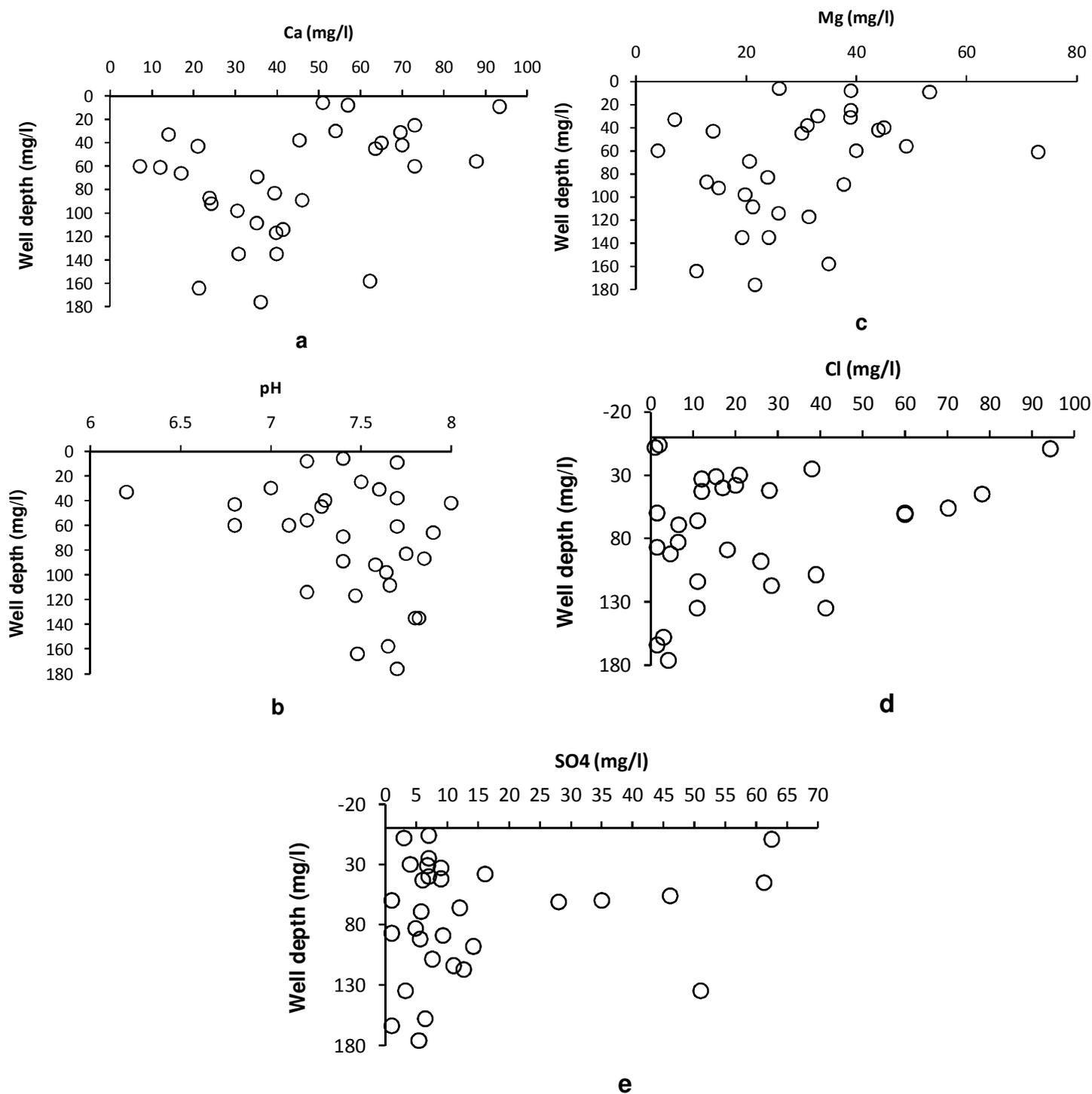


Figure 4. Distribution pattern of chemical constituent with the total well depth.

characterize the recharge mechanism and geochemical processes in the arid environment. The interpretation of the plots from the data obtained from Walton (1996) indicate that rapid infiltration through fractures or dissolution cavities could result low degree of water-rock

interaction and hence, low salinity and high-land water exists within the dolomitic aquifer that contain low chloride and depleted $\delta^{18}\text{O}$ (Figure 8a). However, the relatively high chloride polluted water show depletion in $\delta^{18}\text{O}$. The variation diagrams are found to be supportive

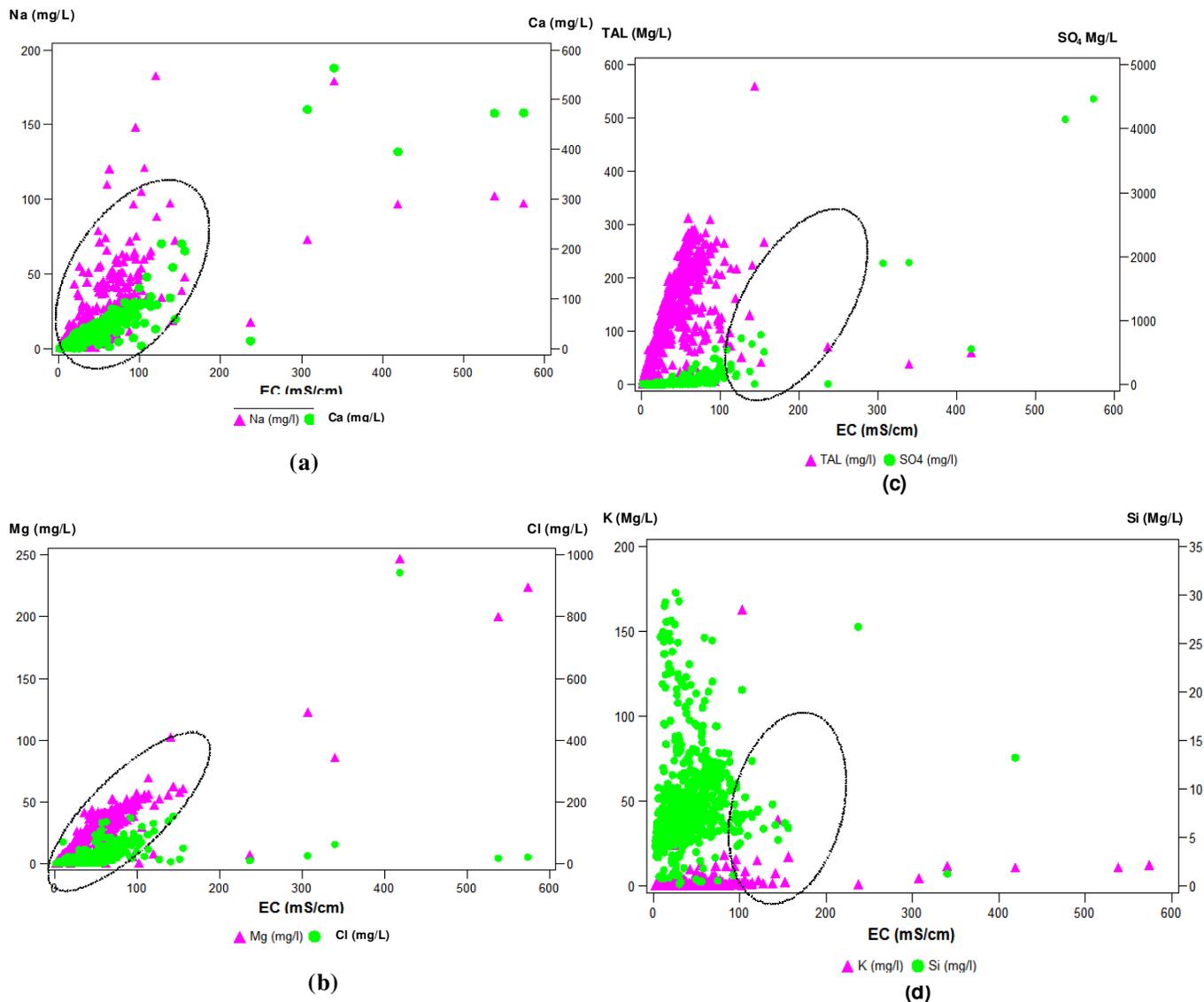


Figure 5. Control pattern of different ions over electrical conductivity.

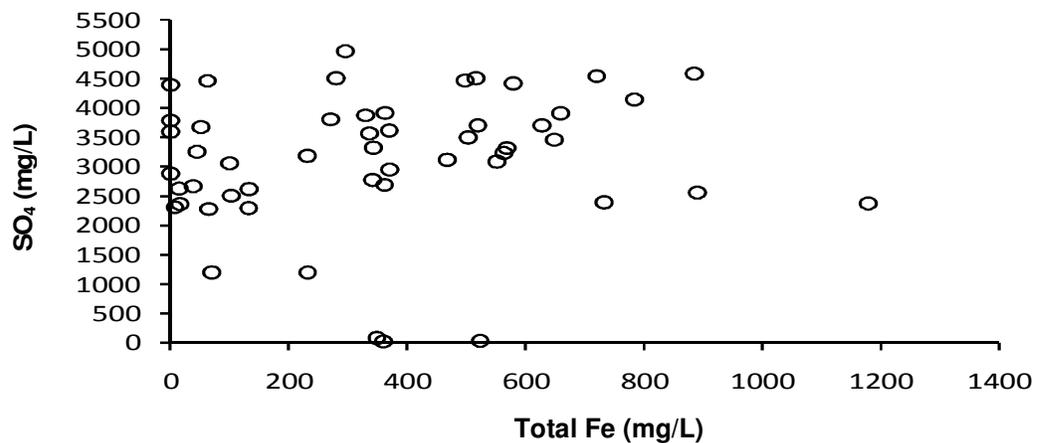
to the occurrence of dominantly shallow circulation. The provenance of dominant groundwater circulation lies between the surface and 40 m depth (Figure 8b) from the potential recharge zone. This profile is presumed to be dominated by secondary structures mainly dissolution cavities.

The Tritium plot on Figure 8a to c confirms the presence of shallow occurrence of dilute water (^3H content of at least 5TU) with low chloride. The range of ^3H indicates possible mixing of old and young water within the dolomitic fracture system where the geoenvironmental setting is represented by an open system. From the distribution of plots on Figure 8c, it can be observed that there is slower moving older component of groundwater (ore depleted $\delta^{18}\text{O}$ and low ^3H) that mixes

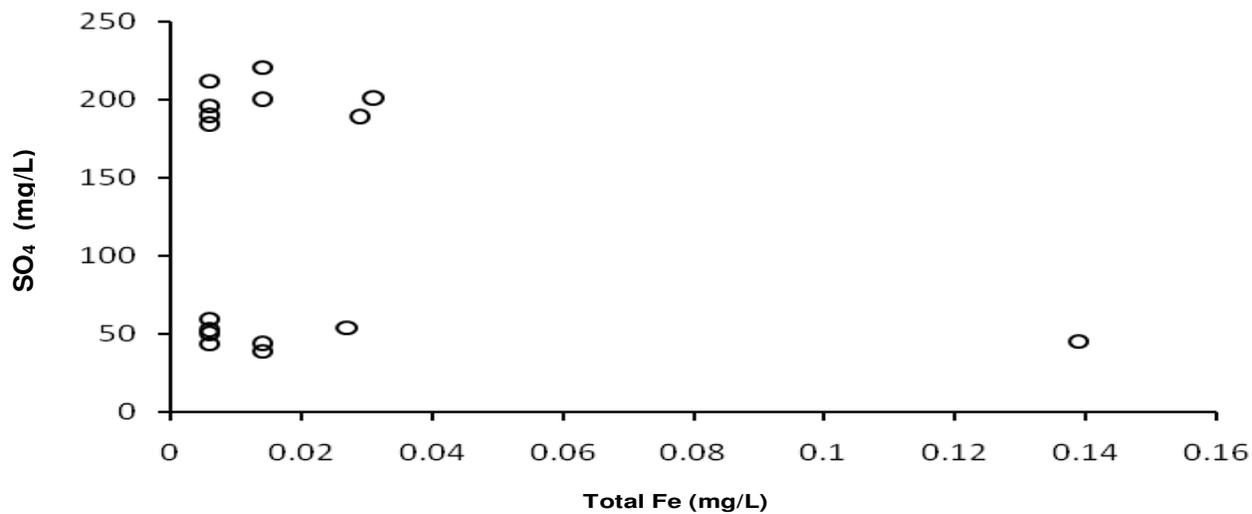
with relatively young and shallow moving or locally recharged water.

Principal component analysis

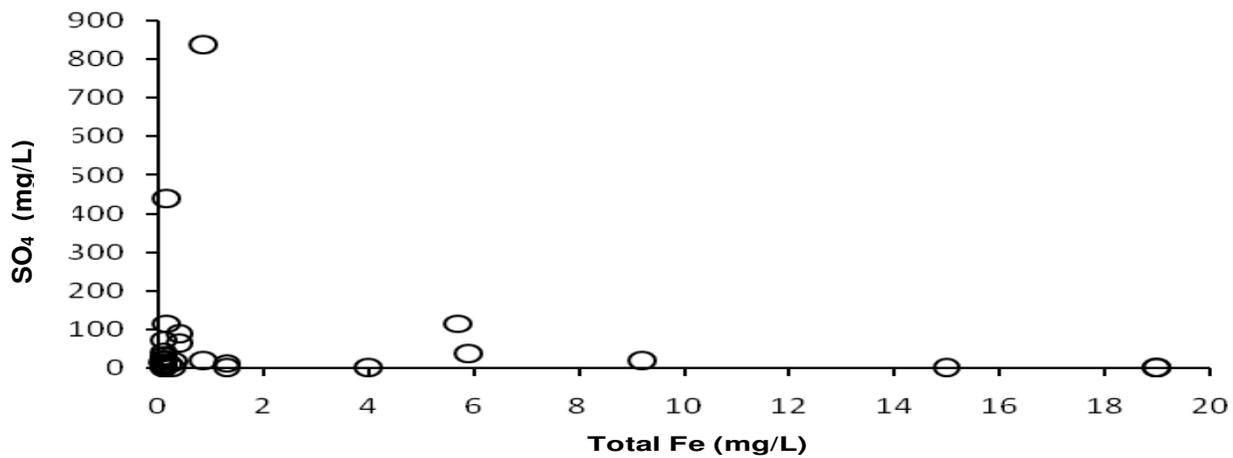
Principal component analysis (PCA) was used to identify chemistry of dominant groundwater types. PCA helps to identify common geochemical categories and grouping water quality types besides the interrelations to the aquifer. PCA was used in discriminating different water groups in various parts of the world such as in Duane et al. (1997), Barnes et al. (2001), O'Shea and Jankowski (2006), Dong et al. (2007) etc. For the PCA, seven parameters were considered. These are Ca, Mg, Na, K, Cl,



(a)



(b)



(c)

Figure 6. The distribution of total Iron and SO₄ within the boreholes (a = gold mine area, b = Sterkfontein area, c = Olifantsfontein area).

Table 3. The impact of AMD as observed from total iron and sulphate composition from the groundwater samples.

Sample code	Latitude	Longitude	Fe (mg/L)	SO ₄ (mg/L)	Sample code	Latitude	Longitude	Fe (mg/L)	SO ₄ (mg/L)
W1	-26.1081	27.72278	0.013	3789.89	W39	-26.1133	27.72278	359.88	15.64
W2	-26.1081	27.72278	563.01	3238.15	W40	-26.1133	27.72278	519.32	3709.50
W3	-26.1081	27.72278	231.77	1194.37	W41	-26.1133	27.72278	369.81	2953.56
W4	-26.1081	27.72278	69.375	1194.37	W42	-26.1133	27.72278	0.06	3596.55
W5	-26.1081	27.72278	132.78	2620.67	W43	-26.1133	27.72278	362.65	3917.12
W6	-26.1081	27.72278	361.80	2692.11	W44	-26.1133	27.72278	329.25	3878.40
W7	-26.1081	27.72278	64.28	2278.53	W45	-26.1133	27.72278	342.50	3324.10
W9	-26.1081	27.72278	1179.00	2372.03	W46	-26.1133	27.72278	467.10	3116.56
W10	-26.1081	27.72278	890.40	2560.66	W47	-26.1133	27.72278	294.95	4974.11
W11	-26.1081	27.72278	15.51	2365.08	W48	-26.1133	27.72278	341.80	2778.31
W12	-26.1081	27.72278	37.931	2669.01	W49	-26.1133	27.72278	0.01	2885.75
W13	-26.1081	27.72278	99.90	3056.45	W50	-26.1133	27.72278	44.82	3254.04
W14	-26.1081	27.72278	14.313	2629.64	W51	-26.1133	27.72278	230.86	3186.21
W15	-26.1081	27.72278	102.10	2505.04	W52	-26.1133	27.72278	551.90	3087.93
W16	-26.1081	27.72278	132.00	2294.46	W53	-26.1133	27.72278	492.70	2961.63
W17	-26.1081	27.72278	62.40	4466.80	W54	-26.1153	27.72500	76.10	2739.85
W18	-26.1136	27.72278	498.08	4470.65	W55	-26.1153	27.72500	83.69	4176.01
W19	-26.1136	27.72278	516.49	4514.29	W56	-26.1153	27.72500	3.63	3630.53
W20	-26.1136	27.72278	523.27	25.49	W57	-26.1153	27.72500	11.95	1862.09
W21	-26.1136	27.72278	579.24	4423.07	W58	-26.1153	27.72500	986.80	2644.78
W22	-26.1136	27.72278	732.46	2390.39	W59	-26.0789	27.68639	0.01	39.04
W23	-26.1136	27.72278	884.71	4592.93	W60	-26.0789	27.68639	0.01	44.17
W24	-26.1136	27.72278	720.00	4546.96	W61	-26.0789	27.68639	0.01	43.83
W25	-26.1136	27.72278	0.033	4398.14	W62	-26.0789	27.68639	0.01	50.46
W26	-26.1136	27.72278	279.28	4512.53	W63	-26.0789	27.68639	0.01	59.68
W27	-26.1136	27.72278	503.00	3502.78	W64	-26.0789	27.68639	0.14	45.29
W28	-26.1136	27.72278	649.00	3457.99	W65	-26.0789	27.68639	0.03	53.91
W29	-26.1136	27.72278	369.66	3621.41	W66	-26.0789	27.68639	0.01	52.69
W30	-26.1136	27.72278	270.04	3810.06	W67	-26.0579	27.70002	0.01	189.59
W31	-26.1136	27.72278	7.32	2308.90	W68	-26.0579	27.70002	0.02	220.86
W32	-26.1136	27.72278	51.45	3677.80	W69	-26.0579	27.70002	0.01	212.43
W33	-26.1136	27.72278	335.65	3567.20	W70	-26.0579	27.70002	0.01	196.29
W34	-26.1136	27.72278	568.70	3318.49	W71	-26.0579	27.70002	0.01	190.55
W35	-26.1136	27.72278	783.70	4144.95	W72	-26.0579	27.70002	0.01	184.67
W36	-26.1136	27.72278	659.10	3914.46	W73	-26.0579	27.70002	0.03	201.42
W37	-26.1136	27.72278	627.70	3710.56	W74	-26.0579	27.70002	0.01	200.87
W38	-26.1133	27.72278	348.61	73.56					

SO₄ and HCO₃. The five PCs account for 98.993% of the total variability in the data set (Table 4). The loadings are the correlations between the original variable and the individual components. The values indicate roughly the relative contribution/importance of each variable in each principal component (StatistiXL, 2005). The result shows that Ca, Mg, Na and SO₄ have maximum loading on PC₁, which could be considered as a principal chemical constituent of the aquifer in the area except SO₄, which is derived from AMD, while HCO₃ has highest loading on PC₂ and PC₃. The clustering of most of the data points to the origin shows significantly dissimilar data. Figure 9a

shows loading of PC₂ on PC₁ with HCO₃, K and Cl. Possible occurrence could be shallow groundwater with a source from a shale dominated recharge zone, which is the main lithology on the northeren slope of the watershed. Figure 9b shows loading of PC₃ on PC₁ with HCO₃, Mg and Ca. Possible source could be dolomitic rocks. Figure 8c shows loading of PC₄ on PC₁ with Cl, Na and Mg. For such type of composition source rock could be an aquifer made of acidic crystalline rock such as granite and gneiss. However, Cl can be generated from marine precipitation, urban pollution etc. Figure 8d shows loading of PC₅ on PC₁ with Na and



Figure 7. Acid mine decant pictured from one of the streams in the west rand gold mine areas.

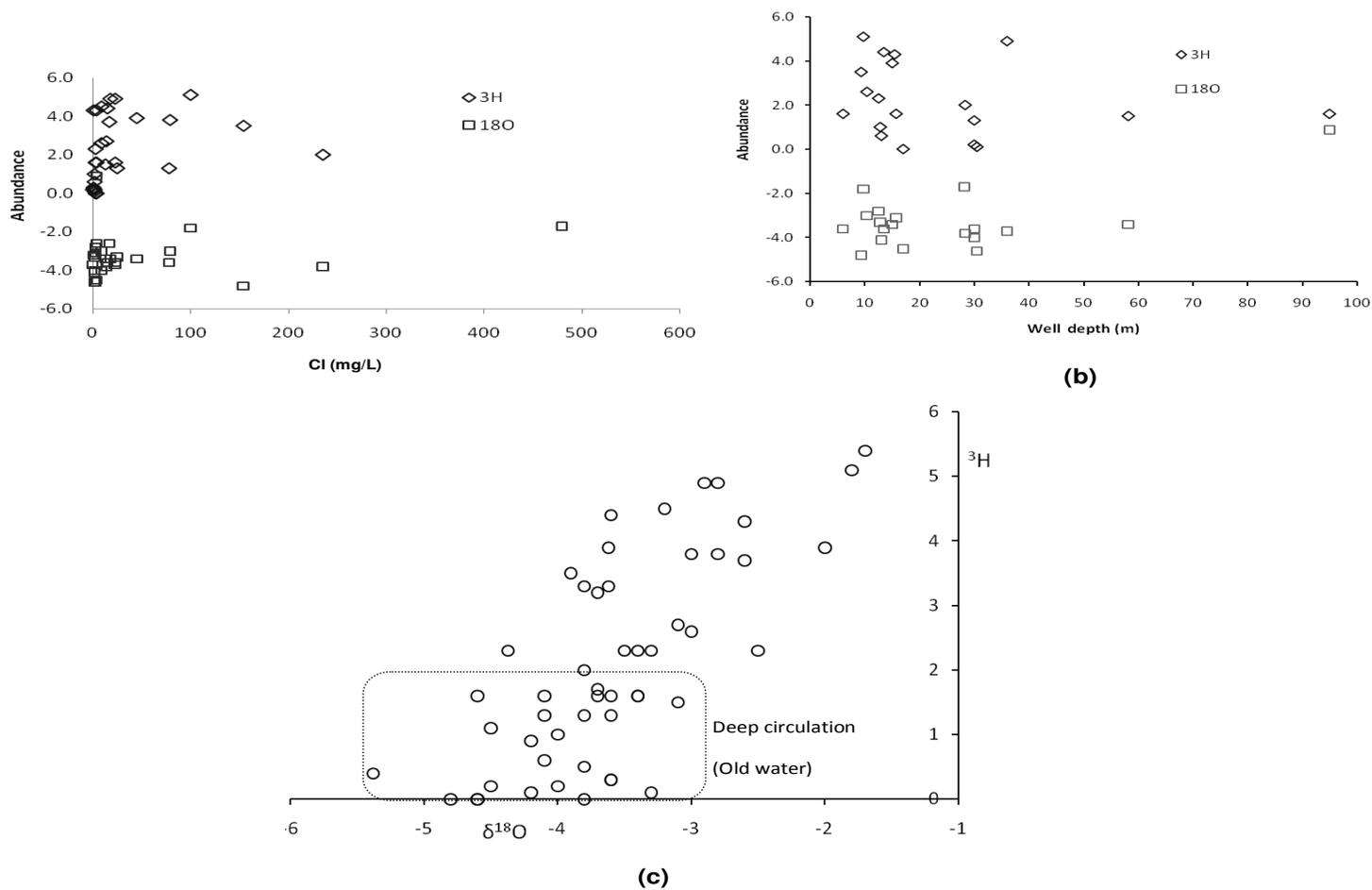


Figure 8. Environmental isotope distribution in the dolomitic aquifer.

Table 4. Weights of the five principal components.

Variable	PC_1	PC_2	PC_3	PC_4	PC_5
Ca	0.878	-0.426	0.102	-0.071	0.047
Mg	0.831	-0.119	0.489	0.045	-0.181
Na	0.814	0.085	-0.408	0.225	0.325
K	0.577	0.488	-0.323	-0.565	-0.058
Cl	0.687	0.489	-0.287	0.367	-0.260
SO ₄	0.781	-0.605	-0.089	-0.099	-0.032
HCO ₃	0.444	0.583	0.653	-0.014	0.183
eigenvalues	3.737	1.387	1.037	0.523	0.246
Cum. %	53.387	73.200	88.019	95.485	98.993

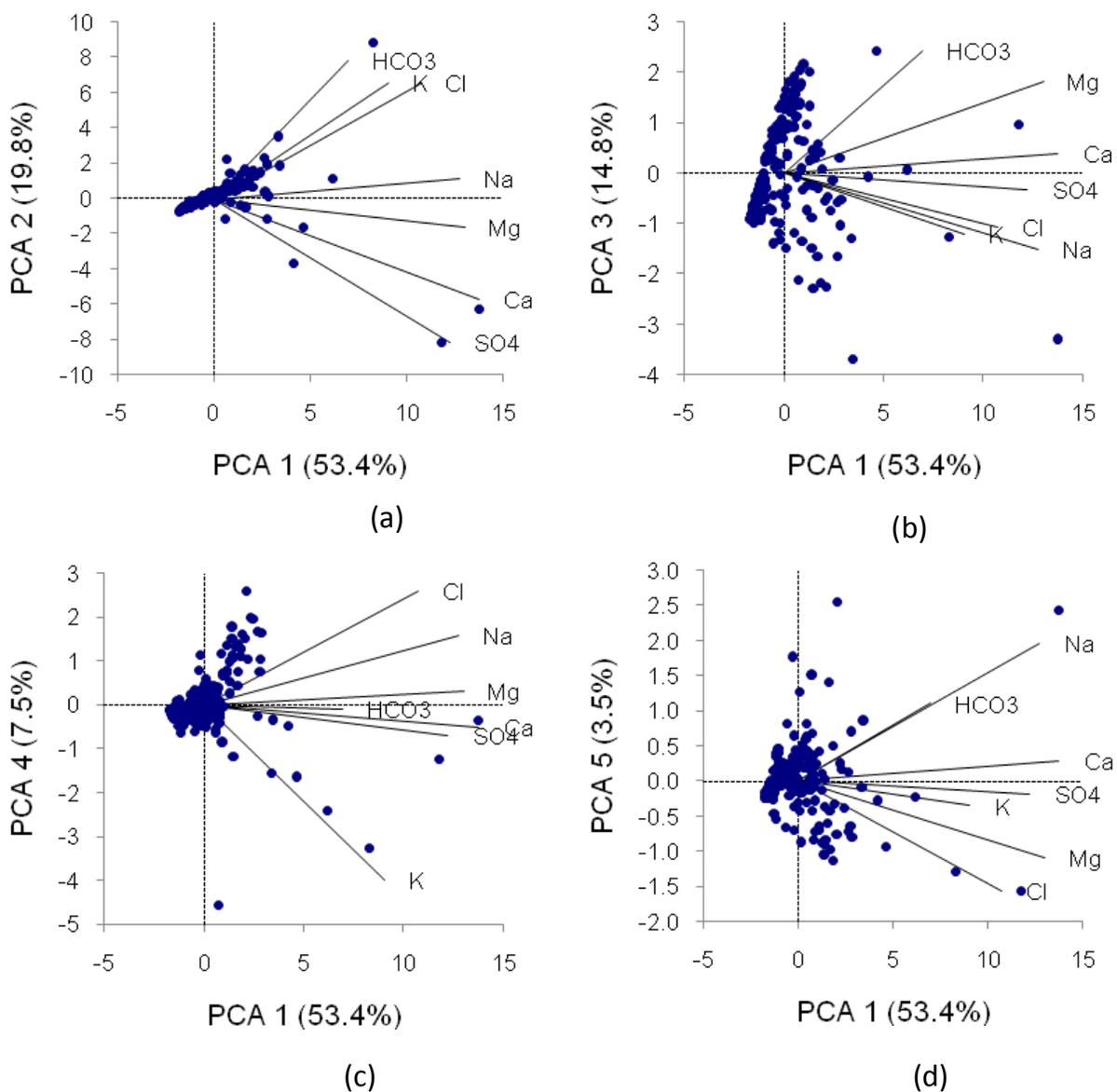


Figure 9. Loading plots of component 2 to 5 on component 1 of the groundwater quality (a: Shallow zone aquifer in the recharge area made of shale, quartzites; (b) dolomitic aquifer, (c) acidic crystalline rocks aquifer such as granite and gneisses, (d) weathered zone aquifer in low altitude areas).

HCO₃ which represents particularly shallow circulating groundwater within the weathered zones rich in clay.

Conclusions

The extreme vulnerability of the geoenvironmental setting of the Johannesburg area has highly impacted the groundwater resource where the influence of the lithology and pollution on the water composition is shown by the variation in the groundwater quality. The study revealed the loss of major ions with depth in the crystalline aquifers of the study area which shows the main movement mechanism of chemical constituents is diffusive type, which instead indicates the decrease in water velocity with depth. The diffusive circulation could also be attributed to fracture sealing by calcite precipitation that reduces the available permeability with depth. The dissolution of minerals in the acidic environments due to acid mine drainage has important contribution for the evolution of ions in the groundwater. Rapid infiltration through fractures or dissolution cavities result low degree of water-rock interaction and hence, low salinity highland waters exist within the dolomitic aquifer that contain low chloride and depleted $\delta^{18}\text{O}$. The provenance of dominant groundwater circulation lies close to the surface to the depth of 40 m from the potential recharge zone. Within the weathered crystalline aquifer, there is slower moving older component of groundwater (depleted $\delta^{18}\text{O}$ and low ^3H) that mixes with relatively young and shallow moving locally recharged water.

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