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A preliminary analysis of the groundwater recharge to the Karoo formations, mid-Zambezi basin, Zimbabwe

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Abstract

A multi-disciplinary study is being carried out on recharge to the Karoo sandstone aquifer in the western part of Zimbabwe, where recharge is controlled by the presence of a thick, confining basalt layer. The aquifer is geographically extensive, and has been identified throughout the southern part of the mid-Zambezi basin (Fig. 1). The potential for groundwater abstraction seems to be huge.

The key issues in this part of the study are the extent of the recharge area and the recharge rates. The direct recharge area has previously been considered to be the area of outcrop of Karoo Forest sandstone, before it dips below an impervious basalt cover. However, resistivity profiling shows that the basalt at the basin margin is weathered and fractured, and probably permeable, while the basalt deeper into the basin is fresh, solid and impermeable. Field and laboratory analysis of 22 groundwater samples support this extension of the recharge area to include a large area below the fractured basalt. CO₂ gas pressures, calculated with the code PHREEQC using field measurements of pH and alkalinity, show that below the fractured basalt the groundwater is an open system in contact with atmospheric CO₂. The ¹⁴C and nitrate concentrations in this groundwater also indicate that recent infiltration takes place.

The chloride contents of the rainfall and the groundwater in the recharge area have been measured to calculate direct recharge from rainfall. These data indicate that the direct recharge is in the range of 10–130 mm/yr, with an average value of 25 mm/yr. Preliminary results of recharge estimate using ³⁶Cl data suggests lower direct infiltration rates, but further studies are needed.

The combination of hydro-chemical, isotopic and geophysical investigations show that the recharge area extends well beyond the sandstone outcrop area, northwards beneath the basalt some 20 km beyond the basalt margin.

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1. Introduction

The Karoo sandstone aquifer has, since 1970, been commercially exploited around the town of Nyamandhlovu for irrigation, and in recent years, the aquifer has been considered as a possible additional water source for the city of Bulawayo. Studies on the recharge to the aquifer are now required in order to ensure that the aquifer is not over-exploited and that a sustainable abstraction rate is maintained.

In this paper, some of the ongoing activities regarding assessment of recharge to the aquifer will be presented. The project is a co-operation between the University of Zimbabwe in Harare, the University of Lund in Sweden and the Technical University of Denmark, and the field data have been collected through M.Sc studies. The project has been funded by SIDA.

The rate of recharge to the Karoo aquifer is an important parameter, which will control the optimum rate of groundwater abstraction from the basin. The two critical factors controlling recharge are (1) the rate of direct recharge by infiltration and percolation into the aquifer system, and (2) the areal extent of over which recharge takes place. These factors are evaluated in this paper. Additional recharge through river bed infiltration is not assessed here.

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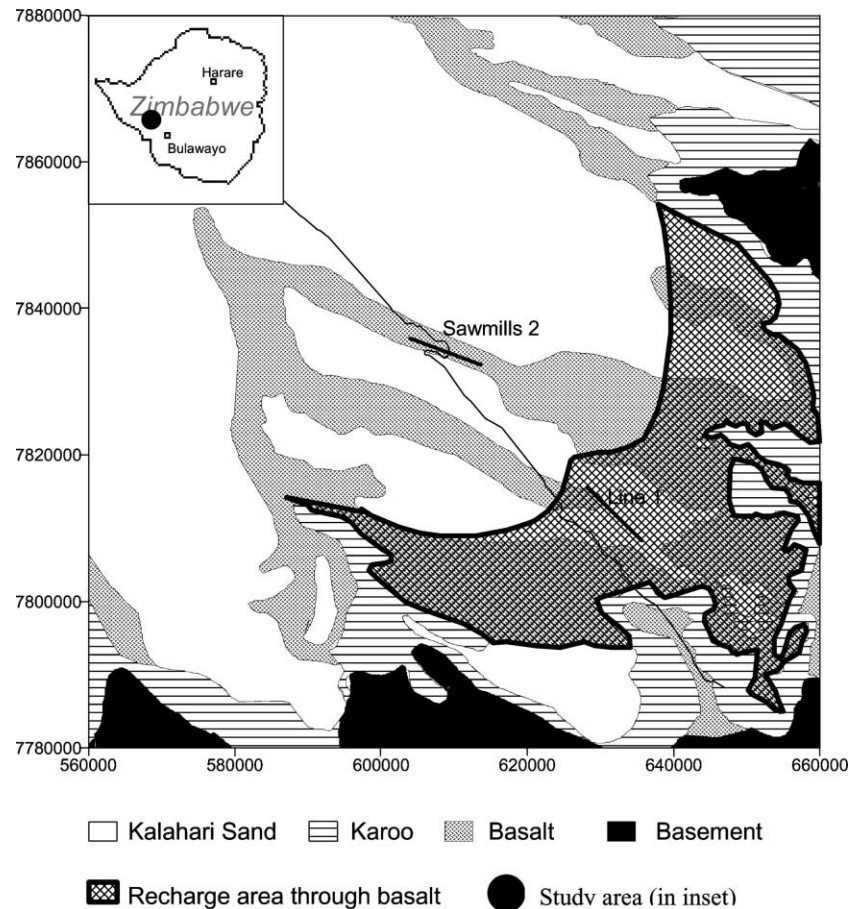


Fig. 1. Geology of the study area, showing the extended recharge zone through the basalts near the basin margin.

2. Hydrogeology and groundwater flow in the basin

The mid-Zambezi Karoo basin occurs in the north-western part of Zimbabwe, extending from the Zambezi river in the north, southwards to the town of Nyamandhlovu, approximately 40 km north of the city of Bulawayo (Fig. 1).

The mid-Zambezi basin is considered to be a half-graben extensional tectonic basin, with the southern margin being the passive margin, filled by gently shelving sediments, which deepen to the north (Orpen et al., 1989). There is some evidence, based on borehole sediment thickness, that the margin is not entirely passive, and that some faulting occurs.

The 20–60 m thick Upper Forest sandstone is the dominant water-bearing zone in the upper Karoo, and the 20–100 m upper and lower Hwange sandstone units constitute the main aquifer in the lower Karoo. The Forest sandstone is unconfined in a 15 km broad belt in the southern-most part of the basin (Fig. 1). Just south of the small town of Nyamandhlovu, the sandstone is covered by a confining layer of basalt, which thickens to a maximum of 90 m in the central part of the basin. Karoo sandstones are present in the entire basin, but the

groundwater conditions flow system in the northern part of the basin is not known.

A piezometric map of the groundwater surface in the study area shows that there is a gradient towards the north-west with a slope of 2.6‰ (Fig. 2). The groundwater is known to be confined towards the north-west, as shown by sub-artesian and flowing artesian conditions which have been observed in a number of boreholes that penetrate through the basalt at Sawmills and other localities.

Given the relatively small groundwater abstraction north of the well fields in the Nyamandhlovu area, the fact that a hydraulic gradient exists shows that a natural flow of groundwater must be taking place towards the north-western parts of the basin, and consequently natural groundwater discharge must occur to the north-west. The groundwater flow can also diverge north of the study area and flow westwards towards Botswana.

Beasley (1983) estimated porosities from densities of a drill core in the Upper Karoo as 9–31%, with an average value of 22%. Based on in situ tracer tests, Banda et al. (1977) estimated the unconfined storage coefficient as around 4%.

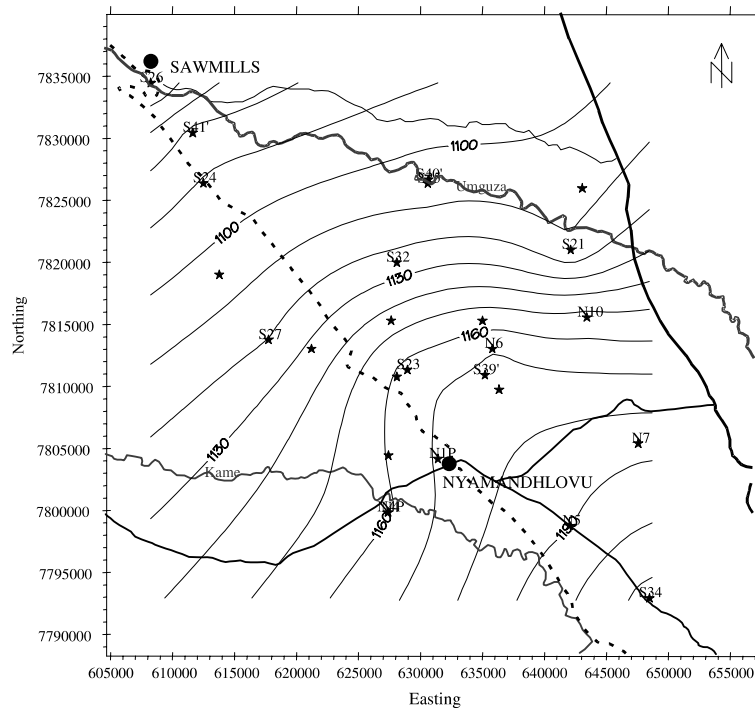


Fig. 2. The hydraulic potential in meter above sea level in the Upper Karoo sandstone based on measurements of the static water table in 21 boreholes during November 1999.

Several authors have performed pumping tests in the Upper Karoo sandstone (Beasley, 1983; SWECO, 1995; Martinelli and Hubert, 1996). Beasley estimated from sieving analyses a hydraulic conductivity of the sand in the range of 6×10^{-7} – 6×10^{-5} m/s, and he reports of transmissivities in the range of 5×10^{-5} – 4.6×10^{-3} m²/s. For consistency of the two data sets, flow must take place in a saturated zone with an average thickness of 100 m. SWECO (1995) estimates a transmissivity of 1×10^{-6} m²/s from a deep borehole at Sawmills.

3. Geophysical investigations

A variety of geophysical investigation methods (resistivity, TEM, gravity, HLEM and ground and aerial magnetic surveys) have been used in the study area to try and determine the aquifer geometry. A key method has been multi-electrode resistivity, using an array of 64 electrodes and a multi-core cable connected to a switching control box, which in turn is connected to an Abem terrameter. This method has been used around Sawmills (Glatz and Persson, 1999) and around Nyamandhlovu (Andersson and Engman, 2000).

Some results are presented here which focus on the Karoo basalt and allow an appreciation of the changing nature of the basalt layer and its probable effect on the groundwater conditions. Two profiles are presented: the first is from the south-eastern part of the study area near

the basin margin (line 1); the second (Sawmills 2) is from the north-western part of the study area much further into the Karoo basin, near Sawmills (Fig. 1).

The first of these two sections show that the basalt near the basin margin is thin, deeply weathered and fractured (Fig. 3a). It is therefore likely to be permeable and the sandstone aquifer underneath the basalt in such areas is likely to be unconfined and receive direct recharge. The second section further from the basin margins shows that the basalt has become thicker, continuous and relatively fresh (Fig. 3b). In such localities, the basalt is likely to be impermeable and act as a confining layer. This interpretation of the geophysical evidence is supported by the presence of artesian wells at Sawmills and further into the basin and by the chemical and isotopic data collected from boreholes in the basin.

4. Groundwater sampling

During the first field campaign in this study in 1999, groundwater was sampled from 24 boreholes and the depths to the water table were measured (Aspelin and Wallin, 2000; Nielsen, 2000). In the field, measurements were made of dissolved oxygen, electrical conductivity and pH in a flow cell, which ensures that degassing does not occur. Dissolved ferrous iron was measured in a field using a HACH 2010 spectrophotometer and alkalinity

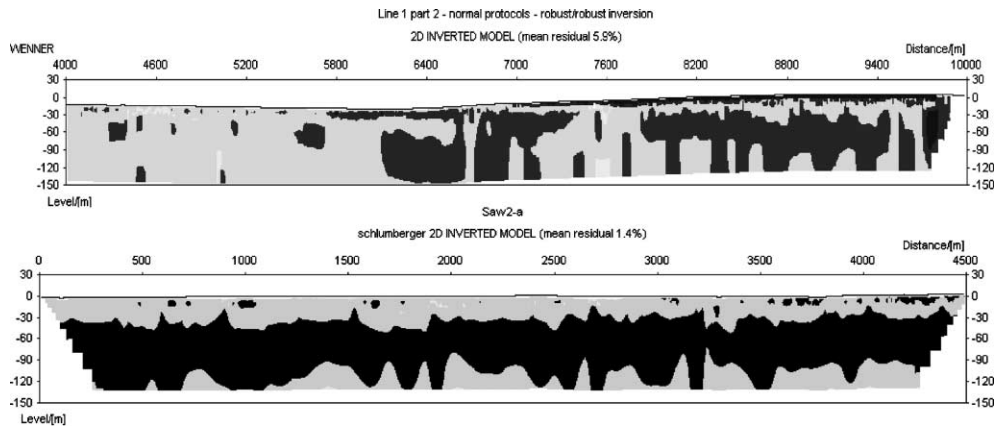


Fig. 3. (a) The two resistivity plots ($4 \times$ vertical exaggeration) show the extent of fresh basalt, which acts as a confining layer to the Karoo Forest sandstone, which lies below. The light colours are resistivity values below $100 \Omega\text{m}$ and the black colour represents resistivity values above $100 \Omega\text{m}$. The upper image is taken at Epping Forest farm, nearer the passive margin of the aquifer to the south-west, and here it can be seen that the fresh basalt is very patchily developed, and is fractured, allowing groundwater recharge. The lower image, taken from Sawmills, shows that the fresh basalt is thick and unbroken here, and hence acts as an impervious layer, resulting in confined conditions in the underlying aquifer.

was determined in the field using the Gran-titration method (Appelo and Postma, 1996).

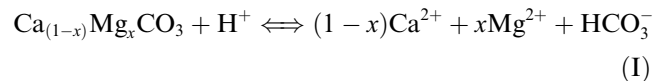
Samples for analysis of cations and anions were filtered, and the sample for cations analyses was preserved with 1 vol.% 7 M nitric acid. The water for analyses of anions was frozen to prevent bacterial reduction of nitrate. Laboratory analyses were done in Lund, Sweden; cations were analysed with optic ICP (Perkin Elmer Optima 3000 DV) and anions analysed with a suppressed ion chromatograph (Idionex DX-100). Tritium was analysed at the University of Waterloo, Canada and the detection limit was 0.8 TU. The ^{14}C content was analysed at the University of Aarhus, and the ^{2}D and ^{18}O at the Geophysical department, University of Copenhagen. ^{36}Cl was done by AMS measurement by direct counting at ETH, Zürich in Switzerland.

4.1. Water types

The results of the analyses in 22 boreholes in the Upper Karoo Sandstone shows that the groundwater can be divided into two overall water types, and the chemical compositions of these is given in Table 1. The spatial distribution of the defined water types is given in Fig. 4.

4.1.1. Water type 1

The water type dominates in the investigated region and has a general composition of Ca-HCO_3 , with a high Mg content and a neutral pH in the range of 6.6–7.7. Calculations with PHREEQC (Parkhurst and Appelo, 1999) shows that the water is saturated with respect to calcite (CaCO_3), or more likely a low magnesium calcite with the composition $\text{Ca}_{(1-x)}\text{Mg}_x\text{CO}_3$. Dissolution of the low magnesium calcite is given in reaction (I)



The produced alkalinity will be in equilibrium with aqueous $\text{CO}_2(\text{aq})$, which again will be in equilibrium with a gaseous $\text{CO}_2(\text{g})$. The overall reaction is given in Eq. (II).



Calculations based on the pH and alkalinity measurements using the computer programme PHREEQC, give values of $\text{CO}_2(\text{g})$ in the range of $1.5\text{--}10 \times 10^{-3}$ atm. These values can be compared with the present value in the atmosphere of 0.3×10^{-3} atm and the highest concentration in contact with soil water, which is 30×10^{-3} atm (Appelo and Postma, 1996). Calculated equilibrium in the $\text{CO}_2(\text{g})$ is in the range of 20–100 mg/l, and these are comparable with observed values in water type 1, which are from 28 to 98 mg/l. These calculations shows that the dissolution of carbonate minerals has occurred in an open system in contact with atmospheric or soil $\text{CO}_2(\text{g})$.

The groundwater in type 1 contains up to 6.4 mg/l of dissolved oxygen, which is close to saturation in equilibrium with atmospheric oxygen. Nitrate is present in concentrations from 0.8 to 71.9 mg/l, and such high concentrations of nitrate must be derived from nitrogenous fertilisers used on irrigated farm-lands in the recharge area, which indicates that nitrate can be used as a tracer in this study area.

The silica content in water type 1 samples is relatively high with concentrations from 15.1 to 35.3 mg/l (Table 1). Calculations with PHREEQC indicate that the water is super-saturated with respect to quartz and other silica minerals in the sandstone. The high silica content comes

Table 1

Chemical composition of groundwater samples from the study area. The groundwater can broadly be divided into the Ca-HCO₃ and Na-HCO₃ water types

Bore-hole	pH	O ₂	EC	Ca ²⁺	Mg _{eq} ²⁺	Na ⁺	K ⁺	SiO ₂	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻	NO ₃ ⁻	F ⁻	pCO ₂ (atm)	C-14 pMC	¹³ C	¹⁸ O	² H	3H TU	36-Cl/L 10 ⁻⁷ Atmos	³⁵ Cl/ ³⁵ Cl 10 ⁻¹⁵
<i>Type 1 Ca-HCO₃ groundwater</i>																					
S20	7.02	4.3	346	28.3	11.4	12.8	0.7	35.3	206.2	2.1	0.2	2.8	0.5	2.0E-03							
N5	7.01	3.3	714	67.9	24.9	23.6	1.2	31.0	441.0	10.4	0.2	7.7	0.3	4.5E-03	86	–	–5.32	–38.2	<0.8		
N1	6.89	3.85	629	65.7	19.4	17.0	1.4	30.7	368.4	17.3	0.1	3.0	0.0	4.9E-03	37	–	–6.68	–45.5	0.9		
S21	6.91	2.4	836	84.6	22.1	22.4	1.6	26.6	463.6	8.3	2.7	22.4	0.0	6.2E-03	86	–13.0	–5.52	–39.2	<0.8	10.0	7.06
S22	6.9	2.3	866	90.9	22.3	24.8	1.9	25.2	363.6	11.2	8.9	44.4	0.0	4.7E-03	82	–10.7	–5.87	–39.2	<0.8		
S23	7.2	3.6	489	46.5	15.5	15.9	1.2	31.4	277.6	4.4	0.4	7.5	0.0	2.0E-03	74	–14.5	–6.19	–42.3	<0.8		
N10	6.86	1.5	660	72.2	18.2	18.8	2.1	25.4	405.7	4.7	0.0	1.7	0.1	4.6E-03							
N7	7.01	0.6	629	65.6	20.9	15.1	1.4	25.1	398.3	2.6	0.1	0.4	0.1	4.0E-03							
S28	6.81	3.0	643	73.1	19.3	8.9	3.3	15.1	395.3	9.0	1.1	7.6	0.0	6.3E-03							
S29	7.07	2.3	511	51.4	14.6	15.8	1.4	28.4	317.2	2.5	1.2	0.8	0.0	2.8E-03							
S30	6.71	1.7	789	80.9	24.2	17.8	2.4	31.1	419.7	20.1	2.1	34.4	0.0	8.5E-03							
S31	6.59	2.6	733	70.2	25.7	16.5	0.4	26.5	362.3	15.7	26.5	31.7	0.0	9.6E-03							
S32	6.88	3.3	648	55.7	14.1	32.5	3.4	19.9	371.5	10.2	1.6	12.2	0.0	5.1E-03							
S33	6.74	3.2	1042	98.9	32.0	33.0	1.5	28.7	534.4	21.6	7.3	42.4	0.0	10.0E-03	93	–11.4	–6.02	–42.3	<0.8		
S34	6.65	3.7	691	75.4	18.7	13.2	1.9	23.5	343.4	18.3	3.4	25.4	0.0	8.0E-03							
S35	7.19	6.4	649	59.6	16.3	18.6	1.3	29.0	223.3	25.8	7.7	71.9	0.0	1.5E-03							
S37	6.8	2.5	617	61.5	20.3	17.2	0.7	32.3	391.6	5.5	1.2	3.6	0.0	6.4E-03	94	–15.5	–6.38	–42.3	<0.8		
S38	6.96	2.1	716	76.3	21.7	19.2	1.5	28.6	462.4	2.1	1.2	0.8	0.0	5.2E-03							
<i>Type 2 Na-HCO₃ groundwater</i>																					
S25	9.1	2.2	465	1.0	0.1	87.3	1.0	6.2	263.5	11.4	1.3	1.4	0.1	2.2E-05	4.9	–11.2	–6.60	–43.7	<0.8	13.4	6.9
S26	9.11	0.2	833	0.5	0.1	154.9	0.7	6.6	457.5	30.2	15.5	0.0	1.9	3.7E-05	0.89	–12.0	–7.10	–47.5	<0.8	10.4	2.03
S27	9.4	1.4	814	0.8	0.0	140.9	0.8	9.9	316.0	24.0	63.4	0.8	4.0	1.4E-05	0.04	–10.8	–6.92	–46.8	<0.8	7.1	1.75
N4	9.38	0.7	1079	44.5	0.2	130.0	2.0	10.0	27.5	21.1	266.9	0.0	5.3	0.1E-05			7.08	–47.0	<0.8		

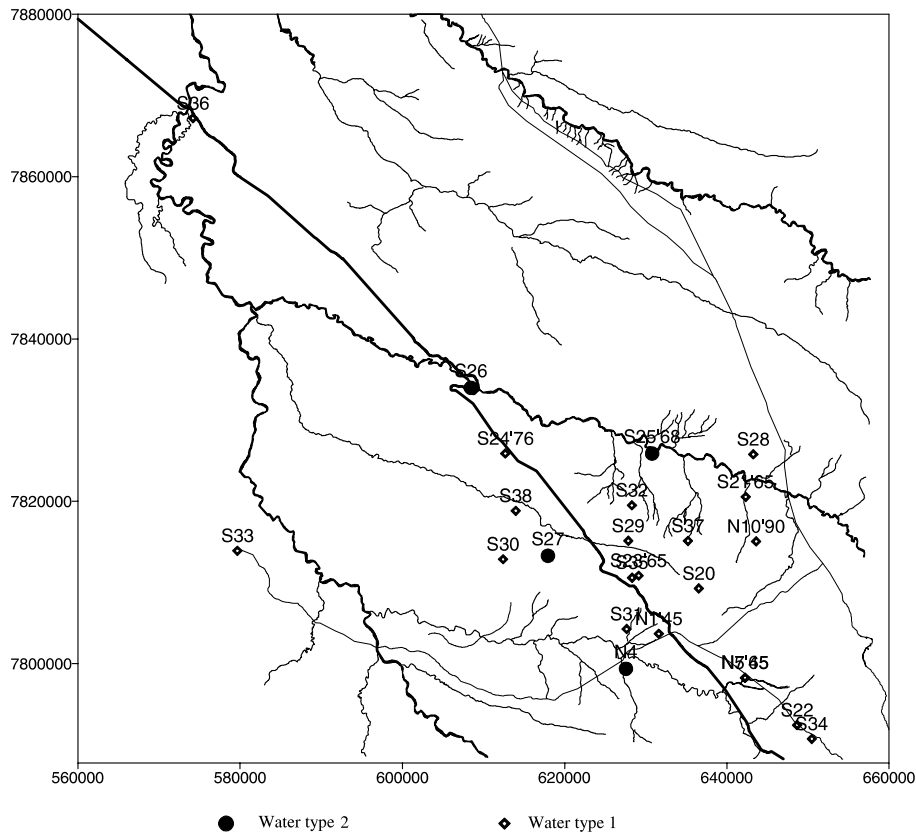


Fig. 4. The spatial distribution of the two main water types in Karoo sandstone.

from weathering of mafic minerals in the basalt layers, and the high silica content can thus be used as a tracer that indicates that the ground water has in contact with the basalt during the recharge process. In a groundwater sample collected in the covering basalt layer, the concentration of silica is also high with a value of 28.9 mg/l (Aspelin and Wallin, 2000).

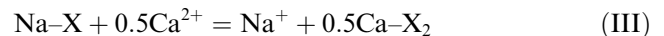
In water type 1, the concentrations of modern C-14 are high with percentages of modern carbon in the range of 74–94 pmc, excluding borehole N1 with 37 pmc (Nielsen, 2000) indicating that mixing with old water is taking place in this borehole. The concentrations of tritium are below the detection value of 0.8 TU, again apart the value from borehole N1, which contained 0.9 TU.

Water type 1 is found in the southern-most part of the study site, from areas in the south where the Upper Karoo sandstone outcrops, and extending northwards some 10 to 20 km into the areas where basalt overlies the sandstone (Fig. 4).

4.1.2. Water type 2

The groundwater defined as water type 2 is a Na–HCO₃ type water. The high sodium content between 87.3 and 154.9 mg/l together with the very low calcium and magnesium concentrations below 1 mg/l and the

high pH values between 9.1 and 9.4 shows that the dominant process is a cation exchange reaction, see reaction (III).



where X indicates the sediment exchanger. Calcium is taken up from water to the exchanger, and sodium is released. The water type thus changes from a Ca–HCO₃ type to a Na–HCO₃ type. The source of the sodium on the exchanger comes from the weathering of minerals, e.g. albite (NaAlSi₃O₈) in the sandstone.

The exchange reaction will have an effect on the pH of the water since the removal of calcium from the water will enhance the dissolution of calcite (reaction I), which consumes H⁺, and therefore the pH will rise. In water type 2, pH values are 9.1–9.4 (Table 1).

Calculations using pH and alkalinity measurements with PHREEQC gives values of CO_{2(g)} in the range of 0.2×10^{-5} – 3.7×10^{-5} atm, values which show that the water is not in contact with the atmosphere, as used CO_{2(g)} is not replenished.

In water type 2, dissolved oxygen concentrations are in the range of 0.2–2.2 mg/l and concentrations of nitrate are from 0 to 1.4 mg/l.

High concentrations of fluoride, up to 5.3 mg/l, are present in this water and these high concentrations of

Table 2
Calculated concentrations of ^{36}Cl in groundwater in the Karro sandstone aquifer for given rates of evaporation loss

	Fall-out $^{36}\text{Cl} \times 10^8$ (atoms/m ² /yr)	^{36}Cl atoms/l 10^7 Infiltration		
		50 mm	25 mm	2.5 mm
Pre-thermonuclear	2.5	0.5	1	10
Thermonuclear (low)	25	5	10	100
Thermonuclear (high)	1250	625	1250	3125

A rainfall of 550 mm/yr is used (Beasley, 1983). The natural ^{36}Cl fall out concentration is taken from Bentley et al. (1986), and thermonuclear values are from Clark and Fritz (1997).

fluoride are associated with elevated concentrations of sulphate, with values up to 266.9 mg/l. These elevated concentrations are found in strata in the uppermost part of the Upper Karoo sandstone, and are most likely associated with dissolution of salt-pans with fluorine and sulphate containing minerals such as fluorite (CaF_2) and anhydrite (CaSO_4).

The silica content in water type 2 is relatively low with concentrations from 6.2 to 10.0 mg/l (Table 1). Calculations with PHREEQC indicate that the water is saturated with respect to quartz and other silica minerals in the sandstone.

Concentrations of modern ^{14}C are low in water type 2 with concentrations from 0.04 to 4.9 pmc, and concentrations of tritium are below the detection limit of 0.8 TU (Nielsen, 2000).

Water type 2 is found in the northern part of the study area where the upper Karoo sandstone is confined below the basalt, which becomes thicker towards the north-west of the basin (Fig. 4). Sample N4 (water type 2) in the southern part of the basin is an exception, and is considered to have derived its chemistry from a local evaporite type deposit.

5. Recharge estimates from chloride concentrations

Estimation of the recharge to an aquifer can be done using the stable chloride isotopes, ^{35}Cl and ^{37}Cl , if it is assumed that the concentration of chloride in the shallow groundwater is due to a further concentration of the chloride in rainwater (Edmunds et al., 1990). Infiltration to the Karoo sandstone occurs most likely both as direct recharge from precipitation and as indirect recharge due to infiltration from stream-beds. The mean annual precipitation in the Nyamandhlovu area is around 550 mm (Beasley, 1983).

The total deposition of chloride in western Zimbabwe, including both wet and dry deposit is approximately 0.5 mg/l, but the figure is not well constrained. Concentrations of chloride in groundwater in the recharge area of the Karoo sandstone (water type 1) are in the range of 2.1–25.8 mg/l, with an average concentration of 10 mg/l. During this year (2001) sampling of groundwater from 15 shallow boreholes in the recharge

area revealed concentrations in the groundwater range from 1.6 to 76.5 mg/l, and the average chloride concentration was again 10 mg/l. One sample from the Khami River contained chloride in a concentration of 72.7 mg/l.

The observed very low concentration of chloride of 1.6 mg/l most likely represents indirect infiltration from a river-bed by storm-water run-off, while the high concentration may be a result of indirect infiltration from ponds, which have experienced evaporation in the dry season. The intermediate chloride concentrations, with an average of 10 mg/l, may then reflect direct infiltration to groundwater. Assuming that the measured concentration of chloride in the shallow groundwater occurs as a result of direct recharge, then values of groundwater recharge to the aquifer can be calculated to be in the range of 10–130 mm/yr, with an average value of 25 mm/yr, occurring over the surface of the identified recharge area.

Measurement of ^{36}Cl contents in recharge waters can also be used to estimate recharge to aquifers, if the fall out of produced ^{36}Cl in the atmosphere is well known and the epigenic production is insignificant (Clark and Fritz, 1997). The natural atmospheric fall out of ^{36}Cl is a function of the latitude (Bentley et al., 1986), and in Zimbabwe, located at 20° south, the fallout is 2.5×10^8 atoms/m²/yr. However, following marine thermonuclear tests in the period 1952–1958, the atmospheric fall out of ^{36}Cl was increased by a up to 500 times greater than the natural level (Andrews and Fontes, 1992).

In the field campaign in 1999, water samples for ^{36}Cl analysis were sampled from four boreholes; S21, S25, S26 and S27 (Table 1). Only borehole S21 is located in the recharge area (Type 1), and the other three is located in the confined part of the aquifer (Type 2). In S21 the measured concentrations of ^{36}Cl is 10×10^7 atoms/l. With a pre-thermonuclear ^{36}Cl concentrations of 2.5×10^8 atoms/m²/yr (Bentley et al., 1986), a concentration of ^{36}Cl in this range can be obtained with an infiltration of 2.5 mm from a rainfall of 550 mm. If, on the other hand, the infiltration occurred after the thermonuclear testing was started in 1952, a ^{36}Cl concentration of 10^7 atoms/l can also be created with an infiltration of 25 mm, if the fall out was increased by a factor of 10 (Table 2).

If the groundwater in the sample from S21 infiltrated in the period after thermonuclear testing was initiated in 1952, elevated concentrations of tritium should be expected in the water, which are not seen (Table 1). However, on the other hand, the concentration of nitrate of 22.4 mg/l in this groundwater sample clearly suggest that the water is relatively young, as only the modern use of fertilisers with a high concentration of nitrate are able to generate such concentrations of nitrate in the groundwater.

Clearly the potential for the use of ^{36}Cl concentrations in groundwater cannot be evaluated on one analysis alone, and more data must therefore be collected.

6. Discussion and conclusions

The results of the geophysical survey using the CVES method and the chemical composition of the distribution of groundwater types in Karoo sandstone shows that recharge occurs in the unconfined part of the aquifer and in the fractured part of the covering basalt layer in the southern part of the basin. In the studied area this means that the area where recharge takes place is not around 1000 km² as stated earlier (Martinelli et al., 1996) but rather 3000–4000 km². The total recharge to the aquifer most therefore have been under estimated in the Martinelli and Hubert, 1996 study. Even this expanded recharge area is an underestimate since it does not account for recharge areas to the west along the southern boundary of the basin or recharge areas to the north along the eastern boundary of the basin.

The estimated annually recharge to the Karoo sandstone of 20–25 mm must be confirmed with numerical modelling of the natural groundwater flow generated by the observed hydraulic gradient. However, the Karoo sandstone must be considered as a double porosity medium, where groundwater flow may or may not be significant in the matrix of the sandstone. Therefore an analysis of the hydraulic behaviour of this dual porosity system must be undertaken before a realistic model can be established. Calibration and validation of such a model will, however, be difficult since the boundary conditions are poorly defined. Therefore dating of the groundwater using methods such as ^{13}C , ^{36}Cl and ^4He can be useful, but this model must take into account that any decrease in the radio nuclide compounds may not be due to a radioactive decay alone, but also due to diffusion into the matrix of the Karoo sandstone (Neretnieks, 1980; Sandford, 1997).

Based on a recharge area of 3000 km², and a recharge rate of 20 mm/yr, a total annual recharge to the aquifer is estimated as 6×10^7 m³/yr, which provides $\approx 160,000$ m³/day. The present pumping rate from the aquifer is

approx. 25,000 m³/day for agriculture and $\approx 20,000$ m³/day for the city of Bulawayo. It therefore appears that there is considerable room for expansion of the total pumping rate from the aquifer, but care should be taken to spread the well-fields across the aquifer in order to avoid excessive drawdown in any single locality.

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