Land-use impacts on the quality of groundwater in Bulawayo

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Abstract

The impacts of land use from commercial, industrial and domestic activities in the second largest city (Bulawayo) in Zimbabwe on groundwater quality are investigated in this paper. Thirty-two boreholes that are located in the Matsheumhlope Wellfield, a basement aquifer that underlies the city of Bulawayo, were monitored during the period between August 2000 and August 2001. The results showed that the majority of the parameters (iron, manganese, copper, nitrate, fluoride, sulphate and cyanide) at most sampling stations are within the recommended and permissible limits specified in Zimbabwe drinking water standards guidelines (SAZS 560:1997). The water can therefore be used for drinking purposes. However, levels of hardness higher than the maximum allowable according to Standard Association of Zimbabwe (SAZ) guidelines were encountered. Microbiological analysis indicates that 27% of the samples showed positive total coliform and 8% positive faecal coliform with their occurrences being randomly distributed spatially and temporally. Comparison of the water quality in the industrial and residential areas revealed statistically significant differences in water quality of the two areas. The study reveals that leaks from industrial and domestic sewers, commonly being experienced due to the age of the sewer lines, are increasingly compromising the quality of the groundwater, while unusually high levels of EC encountered at two sampling stations seem to be related to the geological formation. The results from sampling groundwater within the vicinity of the landfill site in Richmond do not present a picture that is different from the other residential areas monitored, suggesting that leachate is being contained within the landfill liner and does not, as yet, pose an environmental threat to the aquifer.

Keywords: groundwater; water quality; land use; environmental impact

Introduction

Solid and liquid waste disposal and other land-use related activities constitute some of the sources of pollution to the environment on which humans depend for their sustenance. One of the consequences is the deterioration of air and water quality (both surface and groundwater). Bulawayo, the second largest city of Zimbabwe, is in the Matabeleland South region with a semi-arid climatic regime that is characterised by evapotranspiration in excess of rainfall. The region receives low and erratic precipitation with average annual rainfall of about 600 mm which ranges between 199.3 mm and 1 258.8 mm with a standard deviation of 202.3 mm. Potential evapotranspiration ranges from 1 400 mm to values greater than 2 000 mm. Rains generally fall from November to March, and October is usually the hottest month with temperatures of over 40°C being observed. The soil type of the region is closely related to the underlying lithology with grayish to reddish brown shallow to moderately deep soils that are associated with granite and allied rocks.

The city is located about 110 km from the Botswana border in the west, and plays host to a number of industries of various kinds: tanning industries (Midrion Enterprises, Wet Blue Industries), breweries (National Brewery, Ingwebu Breweries), soft drink manufacturing (Schweppes, United Bottlers), textiles (Jeans Company, Security Mills, Miller and Thomson), pharmaceutical (Datlabs, Lancaster Industrials, Zimbabwe Pharmaceutical), plastic and rubber industries (Dunlop), abattoirs and dairy processing (Kelshemar Dairies and Dairy Board Zimbabwe Limited), commercial transportation (Western Transport, Zimbabwe United Passenger Company, Super Godhlwayo), fuel storage, metallic and paint industries. It serves as the headquarters of the country's railway network (National Railways of Zimbabwe). The city derives its potable water supply from five surface water dams (Upper and Lower Ncema dams, Insiza, Inyankuni and Umzingwane) that are located some 60km south-east of the city. The supply from these dams is adequate in years of normal rains, but not in drought years that have, in recent times, shown a recurrence of 10 years (1982, 1992, 2002). These drought years have prompted the adoption and implementation of water conservation measures with consideration being given to the use of reclaimed water and groundwater as supplementary sources. Groundwater was used by the municipality of Bulawayo to supplement its water supplies during the 1992/93 drought and proved a valuable resource. Currently water from private boreholes is mainly used for urban agriculture, irrigation of lawns and parks, and general-purpose cleaning but rarely used for drinking. The aim of the present study is to evaluate and characterise the groundwater quality with the overall goal of exploring its feasibility for industrial, commercial and domestic uses. The use of groundwater has several advantages over surface water which include:

- Availability of groundwater as a naturally occurring reservoir in contrast to a specific localised surface source.
- Less susceptibility to evaporation losses and climate variability compared to surface water bodies like lakes and dams

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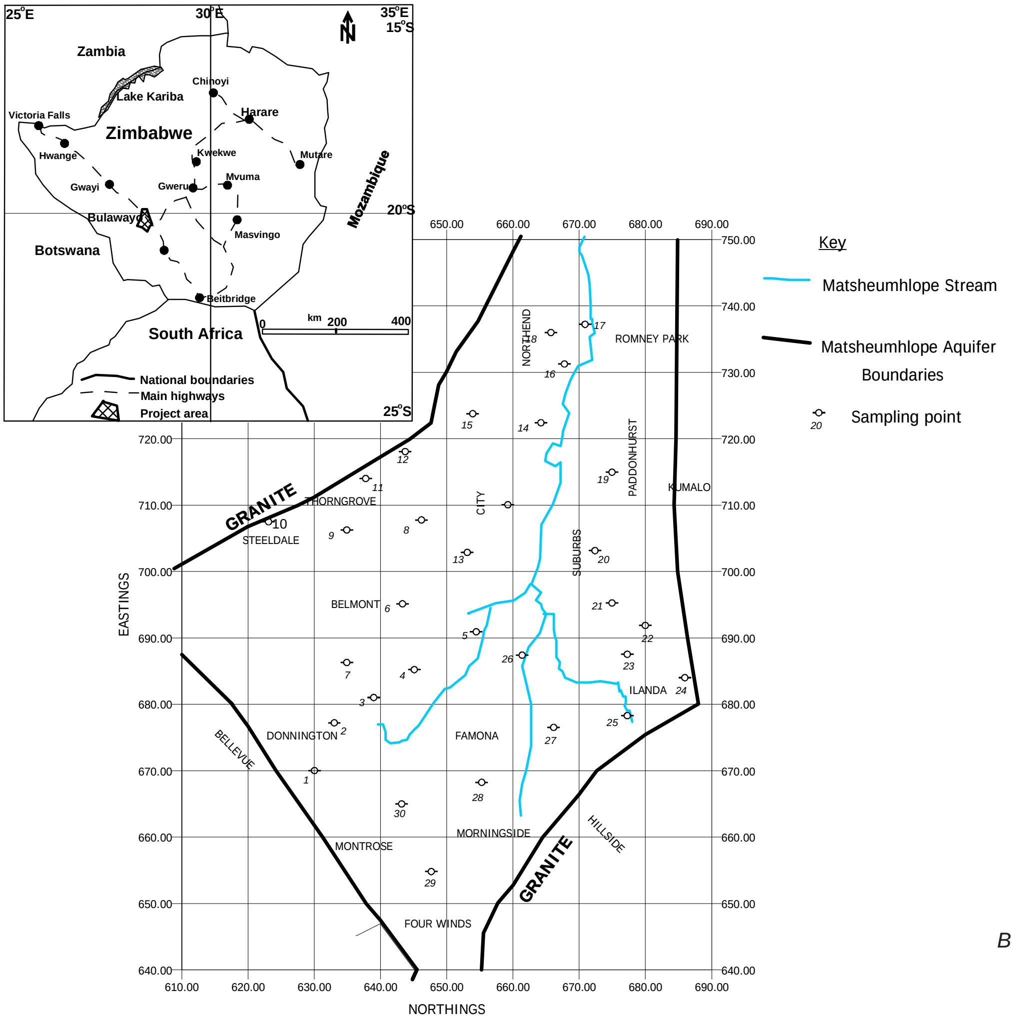

Figure 1
Borehole location map

- Generally superior quality (for most parameters) than surface waters due to the filtering effects of overburden soil and its less vulnerability to anthropogenic activities.

Despite these advantages of groundwater, it is generally known that groundwater quality can be impacted by land-use related activities, particularly in urban environments, with remediation of polluted groundwater being more difficult to achieve than surface waters. Markussen and Moller (1994) report on a study carried out on the quality of the groundwater in aquifers **underlying? (Author?)** Copenhagen, Denmark where the use of a number of wells was discontinued due to reported pollution problems. Sadek and El-Sami (2001) carried out a study to investigate susceptibility of quaternary aquifers in Egypt, in the vicinity of Cairo. Samples were collected at 13 points and analysed for parameters such as pH, EC, major cations and anions, isotopes, nitrates and silicates. The groundwater in Shobra El-Khima was found to be less mineralised than at Imbaba. This was attributed to the smaller thickness and higher permeability of the clay layer that served as a protective layer over the Imbaba area. Wagner and Surkrisno (1994) described the natural groundwater quality of the Bandung Basin in Indonesia and the effects of human activities on its quality. The study revealed that the chief pollution hazards are the infiltration of domestic sewage and discharge of untreated industrial wastewater into the subsurface. Groundwater protection measures, that included proper management of land-use changes and restrictions on pesticide application in the vicinity of water supply springs, were proposed. Numerous studies carried out on the aquifer underlying the city of Nottingham in the UK indicate that sewer leakages have an impact on the groundwater quality, accounting for about 5% of the total recharge to the aquifer (Barrett et al., 1999; Yang et al., 1999 and Cronin et al., 2003). Cronin et al. (2003) made an attempt to characterise the spatial and temporal variations in sewage-related microbial and anthropogenic-related inorganic contamination of the aquifer. These are but a few of the case studies of groundwater pollution-related problems that are attributable to anthropogenic activities. Due to ever-increasing human population in urban settings, coupled with depletion of surface water sources, there is greater demand on the groundwater sources with attendant problems of over-abstraction and ingress of domestic and industrial waste which have negative impacts on groundwater quality.

Study site

The study is mainly concentrated on the Matsheumhlope Wellfield, of which the aquifer boundaries have been suggested by Weaver et al., 1992. Its geology was summarised in Rusinga (2002). The wellfield is about 52 km^2 in areal extent and it covers the commercial district that includes the city centre, industrial areas of Belmont, part of Donnington, Steeldale, Westondale and Thorngrove, and residential areas of Morningside, Greenhill, Montrose, Barham Green, Famona, Hillcrest, Ilanda, Bradfield, Suburbs, part of Paddonhurst and Northend (Fig. 1).

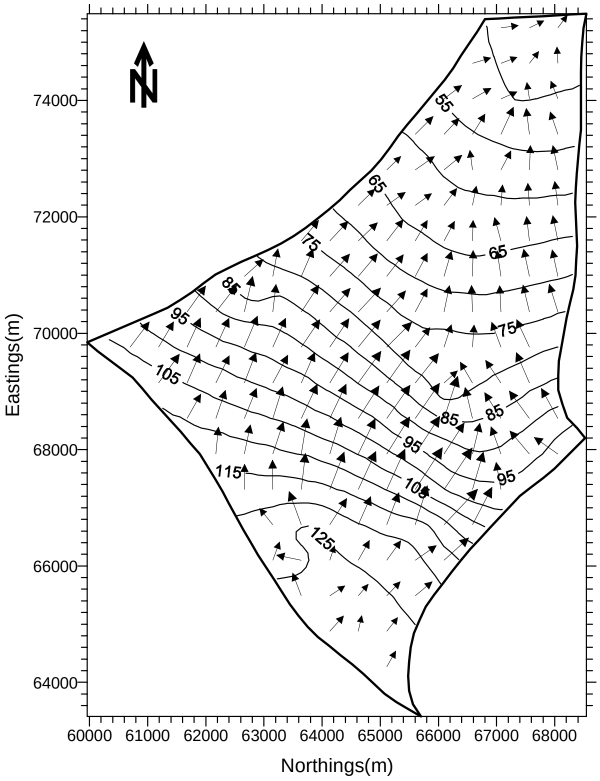

Figure 2
Water table contour map showing the direction of groundwater flow (Rusinga, 2002)

Hydrogeology

The rocks in the Bulawayo area are of the Bulawayan Group sequence of the Archaean age (Garson, 1995). Topographically the area is of the Post-African erosion surface of Miocene age. In broad terms, the geology of Bulawayo is divided into two main formations, granite and greenstone rocks. The Matsheumhlope Wellfied is in the greenstone formation which has two variations, namely the 'Avalon' formation and the 'Umganin' formation. The granite formation is low water yielding while the greenstone is classified as possessing a reasonable groundwater development potential (Martinelli and Hubert, 1985).

Average hydraulic conductivity is moderate (0.55 m/d) and sustainable yields are in the range of 100 to 250 m^3/d (Rusinga, 2002). The aquifer under consideration is mainly unconfined and relatively shallow with an average saturated thickness of 40 m. Depth to water table was observed to vary spatially throughout the aquifer. The general direction of flow is north-easterly with average hydraulic gradient of 1:250 and average flow velocity of 0.4 m/d (Fig. 2). The pattern of groundwater flow generally follows the surface topography with seasonal variations in water levels characterised by rising water levels during the wet months from November to March and declining water levels during the dry months.

Study scope

Thirty-two existing boreholes were sampled during the period between August 2000 and August 2001. It would have been ideal to have a network of sampling points that would provide a representative spread in monitored parameters over the entire aquifer, but limitation in financial resources precluded the installation of new boreholes for sampling purposes. However, attempts were made at ensuring that sampling points were located at the three land-use areas of the city, namely residential, commercial and industrial. Two of the sampling points were chosen outside the project area but within the vicinity of the municipal landfill site at Richmond. This site is about 10 km in the northwest direction from the city centre. These two boreholes were chosen so as to assess the impact of the landfill on the groundwater quality. Figure 1 shows the location of the boreholes (except the two at the landfill), and a list of boreholes and their physical location descriptions are given in Table 1.

Of key concern and interest in groundwater monitoring is the frequency of sampling. Flows in aquifers are much slower than in surface water, so temporal and spatial variations in water quality parameters are more curtailed in groundwater systems. As pointed out in Meybeck et al. (1992), although water quality is a highly variable characteristic of any water body, it is more likely to change rapidly in rivers than in lakes and least likely to change in aquifers. With this understanding, a monthly sampling frequency was adopted. It was assumed that no important alteration in the quality would occur in a period of a month.

TABLE 1
Borehole location physical descriptions

Bore-hole no.	Location	Area	Designation
1	Coats Zimbabwe	Donnington	Industrial
2	NIMR & Chapman	Donnington	Industrial
3	Datlabs	Belmont	Industrial
4	Lancaster Industrial	Belmont	Industrial
5	CH Naake	Belmont	Industrial
6	Ames Engineering	Belmont	Industrial
7	Western Transport	Belmont	Industrial
8	Zupco	Steeldale	Industrial
9	National Foods	Steeldale	Industrial
10	N. Stipinovich	Westondale	Industrial
11	Miller & Thompson	Thorngrove	Industrial
12	Super Godhlwayo	Thorngrove	Industrial
13	D'aguir Tyres	City center	Commercial
14	Hartfield R/Ground	City center	Commercial
15	BCC Roads	Mzilikazi	Residential
16	7 Heathfield Cres	Northend	Residential
17	38 Heathfield Cres	Northend	Residential
18	23 Scott St	Northend	Residential
19	8 Duncan Rd	Suburbs	Residential
20	42 Clark Rd	Suburbs	Residential
21	54 Lawley Rd	Suburbs	Residential
22	Ascot Racecourse	Ascot	Residential
23	30 Phillips Dr	Ilanda	Residential
24	2 Theresa Sly Rd	Ilanda	Residential
25	24 Fraser Close	Ilanda	Residential
26	10 Tweed Rd	Famona	Residential
27	5 Monmouth Rd	Hillcrest	Residential
28	Henry Low P.School	Greenhill	Residential
29	58 Windermere Rd	Morningside	Residential
30	Isinga	Barham Green	Residential
31	6 Princess Rd	Richmond	Landfill
32	6 Cunningham Rd	Richmond	Landfill

TABLE 2
Simple statistics of major ions sampled in the period August 2000-August 2001

	Temp (°C)	pH	EC (µS/cm)	TH (mg/ℓ)	CH (mg/ℓ)	SO_4 (mg/ℓ)	NO_3-N (mg/ℓ)	Cl (mg/ℓ)
Range	13-32.9	5.8-8.2	120-5380	63-5000	18-770	3-410	0.0-44.0	10-1305
Median	23.5	7.0	1060	886	270	133	1.6	84
Mode	24.0	7.0	1050	1050	250	100	0.7	80
Average	23.4	7.0	1179	1050	303	143	4.2	151
Standard deviation	2.799	0.3	638	769	149	79	5.3	204

Note: TH - Total Hardness
CH - Calcium Hardness

TABLE 3
Simple statistics of minor, trace elements and other parameters sampled in the period August 2000-August 2001

	Fe (mg/ℓ)	Cu (mg/ℓ)	Mn (mg/ℓ)	F (mg/ℓ)	PO_4 (mg/ℓ)	NO_2 – N (mg/ℓ)	CN (mg/ℓ)	Turb (NTU)
Range	0.00-3.30	0.0-0.13	0.000-0.017	0.0-5.5	0.00-24.7	0.000-0.940	0.000-0.220	0.0-143.0
Median	0.02	0.00	0.004	0.4	0.88	0.013	0.013	2.2
Mode	0.01	0.00	0.000	0.33	2.75	0.003	0.004	1.5
Average	0.194	0.01	0.005	0.68	1.62	0.041	0.021	5.8
Standard deviation	0.57	0.03	0.005	0.80	2.68	0.084	0.026	12.7

As in most water quality studies, the measures used in this work to characterise the groundwater quality included the physical, chemical and microbiological parameters. The monitored physical parameters were pH, electrical conductivity (EC), temperature and turbidity, while the chemical parameters included total and ferrous iron, manganese, copper, hexavalent chromium, cyanide, total hardness, calcium, sulphate, nitrate, chloride, fluoride and phosphate. The microbiological parameters monitored were the total and faecal coliforms. Statistical comparison was made between the quality of groundwater in the industrial and residential areas on the basis of the standard Mann Whitney U-test. Water quality maps were drawn using SURFER to show the spatial variation of various water quality variables. The maps are used to identify areas of potential water quality problems.

Materials and methods

A preliminary survey was undertaken to determine hydrogeological boundaries, the general spatial water quality variability, anticipated levels of pollutant concentration, and the technical and economic viability of the investigation. It was not possible to have full analyses of all potential pollutants in the aquifer because of large costs involved in sampling and analysis. As Parsons and Tredoux (1993) point out, the ultimate rule in determining the number of parameters to be analysed is a compromise between groundwater quality information requirements and the available resources. Pre-existing wells were used in the development of the groundwater monitoring network because of limited funds that did not allow additional boreholes to be drilled at strategic points.

The physico-chemical parameters were determined with a Paqualab photometer, Hach DR/2010 data logging spectrophotometer, Hach DR/850 pocket colorimeter, Paqualab EC meter, Hach pocket TDS meter, Hach sensor pH meter, Paqualab pH meter and Hach pocket turbidimeter. The microbiological parameters were obtained with a Paqualab Incubator System 50 (420-010 Standard Incubator and 420-015 Universal Incubator). The analytical procedures outlined in the Paqualab System (1998) and Hach (1997) manuals were adopted. It should be pointed out that these procedures were adapted from *Standard Methods* (1989). The membrane filtration and the presence/absence methods were used for the determination of faecal and total coliforms for the microbiological analysis.

Sample collection and preservation

Samples were collected from predetermined points shown in Fig. 1. For the physico-chemical analysis, samples were collected in thoroughly cleaned 500 mℓ, 750 mℓ and 1 ℓ polyethylene bottles and samples were not filtered in the field. In order to collect representative samples, pumps were run continuously for some time before samples were collected. Temperature, pH, EC, total dissolved solids (TDS) and turbidity were measured in the field soon after collecting the samples. Chemical parameters like total chlorine, cyanide, phosphate, ferrous iron, ammonia, total hardness, manganese and calcium hardness were also measured in the field using field kits. For the other parameters (nitrate, nitrite, chloride, fluoride, hexavalent chromium, total iron, copper and sulphate), the samples were preserved by refrigeration and analysed before the maximum holding time elapsed. Samples for microbiological analysis were collected in sterile containers.

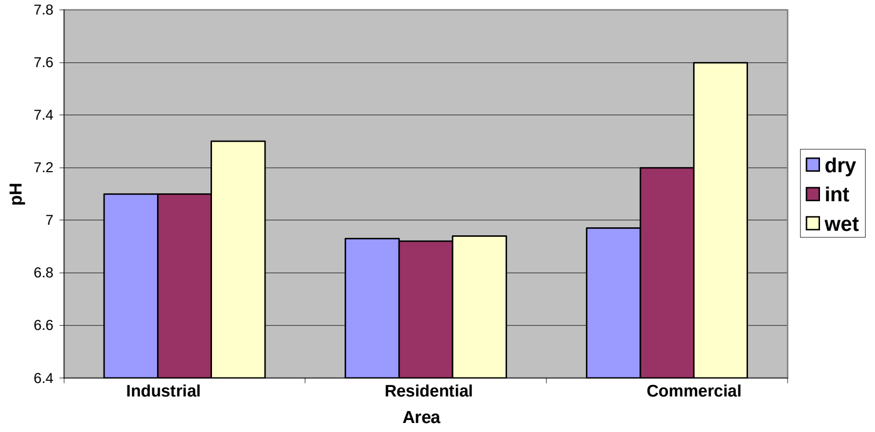

Figure 3
Seasonal variation of pH for different land-use areas

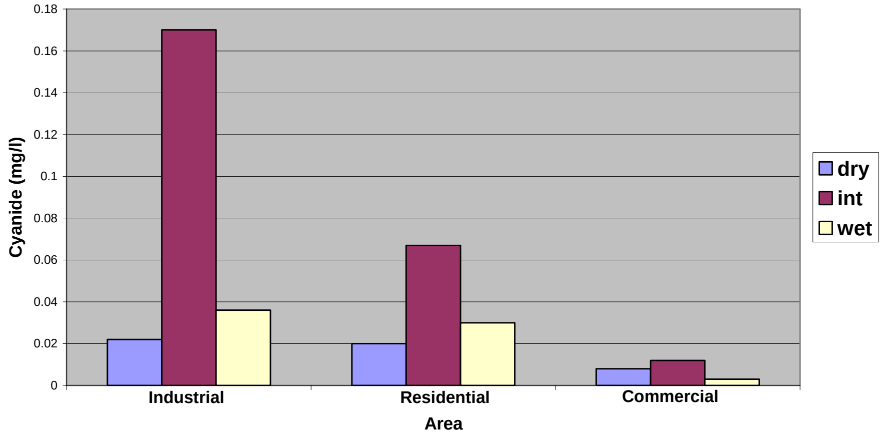

Figure 4
Seasonal variation of cyanide for different land-use areas

Results and discussion

The simple statistics of the parameters are presented in Tables 2 and 3. Frequency analysis of the time-averaged data for all the water quality parameters shows that they do not follow a normal distribution nor any particular distribution pattern. The statistical analysis of the data was hence carried out using nonparametric distribution-free methods. The standard Mann-Whitney U-Test was used to statistically investigate significant differences in the groundwater quality of the industrial and residential areas. A computer program 'RANKINGSUM' coded in FORTRAN was used to perform the Mann-Whitney U-Test (Mangore, 2002). The results from the Mann-Whitney U-test (details of which can be found in Mangore, 2002) show that the levels of water quality parameters from the residential and industrial areas are statistically different.

The temporal trend in the water quality parameters was assessed by examining the seasonal variations of five water quality parameters, namely, pH, CN, NO_3, PO_4 and EC that were continuously monitored over the three climatic seasons. These three seasons were the wet season between December and March, the dry season between August and November, and the intermediate or winter season between April and July. The average values for these parameters were examined in the industrial, residential and commercial areas. The suitability of the groundwater for drinking purposes was assessed by comparing the levels of the various parameters to the Zimbabwe drinking water standards (SAZS 560:1997).

Temporal trends in water quality parameters

From observed water table variations in the aquifer, infiltrated moisture gets to the water table of the aquifer within two months after major rainfall events. The actual time depends on the water-table depth, transmitting capacity of the unsaturated zone, antecedent soil moisture in the unsaturated zone before storm, and the presence of preferential flow paths. It is expected that the impact of the rains, which usually start late in October or early November, with considerable variability from year to year, will be observed in most parts of the aquifer during the months between January and May. These months fall into wet and intermediate or winter seasons, according to the classification of seasons that was adopted.

As shown in Fig. 3, pH is generally in the neutral range for all areas in all seasons but has highest values in the wet season compared to the dry and intermediate seasons. The neutrality of the water suggests that chemical activity will be curtailed to some extent and heavy metals are more likely to remain in suspension than in solution. Figure 4 indicates that cyanide values are highest during the intermediate season for all areas, with pronounced peaks in the industrial areas. Cyanide is known to be in use in electroplating and metal-works industries. Its introduction into the groundwater is most probably through accidental spillage which is then carried by storm runoff and through leakage from faulty sewer lines.

Figure 5 shows the seasonal variation of nitrate. Nitrate values are consistently highest during the dry months when water levels in the aquifer are at their lowest. It is also significant to note that nitrate is higher in the residential area than the industrial and commercial areas. While the peak values of nitrate in the dry months is due to the low dilution ratio during this period, the occurrences of nitrate are most likely due primarily to the use of fertilisers from urban agriculture in the residential areas and sewer leakages of domestic waste which contains detergents and soaps. Figure 6 shows the seasonal variation of phosphate which, to some extent, follows that of nitrate. Highest values are observed during the dry season and in the commercial district. As indicated later in this

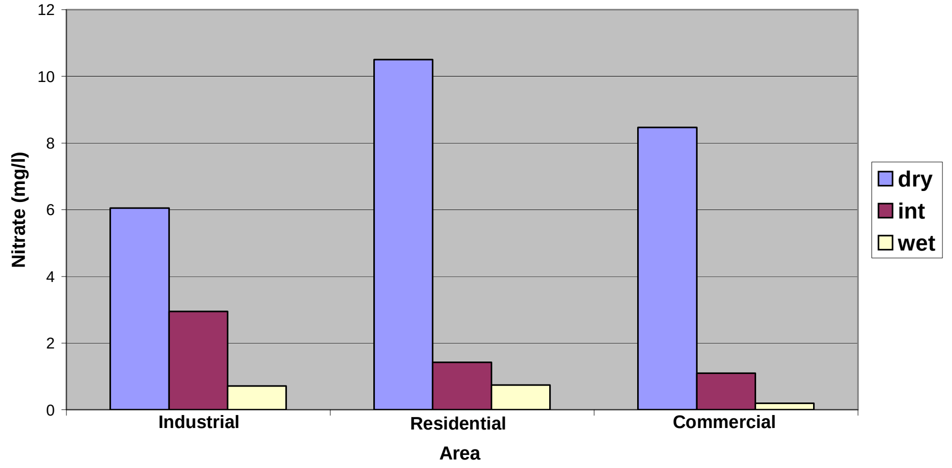

Figure 5
Seasonal variation of Nitrate for different land-use areas

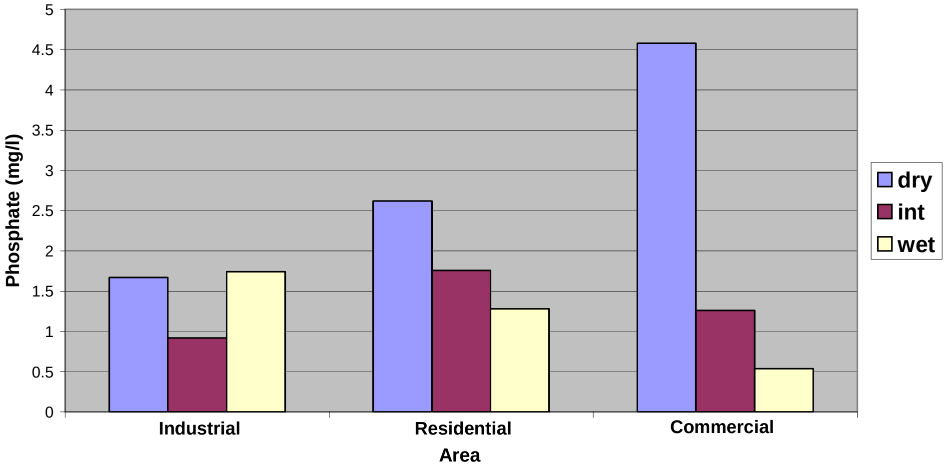

Figure 6
Seasonal variation of Phosphate for different land-use areas

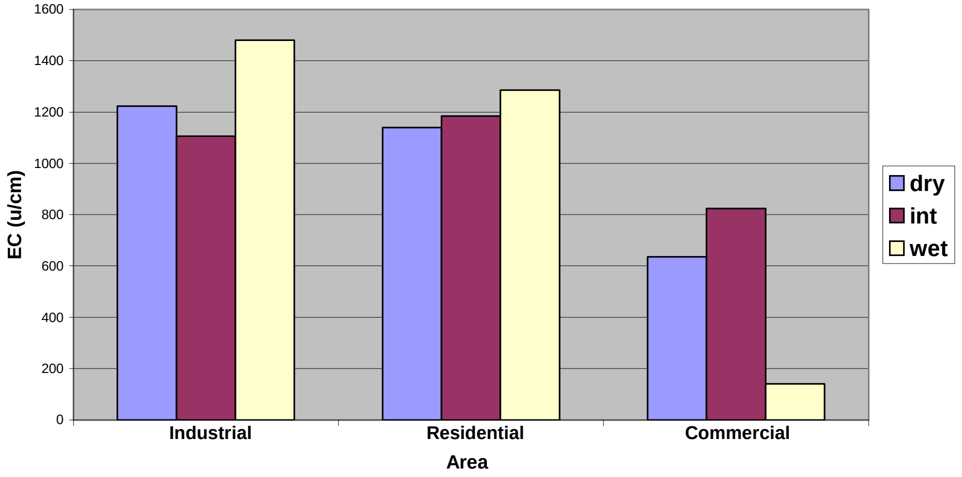

Figure 7
Seasonal variation of EC for different land-use areas

paper, the high phosphate values in the commercial area are most likely due to sewer leakages of domestic waste which contains detergents and soaps from household cleaning and laundries from numerous apartments that dot the commercial district. Figure 7 shows the seasonal variation of EC. It is highest during the wet months for the industrial and residential areas, and during the intermediate season in the commercial area. The impact of high salinity from salts dissolved in water infiltrating from the ground surface is more significant in the industrial and residential areas which have less impermeable areas than the commercial district that has concrete walkways and asphalt-surfaced roads and parking lots. That may account for the high EC values in the industrial and residential areas during the wet months.

Since intensive sampling was carried out for about a year only, the reproducibility of the observed trends from year to year could not be assessed but it is conjectured to be most unlikely, judging from the high variability in climatic conditions experienced in this region. Therefore, no long-term water quality temporal trends can be deduced from the data that are currently available.

Spatial variability of water quality

The spatial distributions of the time-averaged water quality parameters are presented in Figs. 8 to 15. In Matsheumhlope Wellfield,

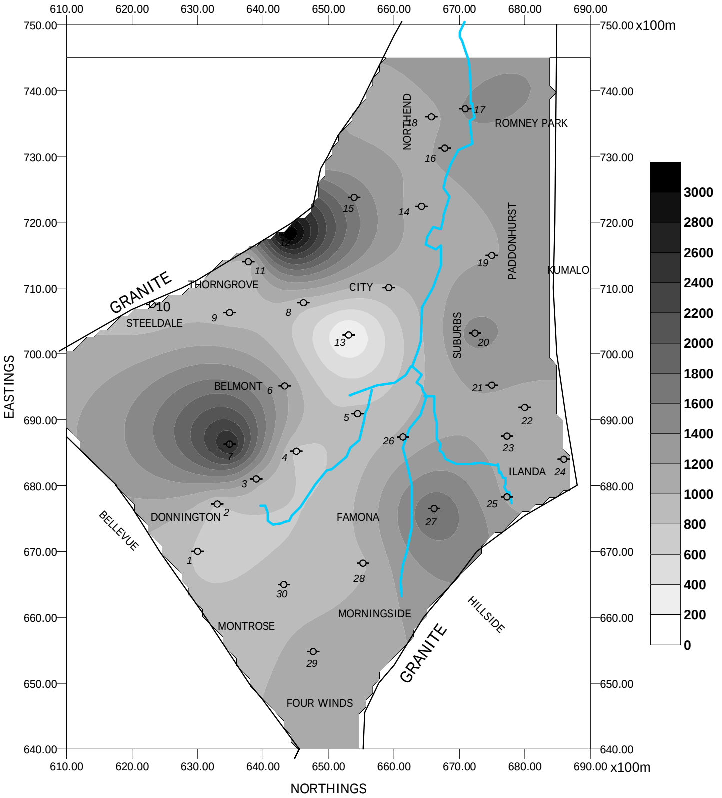

Figure 8
Spatial variation of EC in the study area

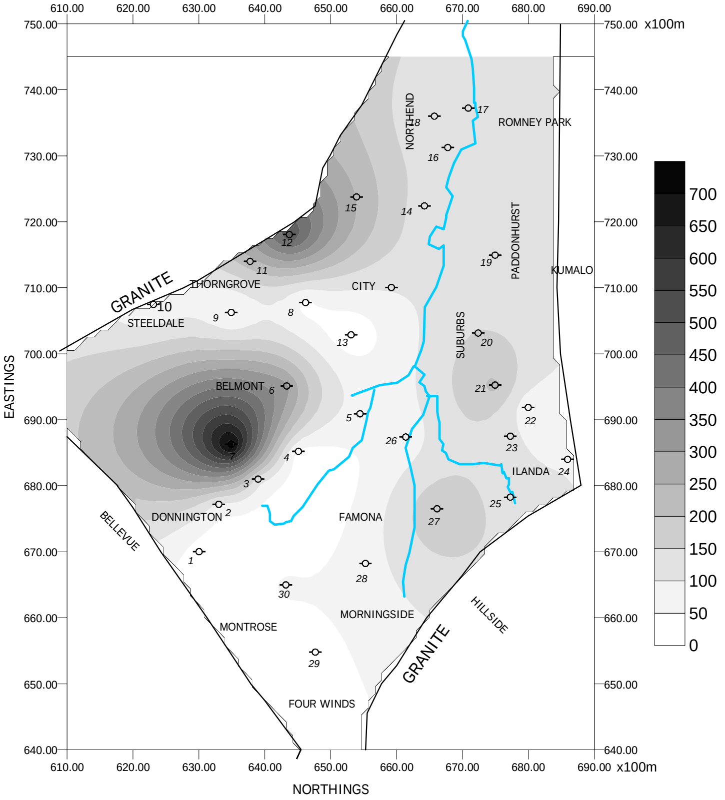

Figure 9
Spatial variation of chloride in the study area

being a predominantly shallow unconfined aquifer system, potential contaminants can enter the groundwater at numerous points that may not always be associated with identifiable sources.

The spatial variability of EC is shown in Fig. 8 with point values ranging from as low a value of 120 µS/cm to very high value of 5 380 µS/cm. Highest levels of EC occur at sampling points 7 and 12 that are respectively within the premises of Western Transport and Super Godhlwayo, of which both are transport operating companies. It may be misleading to ascribe the high levels of EC to the operational activities of these two companies since boreholes within premises with similar operation do not exhibit such high EC levels. The geology of the study area reveals that the two boreholes are located in the Avalon formation whereas others are in the Umganin formation, so that the high salinity levels, that make the water unsuitable for drinking, may be due to the formation geochemistry.

The spatial variation of chloride follows a pattern similar to that of EC (compare Figs. 8 and 9), suggesting that the EC at these points is mainly due to chloride. This is confirmed from the correlation of the EC data and those of chloride, sulphate and hardness that is shown in Fig. 10. This figure shows a higher positive correlation between EC and chloride ($R^2 = 0.738$) than between EC and sulphate ($R^2 = 0.1878$). This confirms that EC is mainly due to chloride. The main source of chloride is from solution of salts from the rock matrix, though further analysis of the mineral content of this rock matrix may be required to confirm this assertion. Leaking sewers could be another possible source of chloride but their contribution will be more spatially distributed in contrast to the location-specific observations made at the sampling Points 7 and 12. In arid regions, water from boreholes in low-lying areas can have high levels of EC. This is due to the fact that these areas act as local retention basins for stormwater runoff, resulting in local rise in water table with evaporation from these surfaces producing ions such as sulphates and chlorides (Lloyd, 1994). Kashef (1987) reports on acute salt build-up in the arid region of Nevada, USA. Mandel and Shiftan (1981) report that in crystalline rock aquifers, it is common to observe higher than expected conductivities in semi-arid regions where highly seasonal rainfall is experienced. As this is the case for Bulawayo it is not surprising to occasionally find higher than acceptable salinities.

Nitrate concentration ranges from low values of 0.0 mg/ℓ Please check 0.0 author and rephrase to considerably high values of 44.0 mg/ℓ. High concentrations of nitrate were observed around Donnington, Montrose and Morningside that are low-density residential areas. Levels of nitrate were generally higher in the residential than the industrial areas (Fig. 11). Nitrate is a valuable indicator of sensitive hydrogeological settings in view of its association with human activities. For the current investigation nitrate contamination cannot be attributed to a specific source. On-site sanitation services like pit latrines and septic tanks are not used in the study area; these can only be found in some residential units outside the study area. Solid waste disposal and urban effluent is centralised to municipal landfills and wastewater

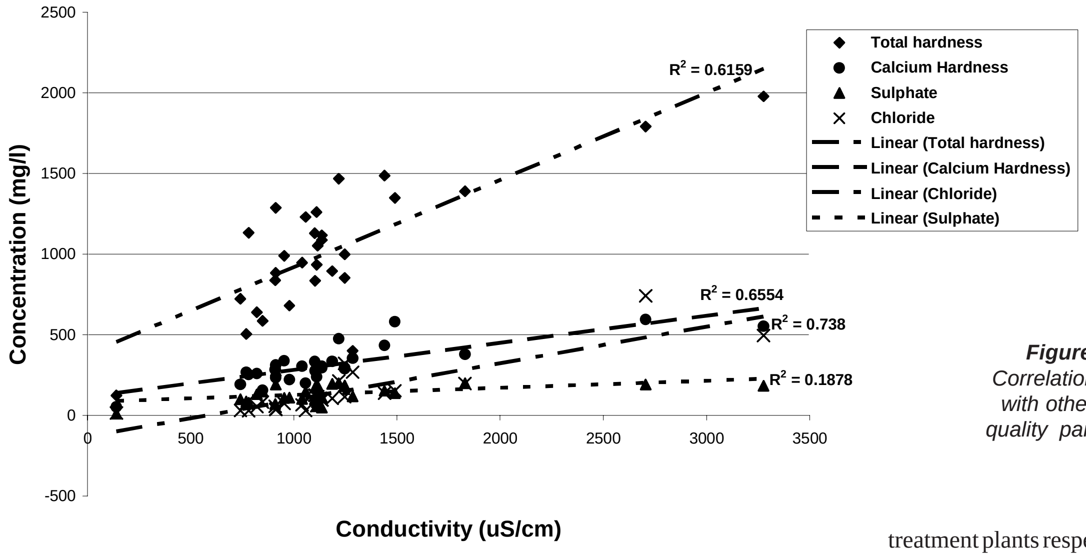

Figure 10
Correlation of EC with other water quality parameters

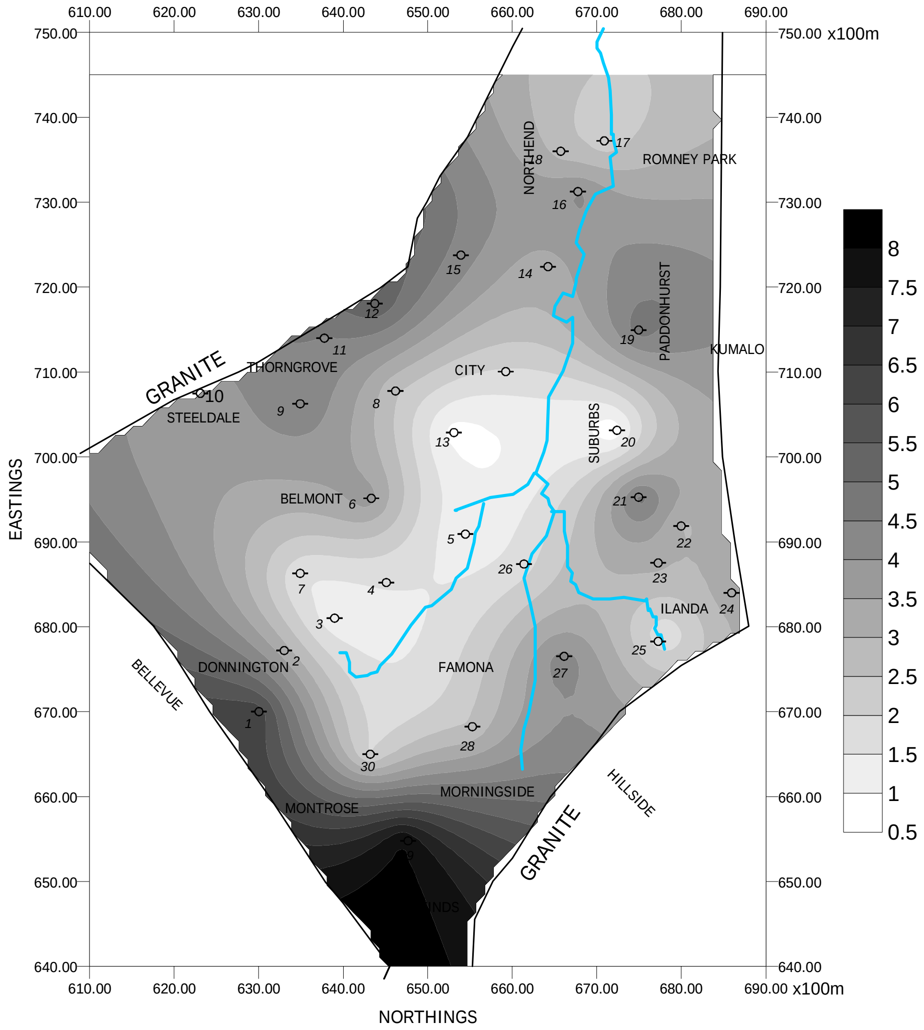

Figure 11
Spatial variation of nitrate in the study area

treatment plants respectively. Levels of nitrates at some sampling points are however too high to attribute pollution mainly to natural nitrate accumulation, and these can be attributed to the seepage of drainage water from lands in residential areas where application of fertiliser for urban agriculture is common.

Orthophosphate concentration ranges from 0.0 to 24.7 mg/ℓ (Fig. 12). Orthophosphates are generally higher in the residential and commercial areas than in the industrial area. This is most probably due to use of detergents in household cleaning, for example, laundries, house cleaning and car washing. Phosphorus is a major constituent of many detergents and therefore found in domestic sewage. The effect of phosphate contamination tends to be localised because of the reaction between phosphate and subsurface materials (Mangore, 2002). As reported by Fourie and Ryneveld (1995) most soils appear to possess the capability of slowing down the transportation of phosphate quite well within a very short distance of pollution. However, the mobility of phosphate varies depending on the hydraulic conductivity and pH of the subsurface. In industrial areas phosphate can be from metal- working industries. High levels of total phosphates were detected in effluents from some industries in the study area with as high as 106 mg/ℓ being observed (Ntuli, 2002), but very little phosphate reaches the water table groundwater mainly due to adsorption and retention by the upper soil layers. The World Health Organisation (WHO) limit for phosphate is 0.3 mg/ℓ (WHO, 1989).

Sulphate concentrations varied from 3 to 410 mg/ℓ. The highest levels of sulphate were observed at sampling point 9 which is within the premises of National Foods in Steeldale industrial area (Fig. 13). A study carried out by Ntuli (2002) to monitor and characterise industrial effluent from edible oil refining and soap making industries in Bulawayo showed that effluent from National Foods is normally high in sulphates (up to 3 721 mg/ℓ). The sulphate is from the acidification and acid-splitting during the process of effluent pretreatment. It is not uncommon for pretreated effluent to be discharged into municipal sewers. Industrial effluents with high concentration of sulphates and biodegradable matter cause oxygen depletion with the oxidation of sulphides to sulphuric acid that has corrosive effects on the sewer pipe material. Most sulphates eventually find their way into the groundwater since the sewers are considerably corroded.

Effluents from tanneries are usually high in sulphate. In the industrial area of Belmont industrial area there are a number of tanneries (e.g Wet Blue Industries and Midrion Enterprises). Another possible source of sulphate is sulphur dioxide from combustion of fossil fuels. Sulphur dioxide from the combustion of fossil fuels (coal, coke) combines with rain to form sulphurous acid (H_2SO_3) and sulphuric acid (H_2SO_4) that is referred to as acid rain. These acids promote the dissolution of metals and their subsequent migration. The acidifying potential of sulphuric acid in soils is largely dependent on sulphate adsorption (Mulder and Cresser, 2002).

Fluoride ranges from 0.01 to 5.5 mg/ℓ with sampling point 10 within N. Stipinovich premises showing fluoride levels above the maximum recommended limit of 1.5 mg/ℓ. Generally elevated fluoride levels occur adjacent to the granite boundary in the North-Western part of the study area (Fig. 14). This could be because the water is in contact with fractured granite rocks. Fluorine usually occurs in groundwater as the fluoride ion and is found in the mineral fluorite (CaF_2) and apatite ($(CaF)Ca_4(PO_4)_3$). Garson (1995) describes the chemical geology of the 'Falls Road Granite Porphyry' (the geological formation where the two landfill area boreholes with elevated fluoride are located) as rocks that are locally rich in euhedral sphene, titanomagnetite and apatite. The source of fluoride is therefore most probably apatite. The fluoride level in the rest of the aquifer is fairly uniform as shown in Fig. 14.

Total hardness ranges from 63 to 5 000 mg/ℓ and calcium hardness ranges between 18 and 770 mg/ℓ. Most of the sampling points showed a total hardness value above the allowable drinking water limits, according to SAZS 560:1997. The spatial variation of calcium, shown in Fig. 15, follows that of total hardness. The high levels of total hardness indicate that the water is unsuitable for laundries and some industrial processes which use boilers. The water is also not suitable for domestic purposes apart from watering of gardens. Consumers in some areas complain that the water is salty. The sensitivity to hardness by consumers is subjective, stemming from the fact they are used to municipal water that is soft. The water can be used for domestic purposes after treatment with lime and soda-ash.

The usual route by which calcium gets into groundwater is by dissolution of carbonate minerals in water containing carbon dioxide (Mandel and Shiftan, 1981).

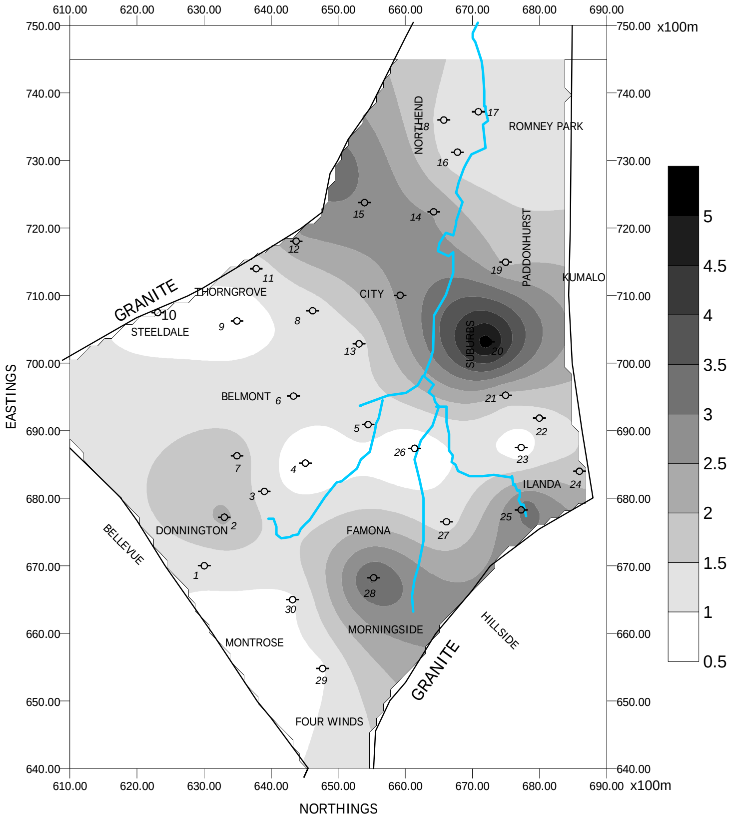

Figure 12
Spatial variation of Phosphate in the study area

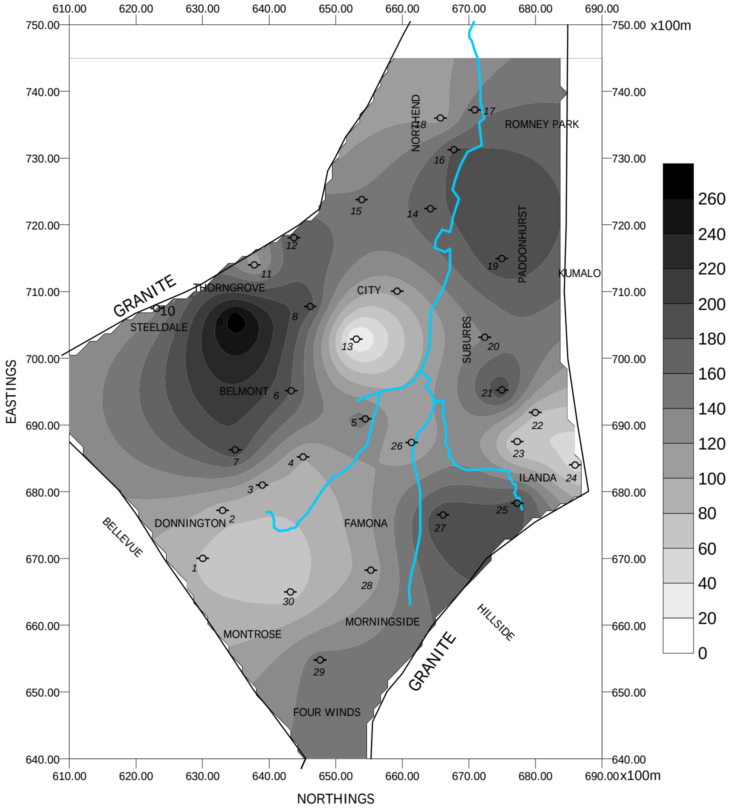

Figure 13
Spatial variation of Sulphate in the study area

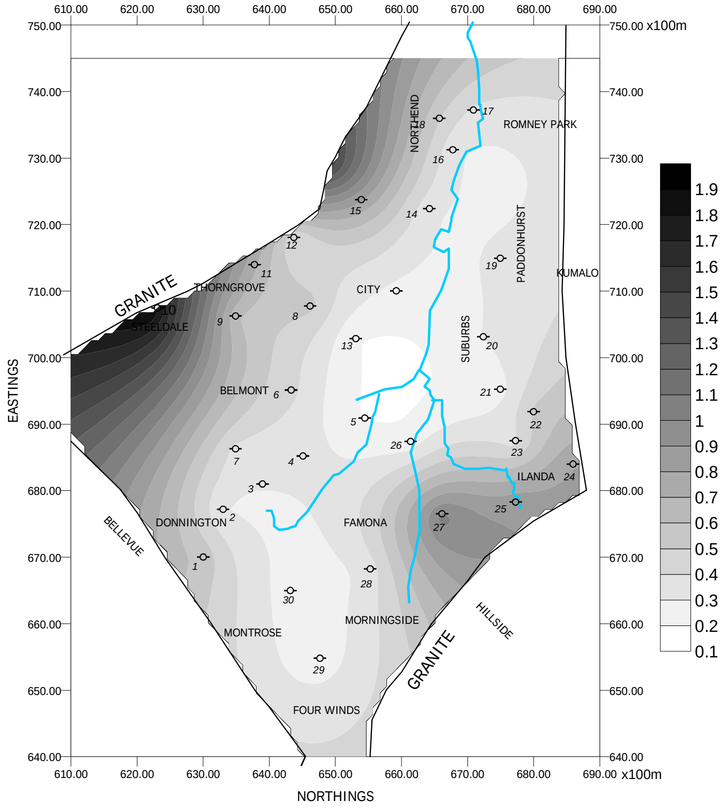

Figure 14
Spatial variation of fluoride in the study area

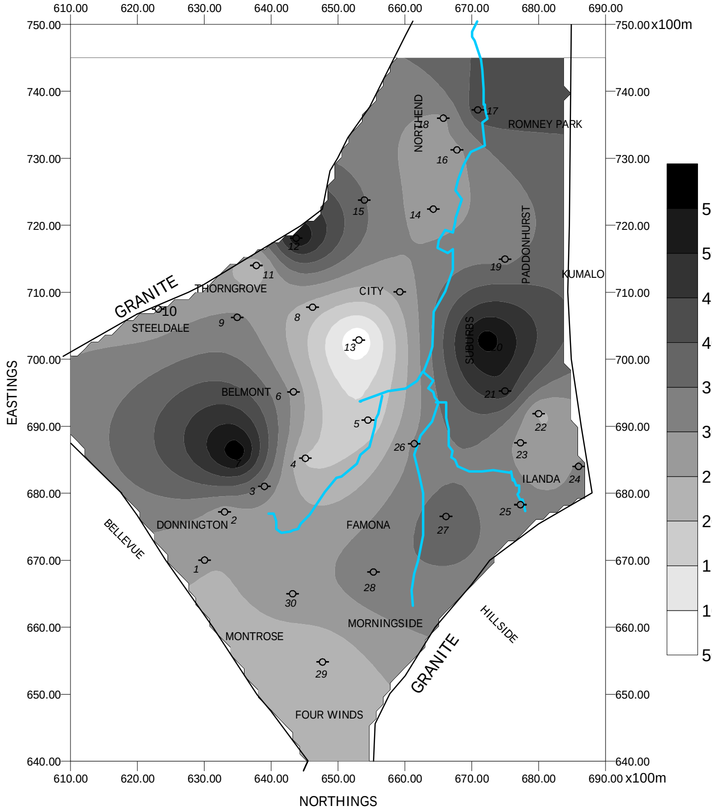

Figure 15
Spatial variation of calcium hardness in the study area

This phenomenon is more pronounced where the water is slightly acidic or acidic. Taylor and Howard (1994) showed that the potential exists in the basement complex of Africa for groundwater quality deterioration to occur due to cations that are contained in the natural weathered rocks. It is possible that the same is the case with the Bulawayo aquifer which is a weathered basement complex.

Generally very low concentration levels were detected for minor and trace elements. The range of cyanide from 0.001 to 0.220 mg/ℓ is generally below Zimbabwe drinking water limits. Hexavalent chromium was not detected in most of the samples. Testing of the hexavalent chromium was discontinued after a few sampling runs. Copper ranges from 0.0 to 0.13 mg/ℓ and generally below drinking water limits. Manganese ranges from 0.0 to 0.017 mg/ℓ. Cyanide, hexavalent chromium, copper and manganese are within the recommended limits for drinking water. Cyanide is used by electroplating and metal-works industries of which there are a number in Bulawayo. The effluents from these industries could enter the subsurface through accidental spillage and leaking sewers. Cyanide is known to be very reactive and that could account for the very low levels that were detected (Barrett et al., 1999). At neutral pH most metals exist in water in the solid phase. The pH of the groundwater is almost neutral. Therefore the actual levels of trace metals in the groundwater could be higher than detected because at the observed pH values most metals tend to be out of solution. Use of waters with high levels of iron and manganese is limited by aesthetic considerations while use of waters with high levels of cyanide, copper and chromium is limited by health considerations.

Iron ranges between undetected levels and 3.3 mg/ℓ. The main sources of iron are dissolution from rock matrix and corrosion of borehole rising mains and piping (Taylor and Howard, 1994). High levels of iron that were detected at sampling point 3 (Datlabs in Belmont industrial area) and at sampling point 28 (Henry Low Primary School in Greenhill/Morningside residential area) are due to corrosion of borehole piping. Boreholes in the vicinity of these two boreholes, with the same geological formation have very low levels of iron, suggesting that the source of iron is chiefly borehole piping. Iron occurs in groundwater mainly as ferrous iron because groundwater is almost oxygen free. On coming in contact with oxygen, ferrous iron is oxidised to ferric iron, which results in formation of reddish-brown precipitate. Formation of the red-brownish precipitate contributes to turbidity. The pattern of the spatial variation of iron, shown in Fig. 16, is similar to that of turbidity. Turbidity is within the recommended drinking water limit at most sampling points. The good quality of the water with respect to turbidity is expected due to the filtering that occurs in the upper soil layers above the water table.

The microbiological results indicate that about 8% showed positive results with respect to faecal coliforms and 27% showed positive results with respect to total coliforms. No definite trend was observed in terms of the spatial and temporal variation of coliforms occurrence, suggesting that the possible source of the coliforms is sewage from faulty sewers, since there are no on-site sanitation services like pit-latrines and septic tanks. The sewerage system is largely centralised, but some sewer lines have collapsed at a number of locations due to the age of the pipes. It is not uncommon to find the contents of burst sewers that run on the ground surface being discharged into natural drainage courses. In a related study, the amount of sewer leakage recharge to the aquifer was estimated as 10 mm/a (Rusinga, 2002). Other studies have shown that leaking sewers have an impact on groundwater quality (Mackay and Riley, 1993; Sadek and El-Samie, 2001; Barrett et al., 1999).

Groundwater quality in the landfill area

For the two boreholes that were monitored in the landfill area, the levels of most water quality parameters were in compliance with the drinking water standards. Levels of fluoride above the limit of 1.5 mg/ℓ were frequently observed at both sampling points, thereby making the water unsuitable for drinking purposes due to the risk of fluorisis. As alluded to earlier, the high fluoride is most probably due to the geochemistry of the formation and unconnected with the landfill which is located in a granite formation. It is worth noting that there were no significant differences (other than fluoride) in the water quality within the vicinity of the landfill when compared to that in the other residential areas, suggesting that landfill liner has not been breached to the extent that leachate from the landfill has a negative impact on the aquifer.

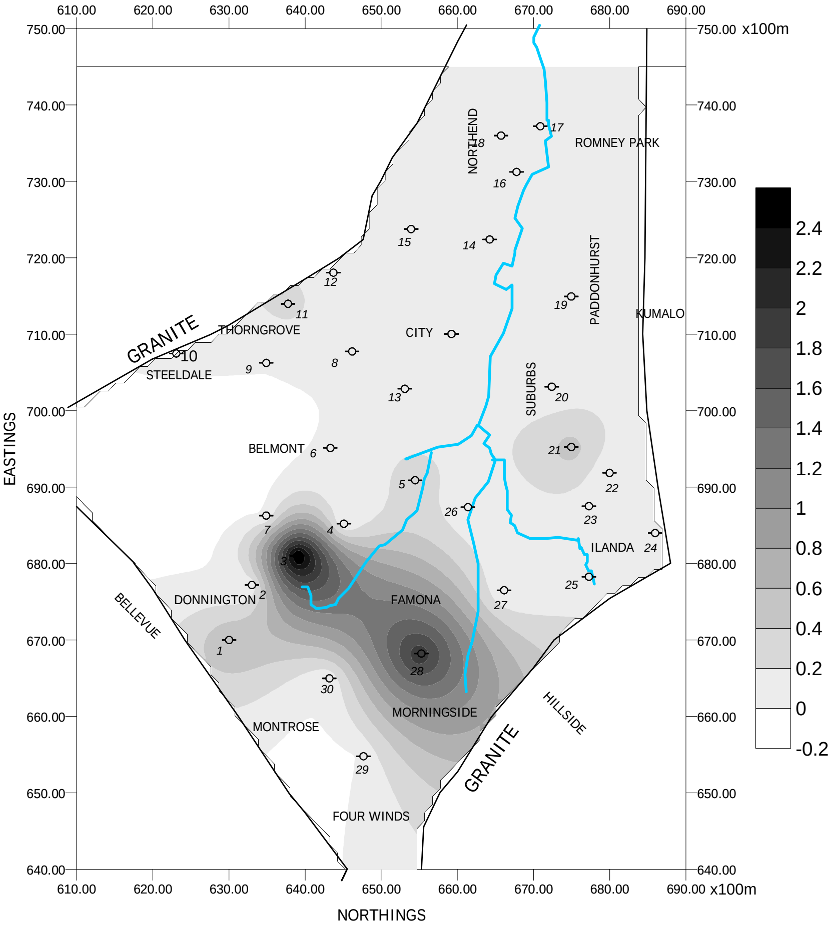

Figure 16
Spatial variation of iron in the study area

Conclusion

The overall goal of this work was to assess the groundwater quality of Bulawayo in relation to various land uses associated with industrial, commercial and residential activities, and solid waste disposal at the landfill site in Richmond. Overall, the groundwater quality of Bulawayo can be considered to be generally good as shown by the results from the monitoring exercise carried out in the Matsheumhlope Wellfield and the landfill area. The majority of the parameters are in compliance with local (SAZS560: 1997) and international standards and guidelines (WHO, 1989). However, the chemical quality of the water with respect to total hardness at most sampling points exceeds the Zimbabwe drinking water limit. The water is therefore not suitable for laundry purposes and industrial boilers except if it is softened or blended with the softer municipal water. The microbiological analysis showed that the water from some boreholes could be contaminated, as shown by the presence of indicator organisms. The random occurrence of these indicator organisms in space and time suggests that they are due to leakages from sewers that criss-cross the aquifer. To avoid health hazards the water must be chlorinated before being used for drinking purposes.

The water quality data were analysed statistically both in time and space. The seasonal variations in some of the water quality parameters identify the pathways of contamination as the leakages from the sewers and accidental industrial spillages that are carried along with infiltrating water via surface runoff. However, no long-term temporal trend of the water quality parameters could be established because of the limited time period over which monitoring was done, thereby highlighting the need for continuous monitoring of the wellfield for a prolonged period. The spatial distributions in water quality parameters confirm the pathways of possible contamination of the aquifer earlier stated. The comparison of the water quality from the industrial and residential areas provided by the standard Mann-Whitney U-test showed that waters from the two areas are statistically different in quality. Levels of parameters like cyanide, conductivity, chloride, sulphate, copper, iron and manganese are significantly higher in the industrial areas than in the residential areas. There are strong indications that the groundwater quality is being adversely affected by land-use related activities, except for the conductivity parameter whose high value can be attributed to the formation geochemistry. While there is no noticeable difference between the quality of water from the landfill site and other residential areas, this study underscores the need for long term monitoring so that the movement of any contaminant plume from leachate through the landfill liner can readily be identified before health problems are encountered by the community.

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