

Current impact of mining alkaline rocks on Save River water quality in Zimbabwe

M. Meck^{a,b,*}, J. Atlhopheng^b, W.R.L. Masamba^c

^a Department of Geology, University of Zimbabwe, P.O. Box MP167, Mt. Pleasant, Harare, Zimbabwe

^b Environmental Science Department, University of Botswana, Private Bag UB0704, Gaborone, Botswana

^c Harry Oppenheimer Okavango Research Centre (HOORC), University of Botswana, Box 285, Maun, Botswana

ARTICLE INFO

Article history:

Received 26 May 2006

Accepted 11 December 2008

Available online 10 April 2009

Keywords:

Phosphate mining
Alkaline rocks
River water quality

ABSTRACT

Alkaline rocks (phosphate deposits in particular) of igneous origin are currently being mined in Zimbabwe. Exploitation of these deposits, which are associated with metals and non-metals, provides a potential for changing the river water quality in the surrounding areas by increasing metal and phosphates levels in the water, thereby endangering the beneficial use of the river. The aim and objectives of this paper are to enumerate the current impacts associated with mining alkaline rocks on Save River water quality in Zimbabwe using the Dorowa mine as a case study. Though there are several impacts associated with the mining of alkaline rocks, this paper deals only with impacts on water quality.

A preliminary assessment of the water quality in the Save River downstream of the Dorowa phosphate mine showed an increase in conductivity, iron content, manganese content, nitrates and hardness when compared to those taken before mining activity began. However, there was no notable increase in phosphate and metals except for Fe and Mn. A plausible explanation for the low phosphate values in the water is that the phosphates are precipitating and settling as sediments. Phosphate is known to effectively remove metals from the surface water through the formation of metal-phosphate minerals. Thus, various pollutants may be adsorbed into sediments accumulated on the bottom of the river. These sediments may accumulate pollutants over long periods and act as new pollutant sources to the overlying water when phosphate desorbs from sediments due to changes in water conditions. Therefore, the sediments can act as a source of water pollution in the future.

1. Introduction

This study evaluates the impact of mining alkaline rocks on the Save headstreams in Zimbabwe. Mining is known to impact the environment in several ways and different types of mines impact the environment differently (Mabvira, 2003). Most mining activities in Zimbabwe take place in Achaean greenstone belts, spread throughout the country. Consequently, most of the work to assess mining impact has concentrated on these rock types. Zimbabwe also hosts mineral deposits in other rock types of other geological ages. Of particular interest (and discussed in this paper) is the occurrence of alkaline igneous rocks of Mesozoic age. Though Walsh et al. (2001) describe several carbonatites, there are major six alkaline ring complexes in Zimbabwe of which four (Mutandawe, Chishanya, Shawa and Dorowa) are host to phosphate deposits and occur in the Save catchment area. Three of these complexes are currently being mined and there are plans to start mining the

fourth one. Exploitation of these phosphate deposits provides a potential for changing the water quality of surrounding areas (Modrski et al., 2001; Malinovsky et al., 2002). The alkaline rocks being mined in the Save catchment are associated with elements (Cu, Ca, W, Mo, Mg, F, Co, Fe and Zn) that can affect water quality. Table 1 shows the alkaline igneous complexes in the Save catchment, their sizes, the associated ore minerals and the elements likely to impact on water quality.

Each ring complex is located less than a kilometer from the Save River or its tributaries and so run-off from the mines and their dumps can easily reach the main river system. This is of concern because the communities around the Save River have no or few alternative water sources to the Save River for their uses, which include domestic use, stock watering, recreation, fishing and irrigation.

There are several impacts associated with mining of alkaline rocks on water quality in the Save basin in Zimbabwe and literature indicates that there is potential for other future impacts. This paper aims to enumerate the current impact associated with mining alkaline rocks on Save River water quality in Zimbabwe by bringing to light the current water quality problems at the Dorowa mine. The scope of the paper is limited to impacts on water quality. Data for sediments were acquired for the sole reason of explaining

* Corresponding author. Address: Department of Geology, University of Zimbabwe, P.O. Box MP167, Mt. Pleasant, Harare, Zimbabwe.

E-mail addresses: mmeck@geology.uz.ac.zw, mmeck@geology.uz.ac.zw (M. Meck).

Table 1

Approximate size, ore and accessory minerals of the alkaline ring complexes in the Save catchment with a list of potential risk elements derived on the basis of the classifications by McBride (1994) and that of Dallas and Day (1993).

Complex	Diameter (km)	Ore and accessory minerals	Elements that can impact water quality
Mutandawe	6	Chalcocite, chalcopyrite, wolframite, scheelite, cobaltite, bismuthinite, sphalerite, galena, silver, ankerite, fluorite, molybdenite, pyrrhotite	Cu, F, Co, Fe, Zn, Ca, Mg, Mn, P, Pb, S, W, As, carbonates and bicarbonates, F, Mo
Chishanya	1.5	magnetite, pyrite, apatite, calcite	Fe, P, Ca, Mg, CO ₃ , F, Cl, S
Shawa	5.5	vermiculite, apatite, calcite, magnetite, magnesite	Fe, Cu, Co, Mg, Ca, W, Al, P, F, CO ₃
Dorowa	3.5	Magnetite, apatite, vermiculite, carbonates (calcite and magnesite) h	Fe, F, P, W, Ca, Mg, Al, CO ₃

the possible partitioning of elements between water and sediments for use in interpreting the water quality. Discussions in this paper are based on a reconnaissance study of the mine. A thorough and more conclusive work is currently being undertaken.

2. Study area – Save River

The study area is in one of the seven catchment areas of Zimbabwe known as the Save catchment. The location of the area is shown in Fig. 1. The study area is part of the upper Save sub catchment and the Save River, which passes through the Dorowa phosphate mine, is the major river. The area is located in the Buhera District of Zimbabwe at 19°04'S; 31°46'E. The mine is exploiting a carbonatite that is associated with foyaite, ijolite and pulaskite rocks (Barber, 1991). The rocks are mineralized with phlogopite, vermiculite and apatite. The major rock being mined at Dorowa is fluoro-apatite ($\text{Ca}_5(\text{PO}_4)_3(\text{OH}, \text{F}, \text{Cl})$), which is associated with a

number of elements. The Save River, the upper portion of which is being evaluated in this paper, is approximately 640 km long and has a catchment area estimated to be 43,000 km² (Marunda, 2001). The river rises as the Save about 80 km south of Harare and flows southeast from the Zimbabwean highveld to its confluence with the Odzi. It then turns south, drops over the Chivirira Falls, and is joined by the Runde River at the Mozambique border. The river then follows an east-northeast course to its mouth near Mambone on the Mozambique Channel of the Indian Ocean. Around the study area (Dorowa), most villagers use the Save river as their primary drinking water source.

3. Materials and methods

Sampling for the study area was carried out during the dry season (September). During this time the water level was very low and flowing very slowly. Both sediment and water samples were

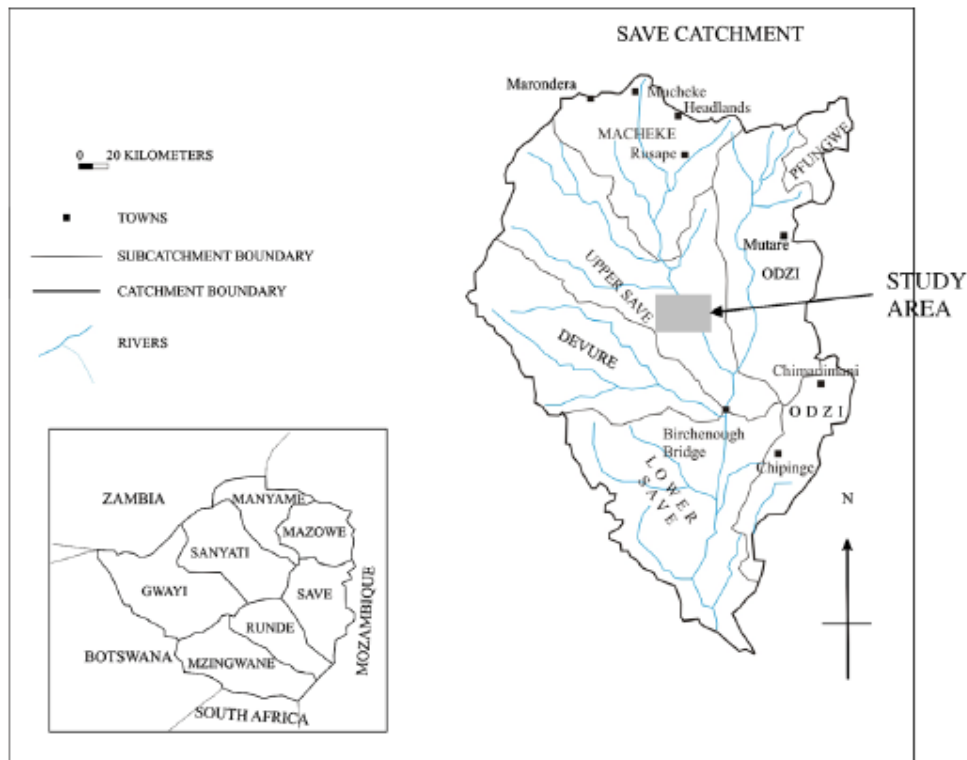


Fig. 1. Location map showing the study area in the Save catchment. The catchment is part of the upper save sub catchment. The small map of Zimbabwe shows the position of Zimbabwe in relation to other African countries as well as the position of the catchment in relation to the other catchments in the country. Study area represented by the grey rectangle.

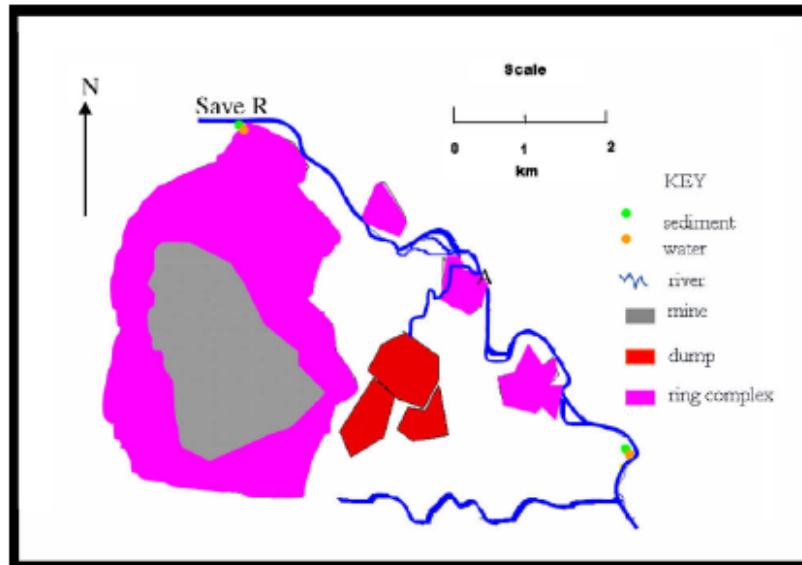


Fig. 2. Sampling points in relation to the river and ring complex. There is no indication of drainage from the dumps reaching the main river upstream of point A. There are however indications that not all drainage flows into the two tributaries shown on the map.

collected along the Save, upstream and downstream of the mine, which is located on the igneous ring complex. The sediments were surface composite samples collected from areas considered to be natural sediment traps, where the net effect is deposition rather than erosion. The sampling was carried out on the river bank on the same side as the mine. The sediment samples were collected in triplicate, as grab samples using polyethylene spoons to avoid contamination. Water from the river was collected from, or close to, midstream. The water samples were collected using plastic sample bottles, rinsed prior to use with distilled water. Two subsets of each sample were taken with each sample filled to the brim of the bottle to exclude oxygen. One set was acidified with 65% nitric acid (HNO_3) to a pH below 2 and another was left unacidified to allow for the analysis of nitrates. Three samples were collected at each site for each of the subsets to allow statistical verification of differences. The sampling locations are shown in Fig. 2. Measurements for pH and electrical conductivity were taken in the field using an electronic HANNA pH/EC meter (model HI 9023 C).

After collection, both samples were stored in a cooler box until arrival at the laboratory where the water samples were refrigerated whilst the sediments were dried. The sediments were then pulverized and sieved. The $\pm 63 \mu\text{m}$ fraction was used in the analysis because this is the fraction size generally accepted to accumulate the greatest concentration of contaminants (Ackermann, 1980; Mudroch and Azcue, 1995).

McBride (1994) has prioritized the following elements as the most toxic from the standpoint of potential hazard to plants, animals and human health: As, Be, Sb, Cd, Cr, Cu, Pb, Hg, Ni, Se, Ag, and Zn. Dallas and Day (1993) classified metals according to toxicity and availability into three categories namely: *non-critical; toxic but insoluble or very rare; and very toxic and relatively accessible*. The very toxic and relatively accessible category contained Be, Co, Ni, Zn, Sn, As, Se, Te, Pd, Ag, Cd, Pt, Au, Hg, Tl, Pb, Sb and Bi in specific forms. On the basis of the classifications by McBride (1994) and that of Dallas and Day (1993), a list of potential risk elements around Dorowa, given the mineralogy of the area (Table 1), was constructed. Elements accordingly analyzed in the water samples were phosphates, nitrates, cobalt, iron, nickel, zinc and manganese.

For sediment samples only the elements which had shown changes were analyzed to compare how these elements were proportioned between water and sediment. Analyses for metals were performed at the Zimbabwe National Water Authority (ZINWA) laboratory using an Atomic Absorption Spectrophotometer (AAS) (model-VARIAN SPECTRAA 200HT). Nitrates and phosphates were analyzed at the same laboratory using a Jenway UV spectrophotometer. Hardness of water was calculated from the values obtained from major cations analysis by AAS as the total Ca^{2+} and Mg^{2+} , with Fe^{2+} and Fe^{3+} present in the sample. Phosphates were, however, not analyzed for sediments due to technical problems at the lab at the time of analysis.

4. Results

4.1. Waste rock dumps

At the mine, the rock dumps are heavily eroded, with material being redeposited in the direction of run-off (mainly eastwards). The Save River passes through the ring complex less than 1 km from the mine dump and some of the effluent from the waste rock dumps enters the river through small streams that drain the dump and mine area.

The small streams draining the mine area are clogged with Bulrush (*Typha latifolia*), also known as the broad-leaf or common cat's tail.

4.2. Water chemistry

The water and sediment chemistry data are presented in Table 2. The data show that downstream water samples have a higher level of iron, manganese, nitrates and phosphates. Conductivity and total hardness also increases downstream. However, there is no notable variation of other parameters such pH, cobalt nickel and zinc within the study area (Table 2).

The level of metals in the sediment is higher than in the water both upstream and downstream (Table 3). The metal levels

Table 2
Water chemistry results compared to WHO drinking water guidelines.

Parameter	pH	EC uS (cm)	HD (mg/l) CaCO ₃	Co (mg/l)	Fe (mg/l)	Mn (mg/l)	Ni (mg/l)	Zn (mg/l)	NO ₃ ⁻ (mg/l)	PO ₄ ²⁻ (mg/l)
Upstream	7.6	205	92	<0.01	0.69	0.10	<0.01	<0.01	0.1	0.01
Downstream	7.4	966	314	<0.01	1.34	0.59	<0.01	<0.01	0.5	0.03
Net Effect	Nil	+	+	Nil	+	+	Nil	Nil	+	+
WDWG	NHC	NHC	NHC	-	NHC	0.4	0.02	NHC	50	-

EC, electrical conductivity; HD, hardness; WDWG, WHO drinking water guideline; NHC, not of health concern but may affect acceptability of water according to WHO, 2004; and -, value not available in the WDWG.

Table 3
Metals concentration (in ppm) in sediments upstream and downstream compared to metal levels in water (An increase is denoted by I, a decrease by D and where the element is not detected it is shown by N).

Metal	Sediment upstream ppm	Sediment downstream Ppm	Water upstream	Water downstream
Ni	0.027	0.035	I	0.01
Mn	0.197	0.083	D	0.10
Co	0.083	0.090	I	0.01
Fe	16.165	23.120	I	0.69
Zn	3.54	2.29	D	0.01

increase downstream in the water for those that were detected. However, metal levels for the sediments increase for nickel, cobalt and iron, whilst manganese and zinc decrease.

5. Discussion

The results show a general trend of metal increase in the water downstream. There is no other major activity taking place around this area that is likely to release iron, manganese, nitrates and phosphates; thus it can be assumed that there are no other sources than the alkaline rocks. The deduction thus made is that the increase is a result of the mining of alkaline rocks.

Though phosphate is being mined, the levels observed are within the WHO, 2004 guidelines. A plausible explanation for the low phosphate values in the water is that the phosphates are precipitating and settling as sediments. Phosphate is known to effectively remove metals from the surface water through the formation of metal-phosphate minerals, thus a concomitant increase of metals in sediments is expected. Though there is no general trend for sediments, it was noted that the sediments contain higher levels of the elements compared to the water, further suggesting that metals are likely to be adsorbing to sediments.

Thus various pollutants may be adsorbed to the sediments accumulating on the bottom of the river. These sediments may accumulate pollutants over long periods and act as new pollutant sources to the overlying water when phosphate desorbs from sediments due to changes in water conditions. Therefore, the sediments can act as a source of water pollution in the future.

5.1. Current problems

5.1.1. Bulrush growth

The excessive growth of bulrush observed in the stream that drains from the Dorowa mine to the Save river is an indicator of high levels of phosphates and if not checked out may lead to eutrophication. This excessive growth can lead to choking of the ecosystem, light reduction and extreme oxygen fluctuations, reduced habitat diversity and ultimately invertebrate and fish deaths in the streams. Sampling in this stream will be carried out for future work.

5.1.2. High electrical conductivity

The observed high conductivity can be explained in terms of the material being dissolved from the ring complex. The dissolved ions

likely to give the high electrical conductivity in this case are iron, manganese and inorganic salts (principally calcium, magnesium, potassium, sodium, bicarbonates, chlorides and sulphates), because the rocks being mined contain high levels of alkaline earth metals. WHO (2004) does not give a drinking water guideline for electrical conductivity but high electrical conductivity is undesirable in drinking water. The value of 966 μ S observed downstream compared to 205 μ S upstream is an indicator of a potential problem.

5.1.3. Hardness

Hardness in water is caused by dissolved calcium and, to a lesser extent, magnesium. Calcium is a major constituent of apatite which is the main ore mineral for phosphate in the Save Catchment area and thus can be used to explain the increase in hardness in the water at the study site. Hardness caused by calcium and magnesium is usually indicated by precipitation of soap scum and the need for excess use of soap to achieve cleaning. The degree of hardness in water may affect its acceptability in terms of taste and scale deposition. Depending on pH and alkalinity, hardness above 200 mg/l, as is the case downstream of the mine where hardness is 314 mg/l, can result in scale deposition, particularly on heating. When the water is used for irrigation, carbonate deposits may clog pipes and coat the inside of water holding tanks. For domestic purposes, hard water is objectionable because of the formation of scale in boilers, water heaters, radiators and pipes. This results in the decrease in rate of flow and heat transfer and in increased corrosion. In addition to its effect on soap consumption, excessive hardness can shorten the lifespan of fabrics and toughen cooked vegetables (Urban Watershed Project – UWP, 1999).

5.1.4. Manganese and iron content

The Save river water is contaminated with respect to manganese and iron. The manganese value of 0.59 (mg/l) downstream of the mine is above the WHO guidelines limit for drinking water of 0.4 (mg/l), yet the water in the river is used for drinking purposes by some villagers around the area (Marunda, 2001). At levels exceeding 0.1 mg/l, manganese in water supplies causes an undesirable taste in beverages. High manganese in drinking water may lead to the accumulation of deposits in the distribution system, form a coating on pipes (black precipitate) and staining sanitary ware and laundry.

The iron content observed (1.34 mg/l) downstream of the mine is also a source of concern, considering that upstream of Dorowa

the iron content value was 0.69 mg/l, which is within the median iron concentration in rivers, reported to be 0.7 mg/l (WHO, 2002). The elevated iron levels can be explained in terms of magnetite (Fe₃O₄), which is associated with apatite in the rocks that are mined. Though WHO does not give a guideline value for iron, on the basis that it is usually not of health concern at concentrations normally observed in drinking-water, levels above 0.3 mg/l, iron causes staining of laundry and plumbing fixtures, changes taste and develops colour (WHO, 2004) which affects the water users. High concentrations of iron (above 0.3 mg/l) in water causes reddish-brown stains on white porcelain, enameled ware, fixtures and fabrics. Iron also promotes undesirable bacterial growth ("iron bacteria") within a waterworks and distribution system, resulting in the deposition of a slimy coating on the piping. Small quantities of iron are essential for plant growth and development; however, toxicity occurs when concentrations exceed 5 mg/l (UWP, 1999).

5.1.5. Nitrates

Nutrient enrichment and eutrophication are of concern since high concentrations of nitrogen can lead to periodic phytoplankton blooms and an alteration of the natural trophic balance. The current nitrate and phosphate levels are, however, not high enough for eutrophication. Nevertheless, these levels still need to be monitored. The observed value in the water of 0.5 mg/l is above the WHO guideline value of 0.3 mg/l. The primary health concern regarding nitrate and nitrite is the formation of methaemoglobinemia, so-called "blue-baby" syndrome.

6. Conclusions

The water samples downstream of Dorowa show an increase in conductivity, iron content, manganese content, nitrates and hardness, when compared to those taken upstream of the mine. Though the geological environment indicates a possible release of metals from both mined areas of the complex and also unmined areas, the latter by natural rock-water interaction processes (Kimball et al., 2002), the local water in the streams is not contaminated with heavy metals in the vicinity of the alkaline complexes. The metals are likely to be adsorbed to the sediment. Thus, the sediment can act as a source of pollution when the overlying water conditions are changed. The release of phosphate will depend on, among other factors, pH, sediment size, cations present and oxygen. Therefore, further work is recommended to be done around the mine to assess the fate of the phosphates and associated pollutants in the Save River, so that the necessary proactive steps in guarding the water quality of the Save River are taken. The authors also recommend that water and sediment samples within the alkaline rock complex itself should also be analyzed thoroughly.

The paper reports a local problem, but the implications are transferable to other areas.

Acknowledgements

This paper is part of a Ph.D. Thesis evaluating the impacts of mining alkaline rocks being carried out as part of a regional program, Sustainable Integrated Management of Arid and Semi-Arid Region of southern Africa (SIMDAS). Thus, this work acknowledges the United Nations Education and Scientific Cooperation (UNESCO) and developed for the SADC region for funding the overall project. The paper also acknowledges University of Zimbabwe Faculty of Science Research funds for funding the reconnaissance visit for this study.

References

- Ackermann, F.A., 1980. A procedure for correcting the grain size effect in heavy metal analysis of estuarine and coastal sediments. *Environmental Technology Letters* 1 (11) 518-527.
- Barber, B., 1991. Phosphate resources of Zimbabwe. *Fertilizer Resources* 30, 247-278.
- Dallas, H.F., Day, J.A., 1993. The Effect of Water Quality Variables on Riverine Ecosystems: A Review. Water Research Commission, Report No. TT61/93. Pretoria, South Africa.
- Kimball, B.A., Runkel, R.L., Walton-Day, K., Bencala, K.E., 2002. Assessment of metal loads in watersheds affected by acid mine drainage by using tracer injection synoptic sampling: Cement Creek, Colorado, USA. *Applied Geochemistry* 17 (9), 1183-1207.
- Mabvira, M.L., 2003. Geochemical modeling of the dispersion of toxic elements from mining activities in Zimbabwe into soils and water systems. Unpublished Thesis, University of Zimbabwe, Harare, Zimbabwe, 169p.
- Malinovsky, D., Rodushkin, I., Moiseenko, T., Öhlander, B., 2002. Aqueous transport and fate of pollutants in mining area: a case study of Khibiny apatite-nepheline, the Kola Peninsula, Russia. *Environmental Geology* 43, 172-187.
- Marunda, C., 2001. A Methodology to study the impact of land tenure regimes on degradation of the Save catchment in Zimbabwe. <<http://www.york.ac.uk/res/ceip/webpages/projects/cpr/zimbabwe/tenure.htm>> (retrieved 08.08.2004).
- McBride, M.B., 1994. *Environmental Chemistry of Soils*. Oxford University Press, New York.
- Modreski, P.J., Armbrustmacher, T.J., Hoover, D.B., 2001. Carbonatite Deposits (model 10; singer, 1986a) US Geological Survey, Preliminary compilation of descriptive geoenvironmental mineral deposit models, Open-File Report 95-831. <<http://pubs.usgs.gov/of/1995/of95-0831/CHAP6.pdf>>.
- Mudroch, A., Azcue, J.M., 1995. *Manual of Aquatic Sediment Sampling*. CRC press, Boca Raton, Florida.
- Urban Watershed Project (UWP), 1999. Dissolved Solids. <<http://www.kernsite.com/uwp/modules/tds/tds.htm>>.
- Walsh, K.L., Siegfried, P., Hall, R.P., Hughes, D.J., 2001. Tectonic implications of four recently discovered carbonatites along the Zambezi Escarpment Fault, northern Zimbabwe. *Journal of African Earth Science* 32, 36-37.
- World Health Organization (WHO), 2002. Iron in drinking-water background document for development of WHO guidelines for drinking-water quality WHO/SDE/WS4/03.04/08. <http://www.who.int/water_sanitation_health/dwq/chemicals/iron.pdf>.
- World Health Organization (WHO), 2004. *Guidelines for Drinking-water Quality*, third ed., vol. 1, Recommendations, Geneva.