REPORT ON THE SCIENTIFIC INVESTIGATION OF THE IMPACT OF MARANGE DIAMOND MINING OPERATIONS ON WATER QUALITY IN THE SAVE AND ODZI RIVERS: INCLUDING ASSESSMENT OF THE HEALTH, ENVIRONMENTAL AND LIVELIHOODS IMPACTS

ZIMBABWE ENVIRONMENTAL LAW ASSOCIATION (ZELA)

No. 6 London Derry Road, Eastlea

Harare, Zimbabwe

Tel: 263 4 253381; 263 4 252093

Website: www.zela.org

JULY 2012

EXECUTIVE SUMMARY

The study of the impact of mining activities on the water quality of the Save and Odzi rivers was commissioned by the Zimbabwe Environmental Law Association (ZELA) in the period 5 – 13 July 2012. This followed widespread reports that water quality had deteriorated to the extent that most ecosystem services (potable water, livestock watering and irrigation) that used to be derived from these natural ecosystems had been lost. The objectives of this study were to determine the water quality in the Save and Odzi Rivers and make appropriate conclusions about the state of the environment and the potential impacts on human health and livelihoods in the Marange diamond mining region. Ten study sites were sampled and this included suitable reference sites were selected on each river outside the diamond mining areas to give comparison of the effects before and after mining discharges. Twenty physical and chemical water quality parameters were measured; along with nine heavy metal elements and four microbiological parameters. The results were evaluated against established W.H.O. standards and Zimbabwe Effluent Standards.

The results of this study have shown large scale impacts that include siltation, chemical pollution and also heavy metal pollution. All these arise as by products of the mining processes. Turbidity and total solids exceeded the environmental limits. Water of high turbidity (hazey, murky water) cannot be used as potable water, and the high total solids also imply that it cannot be used as irrigation water as well as this will damage infrastructure. Downstream of mining activities the water has turned into a red ochre colour, thereby affecting the health of the river system. When in contact with the skin, the water and mud were itchy. It is most likely that the subsistence artisanal fishing that took place before is no longer possible at affected river sites, thereby impacting negatively on people's livelihoods. Similarly, pH was in the high alkaline range as well as C.O.D. These parameters were indicative of some chemical pollution in the rivers. The pH that is alkaline (hard water) is corrosive and can damage plumbing equipment and clothes. High levels of fluoride in the water pose the risk of diseases such as dental and skeletal flourosis. Dental flourosis relates to the poor development of teeth, while skeletal flourosis is a bone disease caused by excessive consumption of fluoride.

Levels of heavy metals showed high concentrations of iron, chromium and nickel in the water. These elements are the major constituents of ferro-silicon, a chemical compound used in the diamond extraction process. Chromium and nickel are potentially carcinogenic agents (cancer causing agents) and therefore they pose an immediate health risk to people and livestock. The high levels of iron in water suggest that the local populations could be at risk of iron poisoning, as they exceeded stipulated W.H.O. standards. Dangerous levels of bacterial contamination (high total and faecal coliform counts) mainly of faecal origin, were detected in the water. The exact sources could not be determined but the mines have to explain and show how their

sewage is treated and disposed of in the mining area. This means sewage treatment facilities must be in place for evaluation. The presence of pathogenic bacteria such as *Salmonella* also represents an immediate health risk for the local communities. A water quality index (WQI) was calculated for each of the river sites, and results showed that most of the river sites were classified as BAD water quality and the reference sites as MEDIUM quality.

The results of this study clearly show the environmental and potential health risks to people and their livelihoods as a result of poor mining practices in the Marange diamond region. Access to this area is severely restricted, but the mines can only be exonerated if they allow independent studies to evaluate the environmental impacts arising from their mining activities. It is recommended that the necessary infrastructure to process ALL waste water from the mines should be put in place, and as part their community responsibility, the mines must facilitate the clean up process. The problems of water quality and environmental degradation need to be addressed in the Marange area before there is irreparable damage to the environment and people's livelihoods.

TABLE OF CONTENTS

PAGE

INTRODUCTION

Mining, due to the nature of its operations, has been traditionally associated with problems of environmental degradation. In Zimbabwe, mining is a significant contributor to the country's GDP like most countries in southern Africa. The problems and economic losses associated with environmental degradation include damage to vegetation, health effects on livestock and humans, shortages of water in terms of quality and quantity. Thus, the long-term impacts on the health of livestock and humans ultimately depend upon the physical and chemical characteristics of pollutants and the exposure to such pollutants. Like many other developing countries, a number of rivers in Zimbabwe are heavily polluted from anthropogenic activities which include industrial, sewage discharges and mining. The discovery of diamonds in the Marange region of Zimbabwe has translated the country into a mining giant. However, the pursuit of economic benefits must not be at the detriment of the natural environment upon which our biodiversity thrives as well as the livelihoods of millions of people who may not derive any direct benefits from mining activities. Mining by its nature, is a major environmental disturbance as it alters the landscape in many ways as minerals are mined and processed. The two main complex processes involved include moving large quantities of earth thereby exposing toxic elements to the environment; and the processes of mineral extraction from the ore generates large amounts of liquid waste that must be disposed of. In order to protect natural resources such as river courses, Zimbabwe has enacted legislation which include the Environmental Management Act and the Water Act (1998).

Diamond ore processing

Separating diamonds from the kimberlite host rock is a non-chemical, gravity-based process which relies on the diamonds' heavier weight to separate them from waste rock. At the beginning of this process, diamond-bearing kimberlite ore is trucked to a storage area outside the process plant. A primary sizer reduces the ore before it enters the plant where it is mixed with water and crushed to less than 30 millimetres. The ore is then conveyed to the dense medium separation circuit. Here fine grained, heavy and magnetic ferro-silicon (FeSi) sand is added to the crushed ore and water mixture. The FeSi magnifies the gravity effect and enhances diamond and other heavy mineral separation. A large magnet recovers the FeSi, which is recycled. Water is also recycled.

The less dense waste kimberlite fraction is directed to the processed kimberlite containment (PKC) area for permanent storage. The heavy mineral concentrate (containing diamonds, garnet, diopside, olivine, and spinel) is conveyed to the recovery circuit. In the recovery building, the diamonds are separated from the waste heavy minerals using X-rays to trigger a unique characteristic of diamonds. Diamonds glow under this kind of light, and photo-electric sensors direct strategically placed air blasts to blow the diamonds off the conveyor belt into diamond collection receptacles. Waste minerals are reprocessed and directed to the PKC.

Problem statement

Communities in the Marange/Odzi region of Manicaland (Chimanimani, Marange, Buhera and Chipinge) have for long relied on the Odzi and Save Rivers for potable water, domestic chores, bathing, fishing and other ecosystem services such as reeds used for the basket making industry. Irrigation schemes that draw water from the Odzi and Save Rivers in the Nyanyadzi, Tonhorai and Birchenough areas have been key to the sustenance of livelihoods of local communities (Pazvakavambwa and van der Zaag, 2001). Since the start of the diamond mining operations, the services that were derived from these rivers have slowly diminished as the water quality has progressively declined. This is to such an extent that communities cannot use the water for drinking purposes anymore whilst coming into contact with the water and mud cause an itching of the skin. The use of ferro-silicon which is an alloy containing silica, iron, chromium, nickel, aluminium and calcium is suspected to be linked to the prevailing environmental problems. Downstream of mining activities the water has turned into a red ochre colour effectively affecting the health of the river system and ecosystem function. It is likely that the subsistence artisanal fishing that took place has been somewhat affected. There have been some studies on the Odzi River well before mining activities (Jonnalagadda et al., 1998; Jonnalagadda and Mhere, 2001) but the sampling sites were situated well before the Marange area.

Main objective

The problems of water quality and environmental degradation need to be addressed before there is irreparable damage to the environment and people's livelihoods. The principal objective of this investigation was to determine the water quality in rivers that flow through the Marange diamond fields where there are several diamond mining operations.

Specific objectives

1. To determine physico-chemical characteristic of river water.
2. To determine levels of heavy metals in river water.
3. To determine the extent of microbiological contamination of the river water.
4. To assess the potential environmental and health risks posed by contaminated water.

STUDY AREA

The Odzi River is situated in the Save River basin, which is one of the seven basins/watersheds of Zimbabwe (Figure 1). It is the main river in the Eastern Highlands of Zimbabwe, where it originates at an altitude of 2500m in the Inyangani mountains.

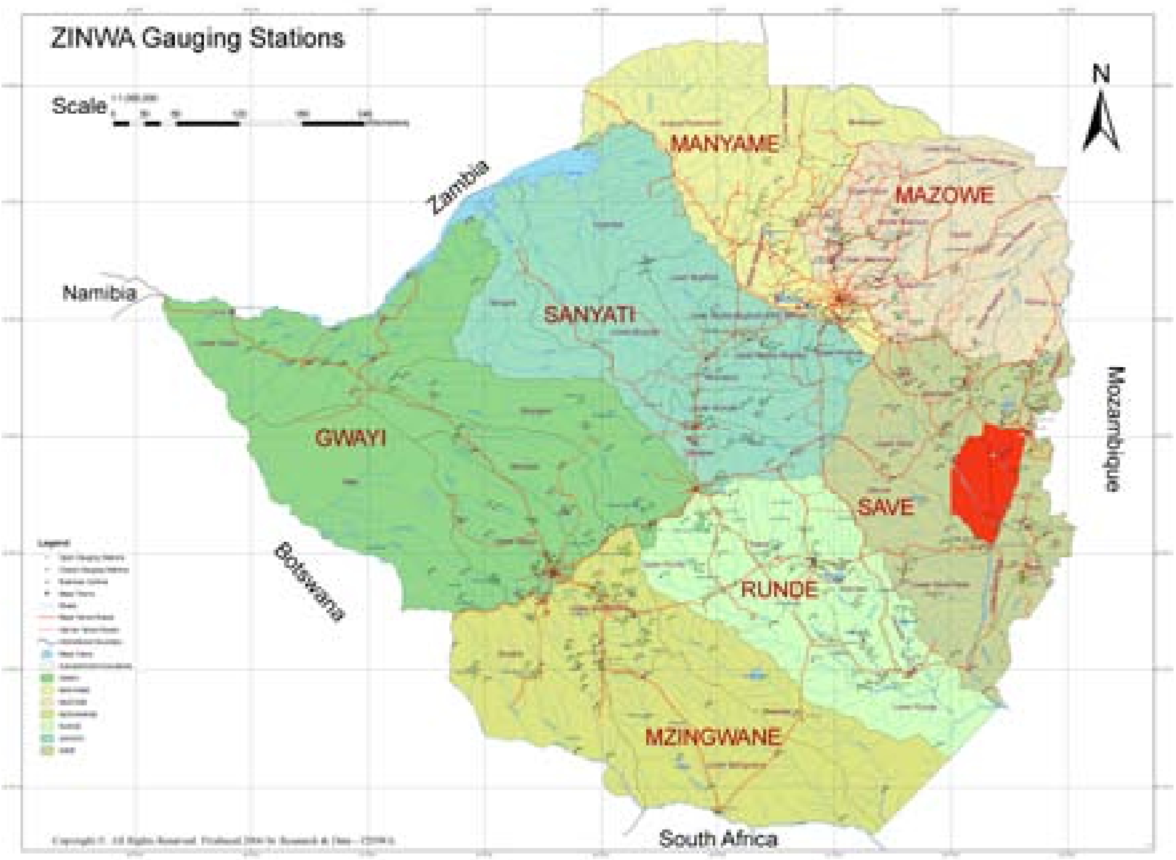


Figure 1. The Catchment map of Zimbabwe showing the seven major river basins. The area marked in red is the Odzi/Save River subcatchments in which the diamond mining operations are situated.

It flows in a southwesterly direction for 150km until it confluences with the Save River. The headwaters of the Save River begin about 80 km south of Harare. The Save River flows southeast with several tributaries feeding it from the highveld (1500 m above sea level) to its confluence with the Odzi River from Nyanga. It then flows south past Birchenough Bridge and confluences with the Runde River just before the Mozambique border (162 m above sea level) in Gonarezhou and then proceeds to the Indian Ocean.

Table 1. The sampling sites and their GPS coordinates

Site	**River**	**Grid reference**
1	**Odzi**	S 19^{o} 42’ 52.5’’ E 032^{o} 25’ 11.6’’
2	**Odzi**	S 19^{o} 46’ 35.1’’ E032^{o} 23’ 21.9’’
3	**Odzi**	S19^{o} 46’ 37.4’’ E032^{o} 23’ 22.1’’
4	**Save**	S 19^{o} 58’ 55.5’’ E032^{o} 20’ 38.8’’
5	**Odzi**	S 19^{o} 14’ 54.7’’ E032^{o} 29’ 19.3’’
6	**Save**	S 19^{o} 26’ 27.7’’ E032^{o} 09’ 13.7’’
7	**Save**	S 19^{o} 37’ 06.4’’ E032^{o} 14’ 25.0’’
8	**Save**	S19^{o} 39’ 19.2’’ E032^{o} 15’ 46.9’’
9	**Save**	S19^{o} 39’ 17.3’’ E032^{o} 15’ 44.4’’
10	**Save**	S19^{o} 39’ 17.7’’ E032^{o} 15’ 44.0’’

Sampling sites were strategically located to determine the nature of the environmental impacts of mining activities in the Marange area. There are four mining companies operating in the Marange area namely: DMC, Mbada Diamonds, Anjin and Marange Resources. Communities have raised concern about effluent discharge from Anjin, Marange Resources and DMC mines. For this purpose, Reference sites were identified on both the Save and Odzi River, and these sites represent conditions in the rivers before the impacts from mining activities. The reference point on the Odzi River was Site 5 situated at Bazeley Bridge, whilst the main reference points on the Save River were Sites 6 & 7. The other sites were then selected to measure the water quality at different points downstream of the mining area. Restrictions to access of the mining area meant that it was impossible to get to the exact point of discharges without endangering human lives. Each site was mapped for coordinates using a Global Positioning System (GPS) Garmin III instrument.

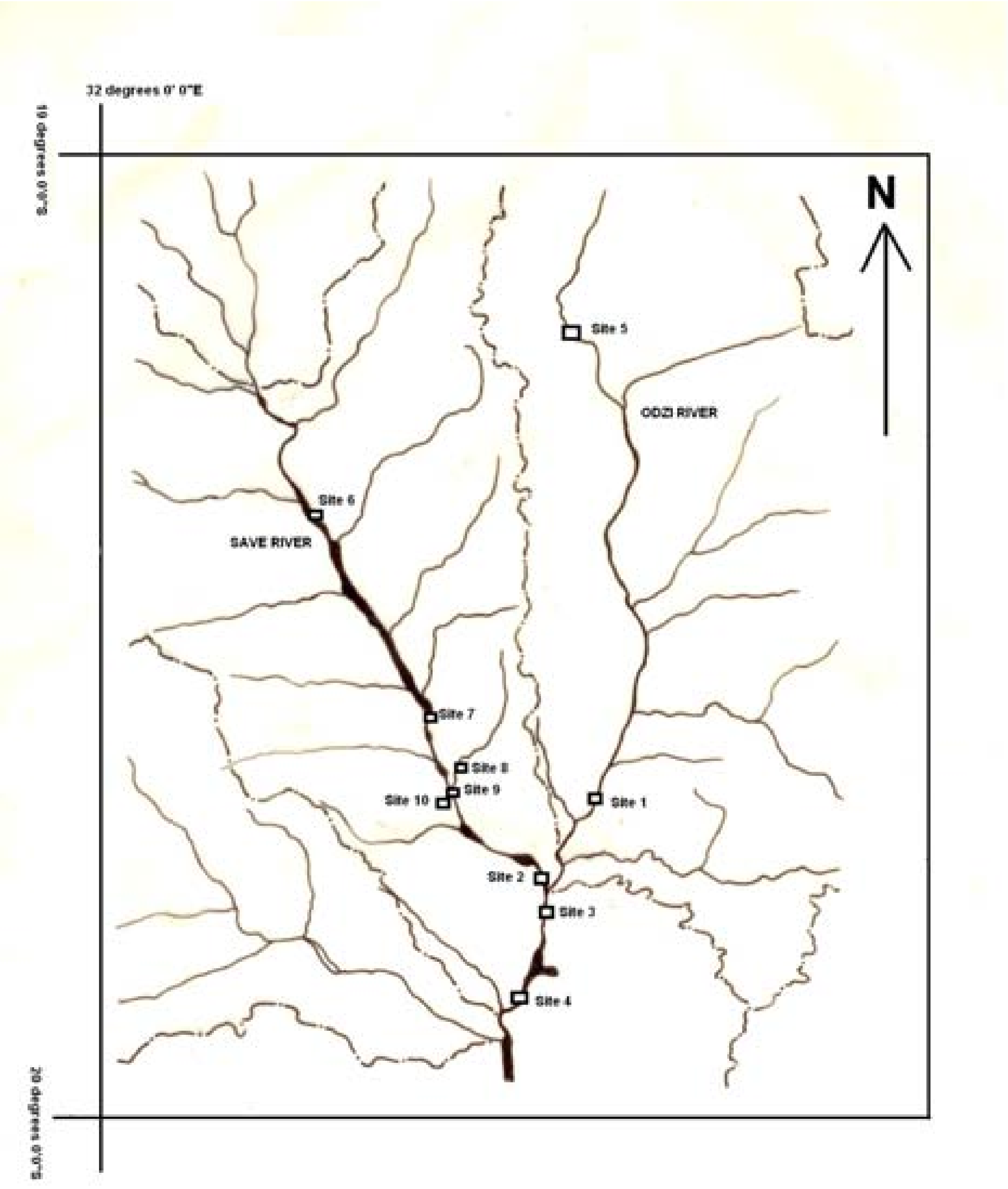
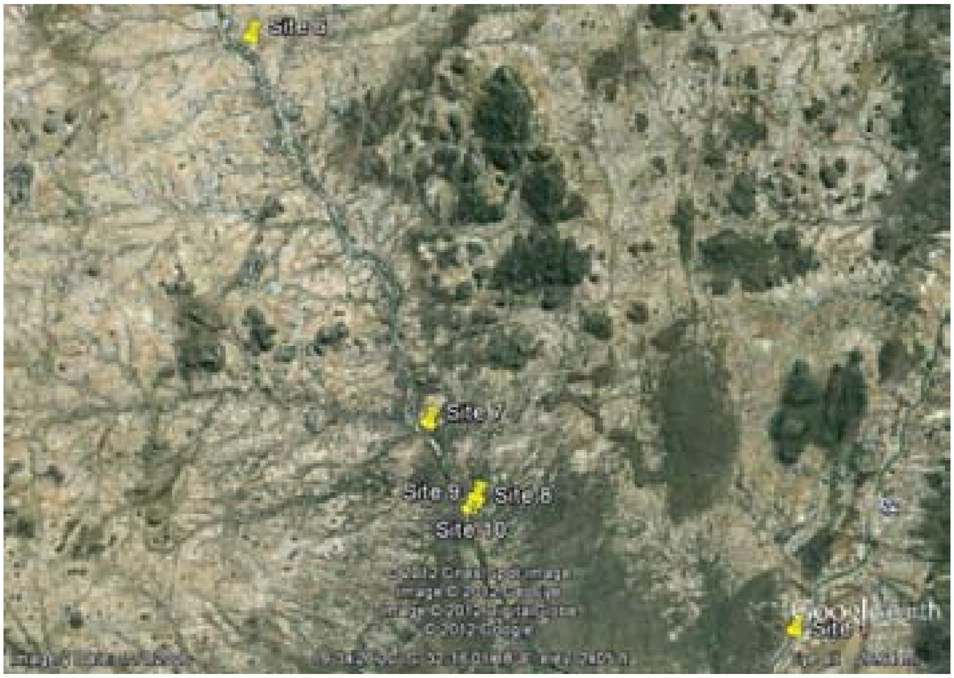


Figure 2. The sampled sites on the Odzi and Save Rivers.

Figure 3. Satellite imagery showing the overview of the entire study area and the marked sampling sites.



.

Figure 4. Satellite imagery showing Sites 6,7,8, 9 and 10 on the Save River and the discharge from Singwizi River.

Figure 5. Satellite imagery showing Sites 1, 2 & 3.

Figure 6. Satellite imagery showing Site 5 at Bazeley Bridge before the diamond mining area.

Photo 1. Site 1 on Odzi River near Nenohwe village (5 July 2012).

Photo 2. Site 2 on Save River near Nechishanye village but upstream of Odzi/Save confluence (5 July 2012).

Photo 3. Site 3 near Nechishanye village at the confluence of Odzi and Save Rivers (5 July 2012).

Photo 4. Site 4 on Save River near Goko village downstream of Save/Odzi Rivers confluence (5 July 2012).

Photo 5. Site 5 at Bazeley Bridge upstream of Anjin Mine and Marange Resources discharge points (6 July 2012).

Photo 6. Site 6 at Save River Bridge near Mafararikwa Village in Marange.

Photo 7. Site 7 on Save River River at Dune/Banda- Maundu Village in Buhera.

Photo 8. Site 8 on Singwizi River (tributary of Save River) near DMC Mine discharge point in Marange (photograph taken at night).

Photo 9. Site 9 at the confluence of Singwizi and Save Rivers (photograph taken at night).

Photo 10. Site 10 on the braided channels of the Save river outside the mining region (photograph taken at night).

MATERIALS AND METHODS

Water Quality

At each river site the following physico-chemical variables were determined *in situ*: dissolved oxygen, temperature and pH (multiprobe HACH LDO meter) and conductivity (WTW LF340 meter). . Total suspended solids were estimated by filtering a known volume of water using Whatman Glass Fibre 47mm filters. These filter papers were dried at 105 °C for 5 hrs and the difference in mass before and after filtration was expressed as mg l^{-1}. Turbidity was measured as NTU using an Orbeco-Hellige Turbidimeter (model 966). Biological oxygen demand was measured by incubating dark bottles in a water bath filled with water from the dams artificially saturated with oxygen for 5 days at 25 °C. Dissolved oxygen in the dark bottles was measured with an electronic probe (multiprobe HACH LDO meter) and BOD calculated by the difference between the initial oxygen level when the water was saturated and the level after five days.

Additional water samples were collected in 500ml plastic bottles for further analysis in the laboratory of the following chemical variable according to methods in Mackereth *et al*. (1978); Bartram and Balance (1996); and Chapman (1997): total and reactive phosphorus (orthophosphate), total nitrogen, nitrates, ammonia and chemical oxygen demand (COD). The nutrients were measured with a HACH DR/2010 portable data logging spectrophotometer using filtered water samples (Whatman GF 47mm filters) except for total nitrogen and phosphorus. All the samples were analysed in replicates of three to assess for variation in the results.

Other chemical variables were measured with a HACH water analysis kit (DR/2010 portable data logging spectrophotometer) using filtered water samples (Whatman GF 47mm filters) except for total nitrogen and total phosphorus. The summary of each method is given but they are described in detail in Farber *et al*. (1960):

(a) *Chemical oxygen demand* - was determined by the reactor digestion method (Test no.8000). The sample was heated for two hours with a strong oxidizing agent, potassium dichromate. Oxidizable organic compounds reacted reducing the dichromate ion ($Cr_2O_7^{2-}$) to green chromic ion (Cr^{3+}). The amount of Cr^{6+} remaining was determined by measuring absorbance at 420nm. The COD reagent also contained mercury ions used to complex chloride interferences and silver ions acting as catalysts. The estimated detection limit (EDL) is 2mg l^{-1}. Precision is at a standard deviation of ± 2.7 mg l^{-1} COD.

(b) *Nitrate-nitrogen* – was determined by the chromotropic acid method (Test no. 10020). The nitrate in the sample reacted to give a yellow product with maximum absorbance at 410nm. Precision is at standard deviation ± 0.2 mg l^{-1} N.

(c) *Nitrite* – was determined by the diazotization (chromotropic acid) method (Test no. 8507). The nitrite in the sample reacted with sulphanilic acid to form an intermediate diazonium salt. This coupled with chromotropic acid to produce a pink colored complex directly proportional to the amount of nitrite present. Absorbance was measured at 507nm. Precision is at a standard deviation of ± 0.006 mg l^{-1} NO_2^- - N

(d) *Ammonia* – was determined by the salicylate method (Test no. 10023). Ammonia compounds in the sample combined with chlorine to form monochlorine. Monochlorine reacted with salicylate to form 5 – aminosalicylate. The 5- aminosalicylate was oxidized in the presence of a sodium nitroprusside catalyst to form a blue colored compound. The blue color was masked by the yellow color from the excess reagent present to give a final green colored solution. Absorbance was measured at 655nm. The precision levels are at standard deviation of ± 0.03mg l^{-1} N.

(e) *Total nitrogen* – was determined using the persulfate digestion method. The alkaline persulfate digestion converted all forms of nitrogen to nitrate. Sodium metabisulphate was added after the digestion to eliminate halogen oxide interferences. Nitrates then reacted with chromotropic acid under strongly acidic conditions to form a yellow complex with a maximum absorbance at 410nm. Precision is at standard deviation less than 1mg l^{-1} N.

(f) *Reactive phosphorus* - Orthophosphate reacted with molybdate in an acid medium to produce a phosphomolybdate complex. Ascorbic acid then reduced the complex producing intense molybdenum blue color. Absorbance was measured at 890nm. Precision is at a standard deviation of ± 0.02 mg l^{-1} PO_4^{3-}.

(g) *Total phosphorus* - was determined using the acid persulfate digestion method. The phosphates present in organic and condensed inorganic forms (meta-, pyro- or other polyphosphates) were converted to reactive orthophosphate before analysis. Pretreatment of the sample with acid and heat provided the conditions for hydrolysis of the condensed inorganic forms. Organic phosphates were converted to orthophosphates by the heating with acid and persulfate. Orthophosphate reacted with molybdate in an acid medium to produce a phosphomolybdate complex. Ascorbic acid then reduced the complex producing intense molybdenum blue color. Absorbance was measured at 890nm. The EDL for this test is 0.04 mg L-1 PO_4^{3-} and the precision level is ± 0.09 mg l^{-1} PO_4^{3-}.

Metal concentrations in water

Metal estimation in water was performed in the laboratory using Flame Atomic Absorption Spectrophotometry (FAAS) (Greenberg et al. 1980). The acid digestion process used for the water and sediments is a strong digestion method and was chosen so that the total metal content could be estimated. The water sample was then aspirated into a flame and atomized.

Quality control

Quality control was assured by the use of procedural blanks and standards. In each case a known concentration of the standard solution was assayed after every ten samples to verify the analytical quality of the result since there was no standard reference material available. In all the cases for sediments, water and fish, a preparation / reagent blank was prepared for every 20 samples and all the concentrations were below the detection limits. Each sample was analyzed in triplicate for repeatability with a relative standard deviation < 5 % for all the metals analyzed.

Microbiological parameters

McConkey broth was used in the determination of Total Coliforms following the 3-tube method and incubated at 37°C. For the thermo-tolerant faecal coliforms, Brilliant Green Bile broth was used and incubation was at 44°C. Faecal Streptococci were determined using Bile Esculin Azide agar incubated at 37°C. Enrichment was done in Selenite broth and plate positive tests on modified Brilliant Green agar.

The Total coliform count is an indicator of general cleanliness of the environment. The Faecal coliforms are an indicator that water is contaminated with human faecal material that may cause a health hazard. The presence of faecal Streptococci is an indicator of how recent contamination occurred as they do not survive for a long periods outside of the human body. The positive identification of *Salmonella* indicates the presence of pathogenic bacteria that can cause illnesses such as gastro-enteritis and typhoid.

Data analysis

The results were assessed against published guidelines from World Health Organization (W.H.O.) because the waters of these rivers are used for domestic uses. Also assessment was also done in relation to the Environmental Management (Effluent and Solid Waste Disposal) Regulations (2007). These standards are presented in Table 2.

Table 2. World Health Organization (W.H.O.) drinking water guidelines and Zimbabwe Effluent Standards for discharge according to the Environmental Management (Effluent and Solid Waste Disposal Regulations Statutory Instrument 6/2007)

		W.H.O. guidelines drinking water	**Zimbabwe Effluent standards**			
Parameter	**Units**		**Blue**	**Green**	**Yellow**	**Red**
Colour	TCU	-	≤15	-	-	-
pH	-	6.5 - 8.5	6 – 9	5-6; 9-10	4-5; 10-12	0-4; 12-14
Turbidity	NTU	5	≤ 5	-	-	-
Conductivity	uS/cm	-	≤ 1000	≤ 2000	≤3000	≤ 3500
Sus. solids	mg/l	-	≤ 25	≤ 50	≤ 100	≤150
TDS	mg/l	1000	≤ 500	≤ 1500	≤ 2000	≤ 3000
Alkalinity	mg/L($CaCO_3$)	-	-	-	-	<500
Total hardness	mg/l($CaCO_3$)	-	-	-	-	-
Phenolic compounds	mg/l	-	≤ 0.01	>0.04	>0.06	≤ 0.1
Chlorides	mg/l (Cl^-)	250	≤250	≤ 300	≤ 400	≤ 500
Sulphates	mg/l(SO_4^{2-})	250	≤250	≤ 300	≤ 400	≤ 500
Phosphate	mg/l(P)	-	≤ 0.5	≤ 1.5	≤ 3	≤ 5
Grease& Oils	mg/l	-	≤ 2.5	≤ 5	≤ 7.5	≤ 10
Detergents	mg/l	-	≤ 1	≤ 2	≤ 3	≤ 5
DO	%	-	≥60	≥50	≥30	≥15
5-Day-B.O.D	mg/l	-	≤ 30	≤ 50	≤ 100	≤ 120
Nitrates	mg/l ($NO^{-}{}_{3}$)	50	-	-	-	-
Nitrites	mg/l($NO^{-}{}_{3}$)	3	≤ 3	≤ 5	≤ 8	≤ 10
Fluoride	mg/l F^-)	1.5	≤ 1	≤ 2	≤ 4	≤ 6
Potassium	mg/l	-	-	-	-	>500
Sodium	mg/l	200	≤ 200	≤ 300	≤500	≤ 1000
Manganese	mg/l	0.1	≤ 0.1	≤ 0.3	≤ 0.4	≤ 0.5
C.O.D.	mg/l	-	≤ 60	≤ 90	≤ 150	≤200
Chromium (Tot)	mg/l	0.05	≤ 1.0	≤ 1.2	≤ 1.6	≤2.0
Copper	mg/l	1	≤ 1.0	≤ 2.0	≤ 3.0	≤5.0
Zinc	mg/l	1.5	≤ 0.5	≤ 4.0	≤ 5.0	≤15
Arsenic	mg/l	0.01	≤ 0.05	≤ 0.1	≤ 0.15	≤ 0.3
Cyanide	mg/l	0.07	≤ 0.07	≤ 0.1	≤ 0.15	≤ 0.3
Iron	mg/l	0.3	≤ 1	≤ 2	≤ 5	≤ 8
Nickel	mg/l	0.07	≤ 0.3	≤ 0.6	≤ 0.9	≤ 1.5
Cadmium	mg/l	0.003	≤ 0.01	≤ 0.05	≤ 0.1	≤ 0.3
Mercury (Tot)	mg/l	0.001	≤ 0.01	≤ 0.02	≤ 0.03	≤ 0.05
Lead	mg/l	0.01	≤ 0.05	≤ 0.1	≤ 0.2	≤ 0.5
Ammonia	mg/l	1.5	≤ 0.5	≤ 1	≤ 1.5	≤ 2
Chromium(vi)	mg/l	0.05	≤ 0.05	≤ 0.1	≤ 0.2	≤ 0.5
Total coliforms	Counts/ 100 ml	0	≤1000	>1000	>1500	≤2000

RESULTS AND DISCUSSION

1.1. General site descriptions

Site 1: The water was turbid (water was cloudy, opaque, or muddy) because of being discharged at Marange-ANJIN Resources mine. The site is about 5km downstream of the mine. It was not possible to sample the point of discharge because of limited accessibility to the plant. Livestock and people cannot use the water for drinking and any other domestic uses.

Site 2: The water was turbid (water was cloudy, opaque, or muddy) at this site and cannot be used to water livestock or other domestic uses. This site is downstream of the discharges from the mining area especially that of DMC mine.

Site 3: The water was again turbid (water was cloudy, opaque, or muddy) at this site and cannot be used to water livestock or other domestic uses. This site is downstream of the discharges from the mining area.

Site 4: The water was again turbid (water was cloudy, opaque, or muddy) at this site and cannot be used to water livestock or other domestic uses. This site is downstream of all the discharges from the mining area on the Save River.

Site 5: Water was clear at this site at Bazeley Bridge and women were actually seen doing laundry at the site. This site is just upstream of the Marange diamond fields mining area and was the **reference point** for the Odzi River.

Site 6: Water was clear at this site and even fish could be seen swimming in the water. Local people were also bathing and swimming upstream. This site was the **reference point** on the Save River.

Site 7: This site was just upstream of the DMC mine point of discharge where the Singwizi River confluences with the Save River. At this site, DMC mine pumps its water from the Save River, and the return flow from the mine comes back through the Singwizi River. The water was clear and indicated good water quality at this site.

Site 8: This site is the point of discharge of effluent from DMC mine. The effluent is discharged into a tributary of Save River called Singwizi River just before the point of confluence of the two rivers. The water was very turbid (cloudy, opaque, or muddy) and the river bed was very muddy and sticky. When in contact with the skin, the water and mud was itchy.

Site 9: This is the point of confluence between Singwizi River and the Save River. At this point the clean water from upstream meets the now dirty, turbid water from Singwizi River. The sample was taken from the braided channel of the Save River that connects with Singwizi River. From the picture, two different waters can be distinguished (**Photo 9**).

Site 10: This site is the point of braiding of Save River. The water sample was taken on the clean side so as to be compared with the point of confluence with Singwizi which will be on the other braid.

1.2. Water Quality: Physico-chemical characteristics

The results of the physico-chemical analyses for all the river sites are presented in Table 3. The water **temperatures** ranged from 19^{o}C-24.5^{o}C at the river sites with the exception of Site 8 which recorded 7.41^{o}C. These water temperatures were typical of cold season temperatures and they did not indicate that activities within the catchment had an effect on them. **Dissolved oxygen** was measured in mg/l and percent oxygen saturation. Several river sites recorded oxygen levels of almost or greater than 5mg/l although only one site (site 3) achieved >100% or supersaturated conditions. However, Sites 4, 8, and 9 had oxygen values of <3mg/l and this indicated oxygen stress or deficits at these sites. Site 4 measures the sum total of all the pollutants from the mining area, whilst sites 8 & 9 were situated at effluent discharge points from DMC mine. Oxygen saturation in the aquatic environment generally refers to the amount of oxygen dissolved in water. Environmental oxygenation is important to the sustainability of a particular ecosystem. Insufficient oxygen (environmental hypoxia) may occur in bodies of water such as rivers, tending to suppress the presence of aerobic organisms such as fish and invertebrates. Deoxygenation increases the relative population of anaerobic organisms such as

Table 3. Physico-chemical characteristics of the different river sites on the Odzi and Save Rivers, July 2012

	River Sites									
Environmental parameters	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Temperature (^{o}C)	21.4	24.1	24.5	20	19	24.6	21.7	7.41	19.3	19.5
Dissolved oxygen (mg/l)	6.17	6.56	8.79	3.4	6.3	6.8	5.6	1.4	2.1	4.8
% oxygen saturation	73.2	83.1	101.3	51.7	78.6	94.2	88.8	48	52	71
Conductivity (µS/cm)	168.2	167.9	186.5	179.7	115.9	81.6	85.9	368	112.7	80.3
Total dissolved solids (mg/l)	101	98	111	117	78	49	54	256	76	53
pH	8.76	9.36	8.63	8.64	7.72	7.51	8.53	9.13	8.90	7.16
Turbidity (NTU)	70.5	397	247	153.1	3.3	1.8	12.5	805	206	12.7
Total solids (mg/l)	421	240	808	720	11	3	7	44320	2885	40
Total hardness (mg/l)	61	54	49	63	37	28	30	47	59.5	48
Chemical oxygen demand (COD) (mg/l)	115	40.5	100.5	55	9	48	106	3585	136.5	70
Biological oxygen demand (mg/l)	6.12	6.12	3.44	3.84	3.25	3.48	5.98	5.98	5.58	4.49
Ammonia (mg/l)	0.001	0.008	0.059	0.050	0.040	0.016	0.006	0.129	0.001	0.010
Nitrites (mg/l)	0.053	0.025	0.015	0.004	0.017	0.014	0.096	0.127	0.106	0.006
Nitrates (mg/l)	0.54	0.42	0.5	0.38	0.38	0.52	0.42	0.58	0.56	0.27
Total nitrogen (mg/l)	0.89	0.47	0.57	0.92	0.70	1.13	0.56	1.29	1.02	0.38
Reactive phosphorus (mg/l)	0.08	0.12	0.05	0.05	0.07	0.00	0.00	0.03	0.03	0.15
Total phosphorus (mg/l)	3.24	3.00	1.62	0.82	0.22	0.08	0.09	0.42	0.25	0.56
Chlorides (mg/l)	28.4	17.7	21.3	30.5	17.7	7.1	4.3	14.2	21.3	21.3
Sulphates (mg/l)	0.317	0.156	0.132	0.082	0.140	0.107	0.358	0.144	0.268	0.206
Flouride (mg/l)	0.55	0.65	0.75	0.40	0.35	0.35	0.35	1.10	0.90	0.25

plants and some bacteria, resulting in fish kills and other adverse events. The net effect is to alter the balance of nature by increasing the concentration of anaerobic over aerobic species.

Ionic conductivity is a measure of ions dissolved in water measured as electrical resistance between two electrodes. It is also closely related to Total Dissolved Solids (TDS) which measures the amount of dissolved ions as mg/l. Sites 8 recorded the highest conductivity of 368µS/cm near the discharge point of DMC mine. There is dilution after confluence with the Save River at Sites 9 & 10. Note that Site 6 (reference point for the Save River) was almost he same as Site 10. On the Odzi River, conductivity was 115 µS/cm at Bazeley Bridge, the reference point for this river, which was higher than that of Save River at Site 6. Further downstream, Sites 1, 2 & 3 recorded higher conductivities >160 µS/cm. The conductivity after all the drainage from the mining areas was integrated was 179.7 µS/cm at Site 4 on the Save River near Birchenough Bridge. The trends in TDS mirrored those of ionic conductivity. Both conductivity and TDS were well within the acceptable limits of W.H.O. and Zimbabwe Effluent Standards.

The **pH** is a measure of the acidity (< 7) or alkalinity (>7) of the water. The **pH** was below 8 at the reference sites 5 & 6 and also at site 10 which was a braided channel not directly influenced by mine drainage. The pH values of around pH 7 indicate good water quality. All the other sites affected by mine discharges recorded pH values of > 8, the worst affected being Sites 2 & 8 (pH values 9.36 and 9.13 respectively). The results clearly indicated that discharges and runoff from the mining areas contained alkaline reagents that were pushing the pH up. The acceptable limits for pH according to W.H.O. drinking water standards is 6.5-8.5 and several sites receiving mine drainage failed to meet this important criteria.

Turbidity is the cloudiness or haziness of a fluid caused by individual particles (suspended solids) that are generally invisible to the naked eye, similar to smoke in air. The measurement of turbidity is a key test of water quality. **Turbidity** was lowest at the reference Sites 5 & 6 (3.3 and 1.8 NTU respectively) and also at sites 7 & 10 (12.6 and 12.5 NTU respectively) that were not directly affected by mine drainage. Sites 2, 3, 8 & 9 all recorded NTU values >200 with site 8 being the most turbid (805 NTU). These sites were all affected directly by discharges from the mining area. At Site 4 there was some dilution and a small decline in turbidity was recorded. Turbidity is normally closely related to amount of suspended solids in water. Results of the **suspended solids (Total solids)** analysis confirmed that most of the turbidity was due to suspended solids while the mud also increased turbidity of the water by affecting its colour. Besides the reference sites, all the other river sites failed to meet the required standard by both of W.H.O. and Zimbabwe Effluent standards which requires turbidity in water to be less than or equal to 5 NTU. Similarly, for total solids, all the impacted sites exceeded the upper limit (RED category) of the Zimbabwe Effluent Standards by being in excess of 150 mg/l suspended solids.

The river sites that were not directly impacted by mine discharges, which include Sites 5, 6 & 7 had lower **total hardness** values than the other river sites. Total hardness is determined by the concentration of multivalent cations in the water. Multivalent cations are cations (positively charged metal complexes) with a charge greater than 1+. Usually, the cations have the charge of 2+. Common cations found in hard water include calcium (Ca^{2+}) and magnesium (Mg^{2+}). Therefore, hard water is water that has high mineral content but is generally not harmful to health. However, it can pose serious problems in industrial settings, where water hardness is monitored to avoid costly breakdowns in boilers, cooling towers, and other equipment that handles water. In domestic settings, hard water is often indicated by a lack of suds formation when soap is agitated in water.

The **chemical oxygen demand (C.O.D.)** is an indirect measure of the amount of organic compounds/pollutants in water. C.O.D is therefore a useful measure of water quality. It is expressed in milligrams per liter (mg/L), which indicates the mass of oxygen consumed per liter of solution. The results for C.O.D. showed that Site 8 had an extremely high COD value of 3585mg/l which indicated direct discharge of chemical organic pollutants into the river from DMC mine. The sites least affected by mining discharges which include Sites 5, 6, 7 & 10 again recorded fairly low COD values of < 100mg/l. Chemical oxygen demand levels were mostly in the yellow category (Zimbabwe Effluent Standards) for the sites receiving mine discharges which clearly indicates that there is a problem of chemical discharge in the mining area. The precise nature of water soluble chemicals i.e. that dissolve in water, cannot be determined easily but its individual constituents can indicate what substance was discharged in water. This section will be discussed further with the heavy metals.

Biological oxygen demand (B.O.D.) is a measure of the amount of dissolved oxygen needed by aerobic biological organisms in a body of water to break down organic material present in a given water sample at certain temperature over a specific time period. Although it is not a precise quantitative test, it is widely used as an indication of the organic quality of water and is a robust surrogate of the degree of organic pollution of water. The results for **B.O.D.** showed that higher values were recorded at sites that were affected by mine drainage (Sites 1, 2 7, 8, & 9), which was also indicative of high levels of organic material. This suggests that soils that are washed in the processing stage of diamond extraction, could be contributing to organic loading when they are eventually discharged into the rivers. It was not clear if there was sewage discharge into the rivers from the mining areas as access was restricted. According to the Zimbabwe Effluent Standards, the levels of B.O.D. measured in this study are within the acceptable range for good water quality.

The nutrient concentrations were generally in the low range for the nitrogen fractions which included **ammonia, nitrites, nitrates and total nitrogen** (Table 3). The levels are not of environmental concern. The levels of **reactive phosphorus** were also low and not of environmental concern, but **total phosphorus** concentrations were notably high at Sites 1, 2 and 3 (Table 3). This probably has nothing to do with mining activities but could be effects of fertilizers used in the Nyanyadzi Irrigation schemes. Such levels are undesirable and could contribute to eutrophication. However, they have no implications on human and livestock health. Nutrient concentrations were in the acceptable ranges according to W.H.O. and Zimbabwe Effluent Standards.

Chloride concentrations were lowest at Sites 6 & 7 on the Save River, and ranged from 17.7 to 30.5 mg/l for all the other sites (Table 3). These values are much lower than the stipulated W.H.O. drinking water standards as well as Effluent Standards. Therefore, they are not of immediate environmental concern. **Sulphates** were measured and concentrations were all < 1mg/l (Table 3). Again this is far below what is stipulated in the environmental standards, and sulphates are not of environmental concern. **Fluoride** concentrations were notably higher at Sites that were affected by mine drainage (Sites 1, 2, 3, 8, & 9) with the highest concentration of 1.10mg/l being recorded at the DMC mine point of discharge (Site 8). Although, it can be argued that nearly all sites recorded Fluoride concentrations < 1.5mg/l (W.H.O.) and < 1.0 mg/l (Environmental Management (Effluent) Standards), there is need for concern as several sites showed increasingly higher values. The results show that something associated with the discharges from the mines contains high fluoride. Site 8 is clearly a distressed site and already exceeds the limits stipulated in the Environmental Management (Effluent) Standards Regulations. Fluoride is highly toxic at concentrations in excess of 1.0 mg/l and cases of fluoride poisoning have been reported in other parts of the world. Health conditions such as skeletal flourosis and dental flourosis are some of the major problems of exposure to high fluoride levels in water. These are diseases whose symptoms include weak bone structure (skeletal flourosis) and poor teeth development (dental flourosis). The situation in the Odzi and Save Rivers needs to be monitored closely because the fluoride levels are dangerously high.

1.3. Water Quality: Heavy metals

The results of the heavy metal analysis are presented in Table 4. Most of the metals that were measured in water were below the detection limit meaning that their concentrations were extremely low in water. Notable exceptions were iron (Fe), nickel (Ni) and chromium (Cr), and these are the major constituents of ferro-silicon. Thus, our hypothesis that the use of Ferro-silicon (FeSi) in mineral processing was causing environmental harm, was confirmed by these results. The concentrations of Iron (Fe) were much higher than W.H.O. limits as well as Effluent standards and placed the affected sites (Sites 1, 2, 3, 4, 8 & 9) into the RED category. This means that local populations are at risk of **iron poisoning, which** is an iron overload caused by excessive iron intake. The first indications of iron poisoning by ingestion are pains in the stomach, as the stomach lining becomes ulcerated. This is often accompanied by nausea and vomiting. The pain then abates for 24 hours as the iron passes deeper into the body and damages internal organs, particularly the brain and the liver, and metabolic acidosis develops. The body goes into shock and death occurs from liver failure. For Chromium (Cr), Sites 1, 4, 8 & 9 exceeded the

W.H.O. limits, whilst Sites 2 & 3 were marginally close. Nickel concentrations were highest at Sites 1, 2, 3, 4, 8 & 9 but were less than the stipulated W.H.O. standards. However, the rising concentrations of these elements are cause for concern because they are cancer causing agents and monitoring is needed for the future. The failure to recover the FeSi after diamond extraction by the mines and allowing it to flow into the rivers is causing environmental damage and putting people at risk of exposure carcinogenic agents (cancer causing). There was no evidence from the metal results that besides the activities of the diamond mines, there were other mining activities adversely affecting the water quality.

1.4. Water quality: Microbiological characteristics

Total coliform counts were all greater than 1100 which is unacceptable according to W.H.O. drinking water standards and indicator poor water quality according to the effluent standards. W.H.O. standards stipulate that not a single coliform should be found in drinking water. Coliform bacteria generally occur in high numbers in human faeces. The faecal coliform investigation confirmed that all river sites were contaminated by human waste and that this contamination was very recent. This stems from the fact that faecal coliforms cannot survive in the environment for a long time. Similarly, total bacterial counts indicated large amounts of bacteria in the water.

The presence of pathogenic *Salmonella* highlights the seriousness of the problem. Many infections are due to ingestion of contaminated food that has come into contact with contaminated water. A distinction is made between enteritis *Salmonella* and Salmonella typhoid/paratyphoid *Salmonella*, where the latter—because of a special virulence factor and a capsule protein (virulence antigen)—can cause serious illness. Infants and young children are much more susceptible to infection, easily achieved by ingesting a small number of bacteria. After a short incubation period of a few hours to one day, the germ multiplies in the intestinal lumen causing an intestinal inflammation with diarrhea that is often bloody. In infants, dehydration can also cause a state of severe toxicosis. Enteritis *Salmonella* can cause diarrhea, which usually does not require antibiotic treatment. However, in people at risk such as infants,

Table 4. Heavy metal concentrations (mg/l) measured at the different sites on the Odzi and Save Rivers, July 2012. The abbreviation "n.d." means "not detectable"

	River Sites									
Metal (ppm)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Arsenic	n.d.	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
Copper	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Cadmium	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Lead	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Manganese	n.d.	n.d.	n.d.	0.01	n.d.	n.d.	n.d.	0.42	0.05	n.d.
Iron	18.8	37.45	11.25	34.1	0.16	0.007	0.05	77.85	44.65	n.d.
Chromium	0.07	0.04	0.04	0.05	0.001	<0.001	0.01	0.08	0.05	<0.001
Nickel	0.01	0.03	0.03	0.01	<0.001	<0.001	<0.001	0.04	<0.001	<0.001
Mercury	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

Table 5. Microbiological characteristics of the different sites on the Odzi and Save Rivers, July 2012

	River Sites									
Site	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Total Coliform/100ml	>1100	>1100	>1100	>1100	>1100	>1100	>1100	>1100	>1100	>1100
Faecal Coliform	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve
Salmonella	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve	+ve
Total Bacteria Count /100ml	>300	>300	>300	>300	>300	>300	>300	>300	>300	>300

small children, the elderly, *Salmonella* infections can become very serious, leading to complications. If these are not treated, HIV patients and those with suppressed immunity can become seriously ill. The results are not surprising since the river is used for many household purposes and the use of bush latrines can also contribute to this problem through runoff. Although the problem of bacterial contamination cannot be wholly attributed to the mining activities (at least from what we know at the moment), the mines also need to prove beyond reasonable doubt that their sewage waste disposal methods meet legally accepted standards. At the moment it is not known what happens to the sewage generated by the mining community. There is also need for community social responsibility by the mine which could include the construction of Blair toilets for rural communities. This is well within the financial capability of the diamond mines. It must be noted that Zimbabwe has a very recent and unfortunate history with regards to waterborne diseases. The cholera outbreaks of 2008/2009 and the most recent typhoid outbreaks are clear reminders that the problems of microbial contamination cannot be taken lightly.

Water Quality Assessment using water quality index (WQI)

To assess the overall water quality of the rivers sites that were sampled on the Odzi and Save Rivers, The National Science Foundation Water Quality Index (WQI) was used (Ott, 1978). The eight indicator parameters used in the water quality assessment were as follows: dissolved oxygen (%), faecal coliforms, pH, BOD, total phosphorus, nitrates, turbidity and total solids. The water quality ranges have been defined as follows:

- 90-100 : EXCELLENT
- 70-90 : GOOD
- 50-70 : MEDIUM
- 25-50 : BAD
- 0-25 : VERY BAD

Table 6. Results of the Water Quality Index (WQI) for each of the sampled river sites

		River sites Quality Index									
Parameter	**Weight**	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 5**	**Site 6**	**Site 7**	**Site 8**	**Site 9**	**Site10**
Dissolved oxygen	0.17	79	89	99	46	85	98	94	41	46	76
Faecal coliform	0.16	22	22	22	22	22	22	22	22	22	22
pH	0.11	57	37	62	61	91	92	65	45	52	91
Biological oxygen	0.11	50	50	64	62	66	64	51	51	53	58
Total phosphorus	0.10	20	21	30	46	90	97	96	69	87	57
Nitrates	0.10	96	97	97	97	97	96	97	96	96	97
Turbidity	0.08	29	5	5	5	89	94	71	5	5	71
Total solids	0.07	44	67	20	20	82	80	81	20	20	86
WQI	**0.9**	**45.7**	**45.1**	**48.7**	**41.0**	**66.8**	**69.8**	**62.9**	**39.4**	**43.0**	**59.9**

The results of WQI for the different river sites are presented in Table 6. The results show that Sites 1, 2, 3, 4, 8 and 9 fell into the BAD water quality criteria. These were the same sites that were most affected by mine discharges into the rivers. The relatively less impacted sites 5, 6, 7 and 10 were in the MEDIUM category. These results highlights the urgency that is needed to address the water quality problems in this region because as the results show, even the less impacted sites are already high vulnerable and could easily fall into the BAD/VERY BAD categories.

CONCLUSION

The investigation into the water quality of the Odzi and Save Rivers in an area where there is diamond mining has highlighted serious environmental problems that need to be urgently addressed. The Save and Odzi rivers were already in a vulnerable state before the mining activities began mainly due to problems of siltation from the communal areas. The start of mining ventures has resulted in large volumes of silt-laden water being discharged into the rivers. The problem of silt from mine washings is not a difficult one to deal with if the will is there. The mines need to construct tailings dams which act as sedimentation ponds. They should then discharge the water into the tailings dam and allow sediment to settle. The water can then be pumped from the tailings dams and recycled. The levels of suspended silt in the rivers means the water cannot be used for irrigation as this would cause damage to pumps and other irrigation infrastructure. It is not fit for consumption by livestock and humans. The fluoride concentrations in the water, especially where there is strong influence of mine discharges, is of serious health concern (causes bone and teeth diseases) and needs to be investigated further.

The second major problem that was clearly identified was that of chemical pollutants being discharged into the rivers after the washings were done. According to the technology that is being used, the ferro-silicone must be recycled after the diamond extraction. It is not clear why this is not being done but the results confirm large amounts of ferro-silicone are also being discharged with waste water into the rivers resulting in the problems of itchy skin and unusable water for irrigation and domestic use. The metal concentrations especially that of chromium which is carcinogenic (cancer causing), are of particular concern being close to or higher than W.H.O. standards for drinking water. The problems of bacterial contamination in the water are of serious concern and pose an immediate risk of outbreaks of waterborne diseases such as diarrhea, cholera and typhoid. Since it is not possible to gain access to the mining area and assess how mines dispose of their human waste, it will be prudent to make the assumption that they could also be contributing to the problem.

It is quite obvious that the water quality problems in this region have far-reaching socio-economic implications for the livelihoods of local communities and the mines must take full responsibility in accordance with the various legal instruments that protect the environment. There is need for a regular monitoring programme to be instituted to assess for seasonal changes in the water quality of these rivers.

REFERENCES

Bartram J. and Balance R. (Eds). (1996). Water Quality Monitoring. A practical guide to the design and implementation of freshwater quality studies and monitoring programmes. E & FN SPON Publishers, London, UK.

Chapman D. (Ed). (1997). Water Quality Assessments. Second edition. E & FN SPON Publishers, London, UK.

Jonnalagadda S.B., Mathuthu A.S. and Mhere G. (2010). Studies on elemental concentrations in the Odzi river waters. *International Journal of Environmental Health Research* 8: 145-152.

Jonnalagadda S.B. and Mhere G. (2001). Water quality of the Odzi River in the Eastern Highlands of Zimbabwe. *Water Research* 35: 2371-2376.

Mackereth, F.J.H.**,** Heron, J. and Talling, J.F. (1978). *Water Analysis*. Freshwater Biological Association, Ambleside, UK.

Ott W. R. (1978) *Environmental Indices-Theory and Practice*, Ann Arbor Science Publishers Inc; Ann Arbor, MI, pp. 202-213.

Pazvakawambwa G.T. and van der Zaag P. (2001). The value of irrigation water in Nyanyadzi smallholder irrigation scheme, Zimbabwe. *Value of Water Research Report* Series No. 4.