Zimbabwe - Strategy for managing water quality and protecting water sources.

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MINISTRY OF ENVIRONMENT, CLIMATE AND WATER

UNIVERSITY OF ZIMBABWE

Zimbabwe-Strategy for Managing Water Quality and Protecting Water Sources

Final Report

Phase 1: Rapid Assessment – Identification and Characterization of Hotspots of Water Pollution and Source Degradation

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List of Acronyms

AMD	Acid Mine Drainage
AMDTF	Analytical Multi-Donor Trust Fund
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DDT	dichloro-diphenyl-trichloroethane
DEM	Digital Elevation Model
EMA	Environmental Management Authority
GIS	Geographic Information System
GMP	Global Mercury Project
GPS	Global Positioning System
IPCC	Inter-governmental Panel on Climate Change
MAMID	Ministry of Agriculture, Mechanization and Irrigation Development
MAR	Mean Annual Runoff
MENRM	Ministry of Environment and Natural Resources Management
MNDWI	Modified Normalised Difference Water Index
MWRDM	Ministry of Water Resources Development and Management
MWRED	Ministry of Water Resources and Energy Development
NASA	National Aeronautics and Space Administration
NDVI	Normalised difference Vegetation Index
NORAD	Norwegian Agency for Development Cooperation
PCB	Polychlorinated biphenyl
PEO	Provincial Environmental Manager
POPs	Persistent organic pollutants
SRTM	Shuttle Radar Topography Mission data
TDS	Total Dissolved Solids
TSS	Total Suspended Solids
WHO	World Health Organisation
WHOARCSSTE-E	African Regional Centre for Space Science and Technology Education in English
ZINWA	Zimbabwe National Water Authority

Executive Summary

The 2013 National Water Policy recognises that the quality and condition of Zimbabwe's surface and groundwater resources are deteriorating. The cholera outbreak of 2008-2009 countrywide that claimed over 4,000 lives as well as the recent typhoid outbreaks in Harare are a clear indications of the need to protect water sources against pollution. The deterioration in the quality of water resources is due to multi-sectoral factors that include discharge of untreated or partially treated wastewater from cities, towns and industries. Challenges posed by the discharge of untreated or partially treated wastewater from cities and towns can be traced to weak waste collection and management by local authorities. Most local authorities lack proper waste collection, disposal and management facilities that meet international standards. As a result, all urban local authorities, including growth points, dispose of solid waste at open dumps that have no linings to prevent leachate from contaminating surface and groundwater. In addition, the mining sector, which has been boosted by the recent discovery of large mineral deposits including diamonds, is a major contributor to point source pollution of water despite the existence of effluent standards and legislation against water pollution.

To address the threats to water quality highlighted above, The Ministry of Environment, Climate and Water, with the support of the World Bank, is preparing a 'Strategy for Managing Water Quality and Protecting Water Sources'. The World Bank has received funds from the Analytical Multi-Donor Trust Fund (AMDTF) and allocated part of the funds for the benefit of the Government of Zimbabwe to prepare such a strategy to support the implementation of its New Water Policy. The strategy will focus on water quality and water pollution as well as source degradation of surface water and groundwater, among others. This strategy will be developed in two stages i.e., Phase 1 and 2. Phases 1 entails developing a methodology for conducting a rapid assessment of water quality in selected pilot areas using specialized tools and techniques (including Remote Sensing, Geographic Information Systems (GIS) and field sampling) as well as identifying pollution hotspots nationwide. Phase 2 will focus on an in-depth assessment of all hotspots across the country.

This report presents results of Phase 1 which focused on the development and testing of a methodology for rapid mapping and classification of water sources, water quality and quantity assessment. This was done in close collaboration with EMA, ZINWA, Catchment Managers, Provincial Environmental Managers (PEOs), and local authorities. In other words, due to the high intensity and widespread nature of the water quality problem, Phase 1 set out to test and apply GIS and Remote sensing tools to calibrate field measured data with satellite signals for specific locations and parameters to enable understanding of the pollution problem broadly and to develop the baseline for establishing changes in water quality over time using satellite remote sensing.

Results of Phase 1 indicate that using data from ZINWA and EMA selected surface water pollution hotspots, including additional control points selected by the University of Zimbabwe team, a field measured data- calibrated GIS and Remote sensing methodology for mapping and classification of water sources, and conducting a rapid water source assessment was successfully developed. Additionally, a GIS-based expert system was successfully developed to characterise groundwater vulnerability in Zimbabwe.

In conclusion, Phase 1 work has demonstrated that, (1) using remote sensing and GIS, it is possible to undertake a rapid assessment of water quality issues for both surface and ground water as a value-addition to of the traditional methods and (2) that the methodology requires a much smaller infrastructure outlay to accomplish. However, this approach requires highly trained personnel, as well as robust data, with all variables measured at the same time. The method is also intolerant of missing data cells. Finally, the field recording sheets must be well designed and data capture from these must be well supervised. Phase 1 provides recommendations for Phase 2, particularly that Zimbabwe implements a robust water quality monitoring programme that has key planning elements that include clear, measurable and well defined objectives. To this end, a review of both institutional and structural aspects for such a water quality monitoring programme needs to be implemented. From Phase 1, an outline of the current status of water quality monitoring in the country is presented and terms of references for Phase 2 are spelt out based on the lessons learnt in Phase 1.

Chapter 1: Introduction and Background

Zimbabwe's freshwater resources, comprising a network of rivers, thousands of small dams, lakes, numerous wetlands, surface water and significant amounts of groundwater, are critical for supporting life, economic development and natural ecosystems. To manage these water resources, the country has been divided into seven catchments: Gwayi, Manyame, Mazowe, Mzingwane, Runde, Sanyati and Save. These seven catchments are named after the main river systems most of which drain into international watercourses. The national surface water generation, i.e. mean annual runoff (MAR) is estimated at 61 mm/year with a coefficient of variation of 122% (ZINWA, 2009). This high coefficient of variation indicates the unreliability of runoff from year to year and hence justifies the construction of dams to provide additional water security in times of water scarcity. Although many dams (~ 14,000) have been constructed on the main rivers for various reasons including supplying water to urban settlements and to irrigate farms, there is still room for additional storage as only 25% of the potential storage has been developed so far (ZINWA, 2009). Apart from surface water, Zimbabwe has significant groundwater resources. However the potential contribution of groundwater to economic development has not yet been fully explored nor fully exploited. While available national water resources are deemed sufficient to satisfy demand based on medium to long term population projections, water quality degradation and a 15% projected decrease in precipitation due to climate change (IPCC, 2007) imply that water managers are confronted with the challenges of dealing with a declining resource and addressing conflicts between competing water users.

The 2013 National Water Policy recognises that the quality and condition of Zimbabwe's surface and groundwater resources are deteriorating. The cholera outbreak of 2008-2009 countrywide that claimed over 4,000 lives (Figure 1) as well as the recent typhoid outbreaks in Harare point towards the need to protect water sources against pollution. This could just be the tip of an iceberg, as it is also known that blue-green algal bloom in lakes is toxic and can pose a substantial health risk for communities accessing affected water for drinking, irrigation and recreation. Specifically, toxins can destroy cells in the liver and other internal organs, and may act on the nervous system leading to respiratory failure. Other health impacts of algal blooms can include gastric upsets, fever, headaches, skin irritations, and numbness and paralysis of the arms and legs. Human deaths have been associated with blue-green algal blooms, and deaths of livestock and wildlife are common (Erin Hestir, CSIRO personal communication).

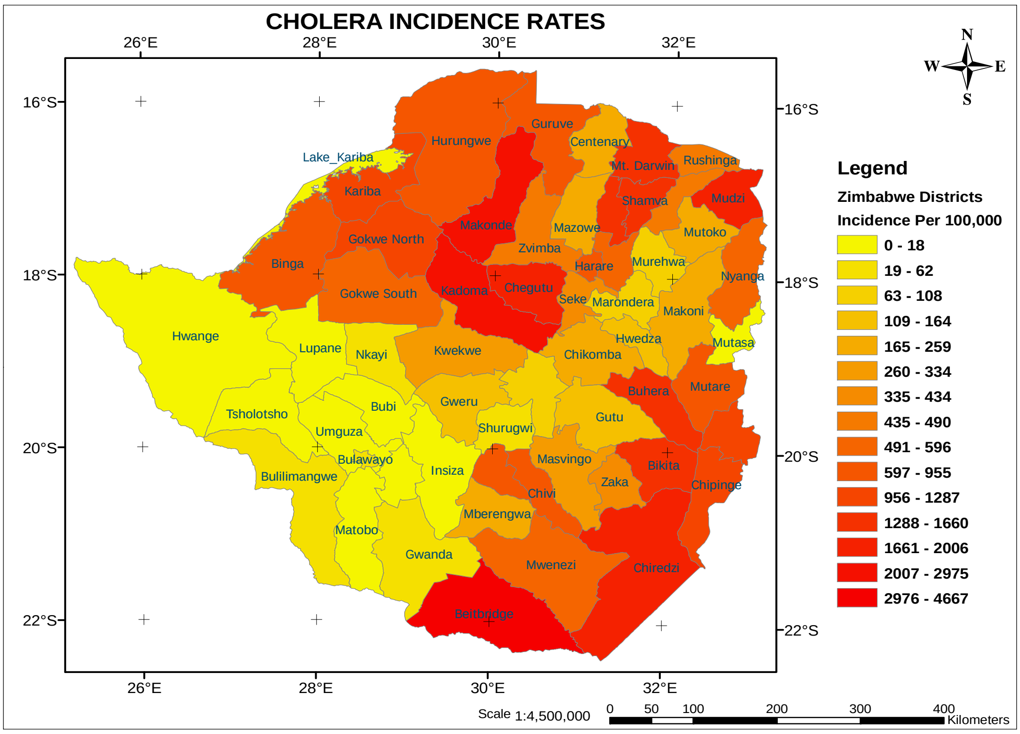


Figure 1: Cholera Incidence Rates for the 2008/9 cholera epidemic in Zimbabwe (*Source: Farai. Kuri PGD Dissertation ARCSSTE-E, Obafemi Awolowo University, Nigeria 2009.* Cholera Incidence Data were obtained from WHOARCSSTE-E - African Regional Centre for Space Science and Technology Education in English)

The deterioration in the quality of water resources is due to multi-sectoral factors that include discharges of untreated or partially treated wastewater from cities, towns and industries. Challenges posed by the discharge of untreated or partially treated wastewater from cities and towns can be traced to weak waste collection and management by local authorities. Most local authorities lack proper waste collection, disposal and management facilities that meet international standards. As a result, all urban local authorities, including growth points, dispose of solid waste at open dumps that have no linings to prevent leachates from contaminating surface and groundwater. In addition, the mining sector, which has been boosted by the recent discovery of large mineral deposits including diamonds, is a major contributor to point source pollution of water despite the existence of effluent standards and legislation against water pollution.

Zimbabwe's water resources are also under threat from various non-point sources. These include fertilisers and agrochemicals used in agriculture, wastewater from livestock ranches and poultry farms, and urban runoff carrying pollutants from vehicles, effluent from industries, wastewater discharged from leaky sewers, as well as the leachates from urban solid waste dumps. Land use changes (e.g. settlement expansion, urbanization, conversion of wetlands into cropland and built-up areas, as well as the conversion of vegetated areas to crop fields) that reduce vegetation cover in catchments are also a major source of water quality degradation.

In urban areas, diffuse runoff now poses major challenges in water quality management, especially given that the standard strategy for waste water management in cities is based on the use of pipes to direct effluent into waste water treatment plants. So far Zimbabwe has not developed a strategy for diffuse source pollution management. In the case of Lake Chivero near Harare, the diffuse source of pollutants are now so numerous that they can maintain the lake in a hyper-eutrophic state even when all point sources from wastewater treatment works have been brought under control. The main diffuse sources of pollutants in Zimbabwe's urban areas now include urban agriculture.

To address the threats to water quality highlighted above, The Ministry of Environment, Climate and Water, with the support of the World Bank, is preparing a 'Strategy for Managing Water Quality and Protecting Water Sources'. The World Bank has received funds from the Analytical Multi-Donor Trust Fund (AMDTF) and allocated part of the funds for the benefit of the Government of Zimbabwe to prepare such a strategy to support the implementation of its New Water Policy. The strategy focuses on water quality and water pollution as well as source degradation of surface water and groundwater, among others. This strategy will be developed in two phases:

i) Phase 1 entails developing a methodology for conducting a rapid assessment of water quality in selected pilot areas using specialized tools and techniques (including remote sensing, geographic information systems (GIS) and field sampling) and identifying pollution hotspots nationwide; and

ii) Phase 2: will be an in-depth assessment of all hotspots across the country.

The Terms of Reference (TORs) of Phase 1 are as follows:

1. Undertake review of published literature and government reports (including River System Outline Plans) and data on point source and diffuse source pollution and surveys of water weeds to identify locations, hotspots and pollution loads. Review literature on water sources and source degradation. In consultation with key stakeholders such as MWRDM, ZINWA, Catchment Offices and sub-Catchment Offices, Ministry of Environment, EMA

and Provincial Environmental officers, Local Authorities, Ministry of Local Government Rural and Urban Development and Ministry of Agriculture, Mechanization and Irrigation Development (MAMID), identify and locate the priority natural water sources (watersheds, springs, aquifers) and built water sources (dams) used for urban water supply and irrigation water supply to be used as a sample for rapid assessment;

2. Define the methodology for mapping and classification of water sources and carrying out a rapid water quality and quantity assessment. This will include:
   (i) developing a methodology of mapping and classification of water sources, and,
   (ii) developing a methodology for carrying out a rapid water quality and quantity assessment. The analysis it to be conducted for both wet and dry seasons;
3. Conduct a rapid water source assessment in consultation with EMA, ZINWA, Catchment Managers, Provincial Environmental Managers (PEOs), and local authorities;
4. Conduct a *rapid water quality assessment* in consultation with EMA, ZINWA, Catchment Managers, PEOs, and local authorities;
5. Analyze and interpret the results;
6. Use GIS and Remote sensing tools to calibrate field measured data with satellite signals for specific locations and parameters to enable understanding the pollution problem broadly and to develop the baseline for establishing changes in water quality over time using satellite remote sensing;
7. Draft Phase 1 report;
8. Present at a workshop (a) the methodology used and results obtained, (b) the maps generated, and (c) develop TOR, work plan and budget for Phase 2 work to scale up the analysis to all pollution and source degradation hotpots across the country; and
9. Submit the final Phase 1 Report.

These terms of reference are clear and the consulting team has accepted them as they are.

Chapter 2: Water quality and source degradation in Zimbabwe

2.1 Introduction

Zimbabwe's water resources - comprising surface and groundwater - are critical for supporting life, economic development and natural ecosystems. Usable water resources are under stress and in recent years water quality has been diminishing rapidly due to pollution. The unavailability of a regular water supply for domestic use in Zimbabwe's urban areas is well-known problem. It is also well-established that when the water is available its quality for human consumption is often questionable. This problem is often framed in local authorities' inability to provide water due to inadequate infrastructure, rather than declining supply from the catchments.

Surface water

In our water quality survey, we noticed that except for Zhove dam in Beitbridge district all other dams were critically low. Many streams and rivers, such as the Mzingwane River are now seasonal rivers. When they do flow, the hydrographs are peaked with reversion to base flow soon after the end of the rainy season. This implies that whatever hydrological income we have it quickly passes through Zimbabwe, leaving little dry season reserves. Those reserves are in the form of reservoirs. While the storage capacity of large reservoirs has not been significantly altered, many of the small reservoirs, such as Nyamabishi Dam in Chiota, are either completely or highly silted. Google Earth images show that many dams have stretches of sand in the inflowing rivers waiting to enter the reservoirs. Thus, many reservoirs now have finite lifetime measurable in decades rather than centuries.

Virtually all large rivers, with the exception of the fast flowing river draining the eastern highlands, show large amounts of siltation. People now cross the Save river at Birchenough bridge on foot, bypassing the bridge. Yet there was once deep dark pools laden with legends and mystery. Mysterious pools, like the Chirikuusti in the Honde valley or the Nyachowa pool in Chogodora in Zimunya were centres of spiritual and cultural focus. Now they are profaned sand pits. The hippopotamus, crocodile and fishes that used to occur in this river are now distant memories of aged generations.

Climate change and land uses changes compound the problem of surface and groundwater availability. There is little we can do about climate, but with regard to lands use we can adopt land use practices that protect catchments and enhance water security.

With regard to water quality, the old Shona adage “mvura haina nganga” - water is innocent - rarely holds now. It is now an undeniable fact that most of our surface water and some groundwater resources need to be treated before they can be deemed safe for human consumption. The sources of contamination are numerous but the main ones include: inadequate sanitation, shared use of water by humans and livestock, frequent sewer outbursts, industrial effluents and alluvial mining. Traditionally local authorities have attempted to control point source pollution, but recent studies show that diffuse source pollution is now a major source of water quality degradation. For example, the rehabilitation of all wastewater treatment works in the Manyame watershed will not alleviate eutrophication in Lake Chivero, but a combination of engineering and ecological approaches that are costly could restore water quality in Chivero in less than ten years

Poverty has lead to desperate activities, and in particular alluvial mining. The use of toxic substances to extract minerals such as gold is slowly poisoning our waters with toxins that do not degrade easily. These are cyanide and mercury, and further prolonged exposure to such toxins can result in serious health problems (Hutton, 1987). Human health risks include the carcinogenicity of arsenic, cadmium toxicity to the kidneys and the destruction of the central nervous system by lead (Fu et al., 2008). In addition, the excavation of riverbanks and transfer of soil into streams for gold panning is changing the flow and nature of our rivers, leading to both physical and ecological damage to our river systems.

The deterioration of water quality poses a direct threat to human health. Recent outbreaks of enteric diseases, such as cholera, typhoid are a clear manifestation of this link. These outbreaks attract international attention and can be dealt with in good time. However, the greater problem is in the insidious diseases which are not obviously linked to water quality. These are disorders of the liver and kidneys and other body organs caused by carcinogens present in drinking water. A study of human milk in Kariba showed that there were significant amounts of PCBs, DDT and its derivatives (Chikuni et al. 1997). The effects of this in bats' milk were shown to result in deaths of the suckling puppies. We do not know yet what the effect in humans is as symptoms of DDT poisoning are similar to malaria symptoms.

One of the effects of global warming is a fundamental change in phytoplankton communities. At temperature above 28^{o}C, cyanobacteria, also known as blue green algae dominate the aquatic phytoplankton. These produce microcystins which are known to be carcinogenic. However for these to proliferate they need water rich with phosphorus, which is the case with Lake Chivero and other eutrophic waters in Zimbabwe. A recent study seems to suggest that the frequency of liver cancer in Harare has been on the increase (Ndebele and Magadza, 2006).

Ground water

Ground water is also of special concern. As our surface waters become increasingly scarce, large population of Zimbabwe are resorting to ground water. In Chitungwiza, Epworth and other informal settlements residents depend on shallow wells. Many of these have been shown to be infested with enteric bacteria, and have been implicated in cholera outbreaks. The special issue is that while pollution of surface waters can be remedied in reasonable time than ground water is contaminated it can take decades and sometimes centuries for the pollutants to disappear. Thus ground water contamination is a persistent problem. Here prevention is indeed better than cure.

The second issue about groundwater is that its replenishment is a function of catchment health. For instance, in degraded watersheds where wetlands have been impaired, the fraction of precipitation that becomes surface runoff increases dramatically. This reduces aquifer recharge resulting in drying up of boreholes and shallow wells.

2.2 Surface water resources

Surface water comprising rivers, dams, lakes, springs, and wetlands is by far the most widely used source of water in Zimbabwe. The distribution of rainfall ranges from about 300 mm/yr in the southern parts of the country to about 1,200 mm/yr in the Eastern highlands. The quality of water in the Eastern highlands is considered good and is classified as “pristine” under the Environmental Management Agency river classification scheme. For example, the City of Mutare is currently abstracting water from the perennial Pungwe River, which requires minimum purification and therefore treatment costs are very low. Relatively clean water is found in most rivers in the eastern highlands, and this may be attributed in part to the fact that they originate from protected national parks (e.g., Rhodes Nyanga National Park, and Chimanimani National Park) under temperate montane forests, both natural and exotic. The streams and dams in the drier parts of the country are more ephemeral and are more vulnerable to siltation and sedimentation. However the water in the Eastern highlands may be cleaner because of high runoff available compared to the drier parts of the country but source protection clearly plays a role.

2.2.1 General factors affecting surface water quality in Zimbabwe

2.2.1.1 Sewage discharges

The most contaminated rivers in the country tend to be those draining catchments with major urban settlements (see Figure 2 showing the location and distribution of urban centres in relation to major catchments). All major catchments in Zimbabwe have urban centres with sewage output ranging from tens of megalitres to hundreds of megalitres per day, most of which finds its way into surface water. Due to frequent sewer outbursts as well as direct discharge of raw or partially treated sewage into public waterways draining urban areas, urban water quality is generally poor. For example, due to sewage discharges, nitrogen (N) levels averaging 13.5 mg/ℓ and phosphorus (P) levels averaging 2.6 mg/ℓ have been measured in the Marimba River which drains into Lake Chivero (Nhapi and Tirivarombo 2004). This concentration level of P far exceeds the statutory limits for sewage discharge into public waterways, which is 0.1 mg/ℓ for phosphorus. The presence of cyanotoxins in Harare's treated drinking water reported in literature can also be attributed to the discharge of raw or partially treated sewage (Mhlanga et al. 2006; Ndebele and Magadza 2006). Little is understood about the impact of sewage discharge in other urban centres hence this needs further investigation.

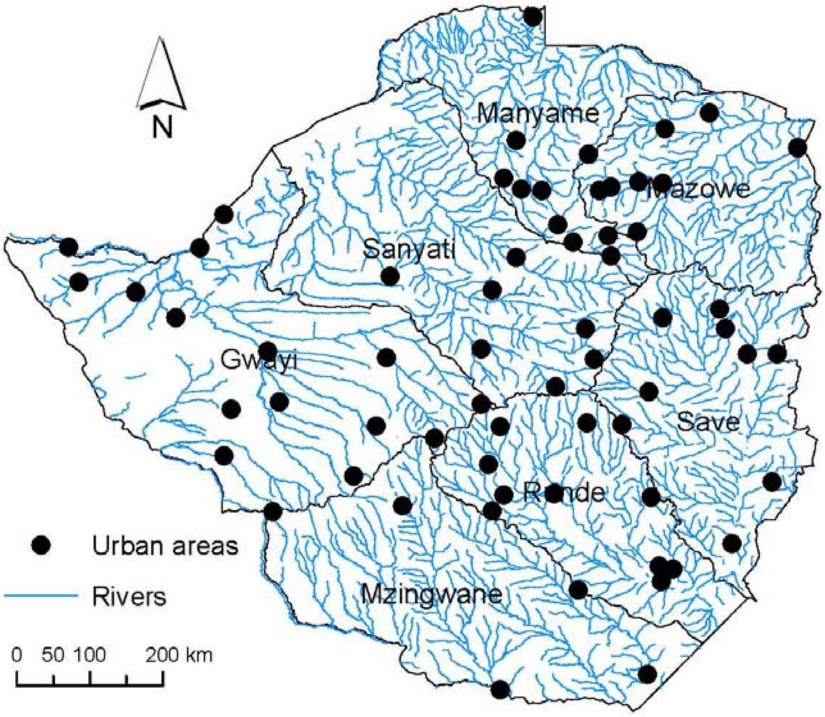


Figure 2: The distribution of urban areas in the seven catchments of Zimbabwe.

2.2.1.2 Mining

Zimbabwe is a mineral rich country with over 40 minerals that can be developed economically. The country has approximately 200 registered 'formal' medium-scale gold mines and thousands of small-scale unregistered gold operations, most of which use mercury (Hg) for the processing of primary gold quartz veins and supergene gold mineralizations. The techniques that are used are inefficient, hence, gold mines, especially artisanal gold mines, are major point and non point sources of Hg and other heavy metals such as arsenic (As) and lead (Pb). Zimbabwe's gold mining activities range from very low technology gold panning (on the major internal rivers) to sophisticated carbon-in-pulp extraction technology practised at an increasing number of larger and smaller mining and tailings dump re-treatment operations. The economic crisis in Zimbabwe saw the closure of most of the big mines that use sophisticated extraction technology and the sprouting of more small-scale and artisanal mining activities. Small scale mining has been practiced since time immemorial by the early Shona and their contemporaries although shallow by contemporary standards, the old workings developed into considerable undertakings, with *open stopes* (narrow deep trenches) and *shafts* (Summers, 1969; Swan, 1994). Small-scale mining is commonly associated with informal, unregulated, under-capitalized and under-equipped mining operations, where technical and management skills are lacking.

A study carried out at Shamva gold mine showed that as much as 20 - 30% of Hg is lost to tailings, soils, stream sediments and water (van Straaten 2000). In another study, results from chemical analysis of water samples collected from tributaries of Manyame river located downstream from four abandoned gold mines in the Beatrice gold belt also indicated the presence of heavy metals (i.e., Pb, Zn and Ni) in surface water (Ravengai et al. 2005b). Figure 3 shows that most gold mines and mills are located in the Sanyati and Mzingwane catchments, while Save and Manyame catchments had the least. With respect to mining, the Eastern highlands of Zimbabwe have previously been viewed as free of water pollution. However alluvial gold mining in Penhalonga and gold panning in Chimanimani now pose a threat to water quality. Information on the impact of artisanal gold mining in other areas on water quality is lacking. For example, the Global Mercury Project (GMP) identified Kadoma-Chakari region as having the highest population of artisanal and small-scale miners in Zimbabwe (~ 20,000) and documented the widespread use of mercury during gold processing, but its impact on water quality was not quantified. The mechanisms through which mercury may impact aquatic ecosystems and human health were however described.

The extraction of other minerals also poses a direct threat to both surface and groundwater quality. Work done at Trojan Nickel Mine (near Bindura) reported high concentrations of sulphide (over 100 mg/*l*) as well as high levels of Pb (> 1.0 mg/*l*) and nickel (Ni) from the rock dump (Lupankwa et al. 2006). Water samples taken from Pote River located downstream from the mine dump had elevated levels of Pb, As and Ni which rendered the water unfit for domestic use. The deterioration in the quality of surface water has also been observed at Iron Duke Mine in the Mazowe catchment. Upstream of the mine premises, water in the Yellow Jacket River was not contaminated yet downstream it was contaminated with iron (Fe), nickel (Ni), copper (Cu), cobalt (Co), lead (Pb), zinc (Zn), and sulfate ions (SO_4^{2-}) (Ravengai et al. 2005a). Acid mine drainage seeping from tailing dams is degrading water quality of the Yellow Jacket and Mazowe Rivers. At Madziva mine, also located in the Mazowe catchment, acidic effluent with high concentrations of iron, nickel and sulphate emanating from the tailings dam was detected in both surface and groundwater (Lupankwa et al. 2004).

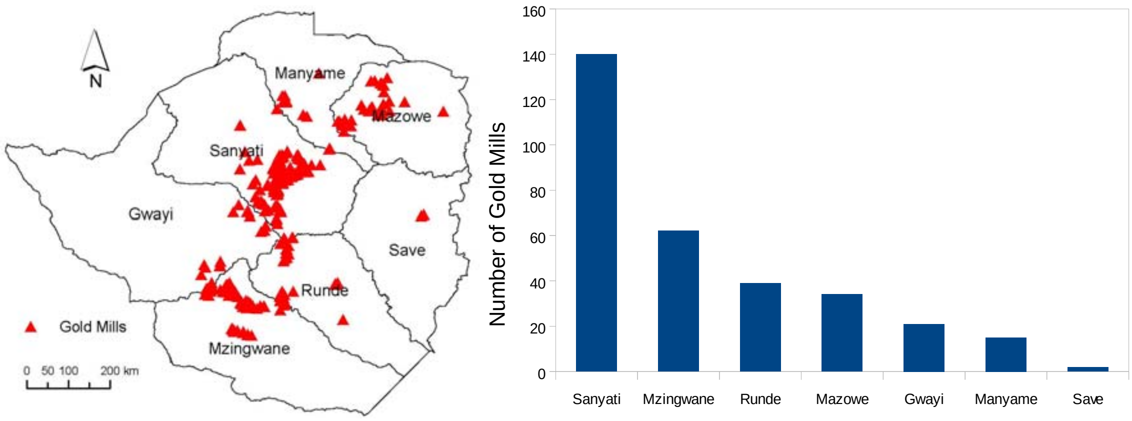


Figure 3: Distribution of gold mills in Zimbabwe (left) and the respective number of gold mills per catchment (right).

2.2.1.3 Industrial effluent

The treatment and disposal of industrial effluent is also a major factor contributing to the deterioration of surface water quality in the country. While most industries are connected to sewerage reticulation, several industries discharge directly into public waters. For example, due to the discharge of industrial effluent, high concentrations of heavy metals were detected in sediment and water samples from the Mukuvisi River downstream to Prospect Industrial Area in Harare (Nyamangara et al. 2008). Heavy metal pollution has been linked to industrial effluent discharge and, in urban centres such as Harare; it has been linked to the deterioration in potable water quality (Zaranyika et al. 1997). Thousands of backyard industries have mushroomed in urban centres, but their contribution to water source pollution is largely unaccounted for. Backyard industries in places such as Mbare have been identified as polluters of the Mukuvisi River, disposing of pollutants such as oils. They also have great potential as diffuse polluters when there is runoff.

2.2.1.4 Agriculture

Zimbabwe's commercial agriculture, especially sugar production and tobacco farming, depends on high inputs of fertilizers and pesticides. The widespread use of fertilizers and agrochemicals makes agricultural runoff a major source of diffuse pollution (Moyo and Mafara, 1997). For example, the lower reaches of the Sanyati River had high levels of nitrogen, while small rivers like Nyaodza also contributed to phosphorus loading in Lake Kariba (Begg, 1970). The lack of up-to-date information makes it difficult to infer the impact of agriculture on water quality and pinpoint pollution hotspots. In communal lands where subsistence farming is predominant, the use of pesticides and fertilizers is not as extensive as in commercial farming but overgrazing and vegetation clearing are common degradative practices. Such practices increase rates of wetland loss, soil erosion and consequently promote the siltation of rivers. Apart from rivers in the Eastern highlands draining into Mozambique, all other major rivers in Zimbabwe are silted to varying degrees, especially in their lower reaches. While this impacts on surface water availability it also has a profound impact on the biodiversity of aquatic fauna due to habitat loss.

2.2.1.5 Aquatic invasive weeds

The presence of aquatic invasive weeds is a manifestation of eutrophication. For example, the invasive weed *Salvinia molesta* (Kariba weed), which has infested in Lake Kariba, declined after nutrient levels dropped. Due to nutrient pollution, Khami dam, Lake Chivero and Lake Mutirikwi have both been infested by water hyacinth (*Eichhornia crassipes*).

2.2.2 Knowledge gaps on surface water quality

In general, there is no comprehensive study giving a national picture of the status of surface water quality in Zimbabwe since all previous studies have focused on few selected rivers, reservoirs, mines and industries. Data on water quality are available from a number of studies that evaluated the quality of surface water in Zimbabwe and most previous studies concentrated on perennial rivers and large reservoirs supplying water to major settlements. As a result, little is known about the threats to and the quality of surface water from wetlands, springs, small rivers, and small reservoirs, which are mainly located in the headwaters of most perennial rivers and large reservoirs e.g., Connemara Dam in Nyanga. In addition, current information is lacking on ambient water quality conditions of many surface water sources.

2.3 Groundwater resources

In Zimbabwe, groundwater may be categorized into: (i) shallow unconfined aquifers developed in the weathered surface layers (the regolith) in crystalline rock areas and associated with high water tables; and (ii) deeper unconfined to confined aquifers associated with sedimentary strata. The majority of people, especially in rural areas, obtain water from the first category where water is accessed from depths up to 20 m. The vulnerability of such shallow groundwater to contamination by unsafe sanitation activities is high. The second category of deeper sedimentary aquifers may be better protected from microbiological contamination, but is frequently more highly mineralized due to its greater age and less frequent flushing. Pumping costs for the deeper groundwater will be higher than for the shallow aquifers and motorized pumps may be required.

Zimbabwe has 10 hydrogeological units as identified in the National Master Plan for Rural Water Supply and Sanitation. These hydrogeological units comprise both primary granular aquifers and secondary fractured aquifers and constitute the basis of the rural water supply system throughout Zimbabwe. However, their overall exploitation is still low.

2.3.1 General factors affecting groundwater quality in Zimbabwe

The quality of groundwater has become an increasingly important global water resources issue for two principal reasons. The first is that groundwater constitutes by far the greatest fresh water resource on the planet, although surface water is still the preferred source in most humid climates. The second reason is that while surface water has a shorter detention time due to flushing by fresh inflows in a matter of a few months to years, groundwater tends to have much longer detention times sometimes up to a thousand years. Contaminated groundwater therefore tends to remain in the aquifer for decades or hundreds of decades, and does not respond readily to clean-up efforts. Entire aquifers may be rendered unfit for use for generations once contaminated. As water availability per capita declines, the threat to groundwater quality, our largest freshwater resource, stands out as one of the major environmental challenges of our time.

The natural groundwater quality in Zimbabwe is generally good, especially in the granitic terrain (± 60% of the country), where the quality is considered excellent. There are natural localized areas with poor groundwater quality. These areas are associated with poor groundwater circulation in confined aquifers, poor recharge in arid areas and hyper-saline paleo-groundwater.

Geogenic sources of groundwater pollution

On a national scale geogenic groundwater quality issues are minor and localized, and it is generally considered that Zimbabwe has no major geogenic groundwater quality issues. The geogenic groundwater quality problems that do exist tend to occur in sedimentary basins in specific localities that are distant from the recharge areas and are thereby associated with poor groundwater circulation. In the confined parts of the lower Karoo, groundwater flow paths tend to be several tens to hundreds of kilometres, and groundwater residence times may exceed several hundreds of thousands of years. Due to these long flow paths and extended residence times, the groundwater in these aquifers tends to be quite highly mineralized.

By contrast, the groundwater in the crystalline basement areas of Zimbabwe are shallow, locally recharged and have short residence times. As a result they tend to be fresh good quality water. The Karoo basin is known to have naturally occurring fluoride in the groundwater from boreholes drilled in the Madumabisa mudstones and lower Karoo sandstone units. Gokwe north, Hwange, Beit Bridge and Save Valley are all areas where geogenic groundwater fluoride has been observed in the groundwater (Norad Map of Groundwater Flouride in Zimbabwe).

Saline groundwater (TDS > 2000 mg/l) is rare in Zimbabwe but such TDS values have been measured in boreholes in the arid Beit Bridge district and in the cretaceous sediments along Zimbabwe's SE border with Mozambique. Some saline groundwater has also been recorded along the Zambezi valley, presumably associated with deep groundwater in the escarpment fault zone and in the deep Kalahari in NW Zimbabwe, likely related to the evaporite sequences in the Kalahari beds. Highly saline groundwater has been observed in the Save valley and is filled with sediments in some parts of the valley. Similarly elevated salinity also occurs in the Karoo basins in Zimbabwe, especially in the confined parts of the aquifers where there is no active recharge. If associated with coal measures, these will produce an unpalatable sulphurous taste in the groundwater (NORAD Map of Groundwater TDS in Zimbabwe). All other groundwater quality issues in Zimbabwe are of an anthropogenic origin.

Anthropogenic sources of groundwater pollution

Groundwater quality may be affected by direct recharge of polluted water generated by a suite of point and non-point sources of pollution. In addition, groundwater may be polluted by river-bed infiltration of polluted river water at some distance from the primary pollution source.

Groundwater pollution does not yet appear to be a major issue in Zimbabwe. Complaints and publicity about groundwater quality hardly feature in our news media and are a minor component in our scientific literature.

Nevertheless, many of the anthropogenic activities that generate groundwater pollution are occurring without adequate safeguards. For example, municipal solid waste dumps are all constructed without an impermeable base and without leachate collection and treatment facilities. Sewage treatment plants discharge wastewater to 'sewage farms' for use as fertilizer without assessment or monitoring of subsequent wastewater discharge to local groundwater. All mining activities in Zimbabwe are now subject to EMA effluent discharge regulations, but many thousands of historic mining waste dumps and tailings dams are generating acid mine drainage (Moreno-Madrinan et al. 2010) and releasing toxic heavy metal enriched acid water to the environment. Industry is in a similar position and old abandoned dumps are still sources of toxic leachate to the groundwater system. Many of the human communities in the urban high-density suburbs also impact on the groundwater system via pit latrines and uncollected domestic waste.

2.3.1.1 Mining

A major source of groundwater anthropogenic pollution is mining and mine waste disposal sites. There are over 8000 mines of various sizes scattered across Zimbabwe, mostly gold mines in the greenstone/gold belt terrain, but also chrome and platinum mines along the Great Dyke and coal mines in the lower Karoo coal measures.

Most of these mines have open shafts, waste rock dumps and tailings dams with exposed sulphide minerals, making them susceptible to acid mine drainage. Air and circulating fresh water react with the exposed sulphides to form sulphuric acid, subsequently dissolving susceptible heavy metals, which are then in solution and mobilized to enter the surface and groundwater systems. The finely ground rock material in the tailings dams presents by far the largest surface area of exposed sulphide minerals and therefore these generate the largest acid mine drainage (Moreno-Madrinan et al. 2010) pollution load.

It is anticipated that the sulphide load in the tailings dams constitutes an AMD threat that will persist for several generations. Mines therefore constitute a very widespread suite of point pollution threats to groundwater in terms of heavy metal contamination, both now and into the future.

2.3.1.2 Sewage

Domestic sewage in the urban areas is generally managed by water borne sewage networks, with septic tanks in the low-density residential areas. Pit latrines are the principal form of domestic waste management in the rural areas. Sewage farms are often overburdened due to expansion of the urban population and lack of investment in new infrastructure. For example, Firle sewage treatment plant in Harare is under-designed for the number of people that use the sewage network and as a result it discharges large volumes of partially treated and untreated domestic waste into both the surface water and the groundwater drainage. This makes it a hotspot of groundwater pollution.

The impact of sewage outbursts on groundwater quality in the high-density suburbs in both Harare and Bulawayo is a cause for concern particularly in light of the frequent outbreaks of diseases such as cholera and typhoid. Due to the decline in water supplies, water both for consumption and for flushing the waste system has declined. As a result, sewers become blocked and burst, leaking effluent into the ground and thus contaminating groundwater. At the same time, treated water supply has declined and residents have to rely on groundwater from shallow hand dug wells and from drilled boreholes. In recent years there have been outbreaks of cholera and typhoid in Harare and these have been linked to deteriorating water quality and limited supply. In Bulawayo, total coliforms and faecal coliforms which pose a threat to human health were found in 27% and 8% respectively of the sampling sites (n = 32) drawn from the Matsheumhlope basement aquifer (Mangore and Taigbenu 2004).

In informal high-density suburbs, sanitation is generally by means of pit latrines, and the impact on the groundwater is even greater. Work done in the semi-formal settlement of Epworth (near Harare) reported significantly elevated levels of coliform bacteria in groundwater samples collected from shallow wells and boreholes scattered throughout the settlement. The highest levels of coliforms (> 10,000 cfu) were measured in water samples from the old parts of the settlement with a high density of pit latrines (Zingoni et al. 2005). It was therefore concluded that most parts of Epworth lack safe groundwater for human consumption. This finding suggests that pit latrines impact both surface and groundwater quality.

2.3.1.3 Solid waste dumps

All urban settlements in Zimbabwe use solid waste dumps to dispose of the waste. Many of these solid waste dumps are poorly constructed and poorly managed without impermeable linings and leachate collection as well as treatment facilities. Waste is generally not separated into waste streams with domestic, industrial and chemical wastes all being disposed in the same dump. As a result, a mixed toxic leachate is generated and discharged into the groundwater system, and this may further discharge as baseflow to the stream system. Golden Quarry and Teviotdale / Pomona dumpsites in Harare are two examples of such facilities.

The capacity to measure persistent organic pollutants (POPs) such as PCB's (Poly-Chlorinated Biphenyls) from solid waste dumps is very limited in Zimbabwe hence such pollutants may already be in the aquifers but remain undetected.

2.3.1.4 Pit latrines

Pit latrines and septic tanks constitute tens of thousands of minor point sources of local bacterial contamination of the shallow groundwater table. Although groundwater is protected by natural filtration against bacteria of faecal origin if proper controls are in place, there is evidence that faecal coliforms from pit latrines are contaminating the shallow groundwater in some parts of the country. This may occur when pit latrines are located too close to water supply wells or boreholes. Although less common, the ground formation may fail to attenuate the bacterial load if flow is fracture flow rather than seepage flow. This process results in bacterial contamination of underground water.

Some data exists on the impact of pit latrines on groundwater quality for Epworth informal high-density suburb in eastern Harare (Zingoni et al. 2005), and there is also a report on the impact of pit latrines on groundwater quality from Chihota communal lands (Dzwairo et al. 2006). Faecal coliforms were also detected in groundwater from some drinking water wells located in sandy soils and on deeply weathered and fractured igneous rocks in the Goromonzi district (Conboy and Goss 2000).

2.3.1.5 Industry

Industry generates effluent and other toxic waste and in many cases such waste is not properly treated. Older factories established before adoption of cleaner technologies in production processes were in the habit of discarding industrial waste into unlined pits and effluent back into the stream system. Such practices have declined with increased environmental understanding and improved legislation and management practices, but the threat to groundwater for these practices still resides in the sub-surface. Chemical industries, such as Chemplex and ZimPhos in Harare, leather tanneries in Harare and Bulawayo, and industries that use large volumes of water and discharge bulk effluent back into the drains, such as the dairy industry, all contribute to groundwater quality degradation.

2.3.1.6 Land degradation and reduced recharge

Decline in groundwater quality may also occur as a result of land degradation. Removal of vegetation cover and erosion of topsoil results in increased run-off coefficients and a concomitant decrease in groundwater recharge. This decrease in recharge creates a threat to groundwater quality in that there is less fresh water entering the aquifer. As a result the remaining groundwater is older and becomes relatively more saline with time. Thus protecting and restoring recharge and retention rates is an important component in protecting the groundwater quality and has been identified as a key strategy in protecting our groundwater resources.

A similar reduction in recharge occurs when urban development takes place, covering the land surface with concrete, tar and other impermeable surfaces. Such developments reduce the area of recharge and the recharge rate. For this reason the development of urban wetlands for housing, infrastructure or commerce should be discouraged and only take place with extreme caution and a proper appreciation of the long-term impacts on groundwater quality.

2.3.1.7 Excessive pumping

A further potential threat to groundwater quality arises from excessive pumping that result in unsustainable drawdown in the water levels. Under such conditions, older and less fresh groundwater can be mobilized from the deeper parts of the aquifer, mixing with the fresher better quality groundwater and thereby reduces the overall groundwater quality. With the reduction of fresh water distribution by municipalities, many private individuals and companies have turned to boreholes to supply their water needs. This increased abstraction together with declining recharge due to climate change suggests that the groundwater resources may become steadily drawn down over time, with an attendant reduction in the quality. If the annual chloride deposition in rainfall and as dry deposition is known, then the chloride content in groundwater can be used to estimate the long term average annual recharge as a percentage of rainfall. Recent groundwater samples from boreholes at the University of Zimbabwe suggest that only 2 % of rainfall becomes recharge. This is equivalent to a recharge rate of 1 litre/second per km^2. Although pumping rates for Harare groundwater are not known, estimates suggest that abstraction rates in the range of between 10 to 15 litres/second is likely. Anecdotal evidence from Harare indicates that the water-table has already declined significantly in many areas.

2.3.2 Knowledge gaps on groundwater quality

A further issue with regards to groundwater quality management in Zimbabwe is that there is very limited data available. Work on groundwater quality has been limited to a few scattered studies. For example, Mabvira (2003) and Ashton et al. (2001) produced general overviews on the impact of mining on water quality in Zimbabwe. Meck et al. (2009 and 2010), Ravengai et al. (2001), Ruzive (2000), Musiwa et al.(2004) and Ngwenya (1997) have assessed the impacts of mining on water quality, but none of these studies specifically focused on groundwater quality. In addition, Ravengai et al. (2004 and 2005) presented data on the impact of industrial effluent on groundwater from a single site in Harare. Love et al. (2006) and Zingoni et al. (2006) reported on the impact of diffuse pollution on groundwater from several localities around Harare. The ZINWA groundwater branch hosts a national groundwater database. This database has entry fields for groundwater quality data for each borehole, but for the most part, these fields are not populated. Where the fields are populated, the data are usually for a single instance in time and there are almost no time series data to show changes to groundwater quality. There are no data on persistent organic pollutants in groundwater and the laboratory capacity to measure such components is not available in Zimbabwe.

During the course of this study, a basic groundwater vulnerability map was produced, but it has not been tested against actual data. There are no contaminant load maps identifying point and diffuse sources of potential groundwater contamination, such as mines, solid waste dumps, industrial developments and agrochemical farming. There are no groundwater hazard maps that combine the groundwater vulnerability with the location of sources of pollution and the risk to human, livestock and commerce. The development and production of such maps will be an important step towards managing groundwater quality in Zimbabwe. Geogenic groundwater quality maps are available for fluoride and TDS (MWRED-Norad 1985), but only have few data points.

There is a need to know more about the groundwater quality especially in areas where groundwater is heavily used, and in areas where it is a strategic resource. This is particularly true of the major urban centres, especially where the surface water sources and the treatment and distribution infrastructure are insufficient to meet demand. In these areas, groundwater is widely used for domestic water supply and the quality of the groundwater is vital. It is important to understand the impact of major point sources, such as solid waste dumps and mines, on the groundwater quality, as well as the extent and distribution of pollution associated with such point sources. The persistence and attenuation of pollutants in the groundwater system needs to be known. Similarly, understanding the impact of agriculture and the application of fertilizers and agrochemicals on groundwater quality is required. Finally, it is important that the vulnerability of groundwater in Zimbabwe is assessed, particularly in relation to sensitive areas, such as the cities.

Chapter 3: Methods

3.1 Review of published literature and government reports

Zimbabwe’s surface and groundwater resources are critical for national economic development yet there is inadequate information about their quality, extent and condition with respect to pollution threats. However, some information can be gleaned from both published and unpublished literature such as government reports. To produce this report more than 40 peer-reviewed scientific articles were consulted to ensure that the proposed methods for rapid assessment of water quality and quantity are consistent with international best practices. All the articles consulted are available in digital format and can be provided upon request. The two main reasons for consulting peer-reviewed scientific literature were to: (i) identify key knowledge gaps, and (ii) select algorithms relevant for rapid assessment of water quality and quantity. The net benefit of this exercise is that the results reported here are comparable to those reported elsewhere.

While the scientific literature provided the basis for the methods used for rapid assessment of water quality and quantity, technical reports such as the 2009 report entitled “An assessment of surface water resources of Zimbabwe and guidelines for planning” published by the Ministry of Water Resources Development and Management were used to evaluate whether satellite-derived estimates of water quality and quantity are consistent with previous ground-based observations. Other government reports and policy documents such as The National Water Policy pertinent to Phase 1 were sourced from relevant government ministries and departments including the Ministry of Water Resources Development and Management (MWRDM), the Zimbabwe National Water Authority (ZINWA), Ministry of Environment and Natural Resources Management (MENRM), the Environmental Management Agency (EMA), and Catchment Councils.

In addition to relying on government reports, interviews with key ZINWA and EMA staff were conducted to assist the team of consultants develop a list of pollution hotspots. From this list, a sample of hotspots representing a wide range of point and diffuse pollution threats in different catchments was produced to guide field measurements of water quality.

3.2 Methods for rapid mapping and classification of water sources

Zimbabwe' surface water sources can be classified into (1) surface streams and rivers (2) and surface water bodies comprising numerous impoundments/dams. These artificial impoundments consisting of small and medium dams with an 'annual yield' as well as large dams with a carry-over storage capacity have been established as part of the country's overall water development strategy (Ministry of Water Resources and Development 1984). The methods that permit rapid assessment of these surface water bodies differ.

3.2.1 Methods for rapid mapping and quantification of rivers and streams

A 90-m NASA's Shuttle Radar Topography Mission data (SRTM) digital elevation model (DEM) was used to delineate watershed boundaries, extract river topology, and stream networks using standard DEM hydro-processing algorithms in an open source GIS. Next, Strahler's stream order was calculated to further classify the streams and rivers by order.

3.2.2 Use of satellite remote sensing for rapid mapping of surface water bodies

Recent developments in remote sensing technology make it possible to map surface water and monitor the dynamics of surface water throughout the year. In this study, the recently developed Modified Normalised Difference Water Index (MNDWI) (Ji et al. 2009) was applied on Landsat 8 imagery over Zimbabwe between 19 April 2013 and 30 May 2013 to map surface water bodies in catchments covered by the Landsat scene. The MNDWI is calculated as follows:

$$MNDWI = \rho_G - \rho_{SWIR} / \rho_G + \rho SWIR$$

Where: ρG is reflectance in the green band of the electromagnetic spectrum (i.e., Band 2 of Landsat 8) while ρSWIR is the reflectance in the short wave infrared region of the electromagnetic spectrum (i.e., Landsat 8 Band 6). This spectral index is based on the fundamental idea that water absorbs energy at near-infrared (Munir,1996) and shortwave-infrared (SWIR) wavelengths. Hence, MNDWI values greater than 0 indicate water while MNDWI values below 0 indicate non-water features. In this study, Landsat 8 data were freely downloaded from http://glovis.usgs.gov/ and were converted to top of atmosphere reflectance.

3.2.3 Rapid assessment of catchment condition and source degradation

Water source degradation or catchment / water source condition was estimated using a remotely sensed normalised difference vegetation index (NDVI) which is an estimate of green vegetation density over Zimbabwe between 19 April 2013 and 30 May 2013. The reasoning behind use of this simple satellite-based index is that holding other factors constant, the better protected the catchment the higher the vegetation cover and the higher is its mean NDVI value. NDVI is estimated as follows:

$\rho NIR - \rho R / \rho NIR + \rho R$

Where: ρNIR is reflectance in the near infrared band of the electromagnetic spectrum (Landsat 8 Band 5) while ρR is the reflectance in the red region (Landsat 8 Band 4) of the electromagnetic spectrum. NDVI values below 0 indicate water while NDVI values above zero indicate different land surfaces from bare ground (0-0.1) to dense green vegetation (0.5-1). Using GIS overlay, we calculated the mean NDVI in each of the hotspot watershed sampled using zonal statistics operation. Next, we used the regression to relate TSS estimated for each hotspot watershed with remotely sensed mean NDVI. The objective was to test the whether water source condition or watershed condition estimated using NDVI can significantly be used to predict TSS in watersheds.

To relate catchment condition and source degradation, a total of 89 sites distributed in all the seven catchments were sampled as shown in Figure 4. Data on key water quality parameters such as chlorophyll-a, turbidity, total nitrogen, total phosphorus and suspended solids were regressed against the mean NDVI estimated from the watershed delineated using the sample site as the pour point in an open source GIS. To determine the critical value of mean vegetation index, the regression equations derived were set to zero and solved for x where x is the mean NDVI of a watershed.

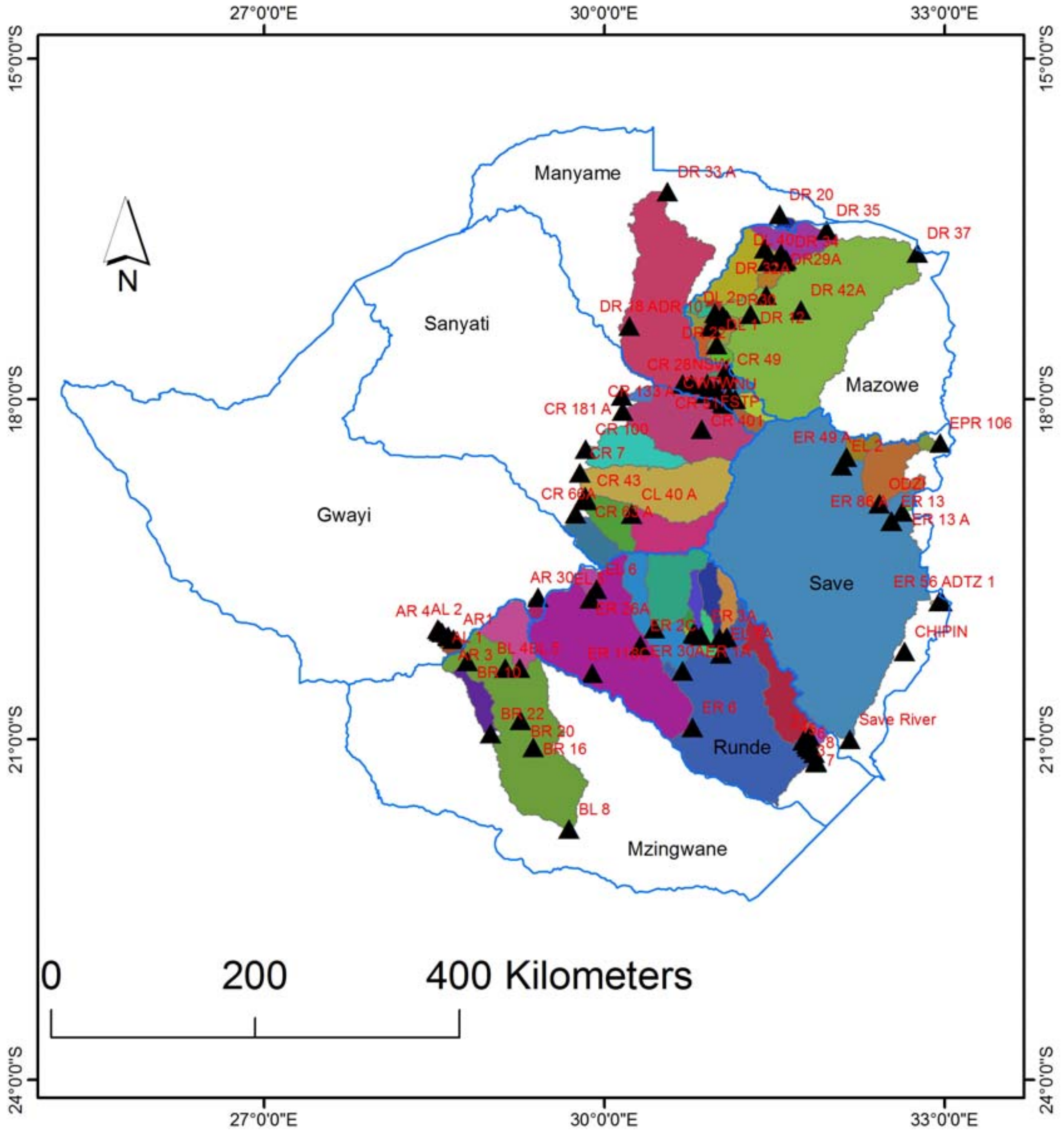


Figure 4: Map showing the location of sample sites and their respective watersheds in all the seven catchments of Zimbabwe.

3.2.4 Rapid assessment of water quality of reservoirs

3.2.4.1 In-situ measurements of water quality parameters

The utility of satellite remote sensing for conducting rapid assessment of water quality was tested in Lake Chivero and Mazvikadei dam (Figure 5). As of June 2013, Lake Chivero was ~24 km^2 in area while Mazvikadei dam was ~21 km^2 in area. The maximum depth in Chivero has been estimated at 22 m while that for Mazvikadei is similar (26 m). These comparisons suggest that the two reservoirs have similar limnological characteristics. However, they greatly differ in terms of the degree of watershed protection, pollution threats and trophic state. Previous research has established that while Lake Chivero is a hyper-eutrophic lake dominated by cyanobacteria with a virtual absence of zooplankton, Mazvikadei has a healthy green algae and a thriving population of zooplankton. In addition, the catchment of Mazvikadei is relatively well-protected although of late it is under threat from artisanal chrome mining and commercial agriculture while Chivero's catchment is not well-protected. The main reason for selecting these reservoirs was to test the utility of satellite remote sensing for rapid assessment of water quality in other reservoirs. The logic adopted is if satellite remote sensing can yield results that agree with ground observations in these two lakes with different trophic states it will likely work for rapid assessment of water quality in other Zimbabwean reservoirs. It was not necessary to sample all the reservoirs in all the catchments, but the rapid method to be developed was supposed to be easily adaptable to any reservoir.

Chlorophyll-a concentrations, Secchi disk depth and turbidity which are directly linked to trophic state and are amenable to measurement by satellite remote sensing hence they are widely used to monitor water quality (Lanthrop 1992; Kloiber et al. 2002; Olmanson et al., 2008). In the present study these three water parameters which can be sensed from satellite platforms (Sass et al. 2007) were used to characterise the water quality of two reservoirs located in Manyame catchment.

Field data on chlorophyll-a concentrations, Secchi disk depth, turbidity and other water quality parameters such as total coliforms were collected under clear blue skies from 80 sample stations within 7 days of satellite overpass in Chivero and Mazvikadei. Half of the sample stations were in Chivero (~24 km^2 in area) and the other half were in Mazvikadei dam (~21 km^2 in area). Sample stations were chosen randomly in a geographic information system.

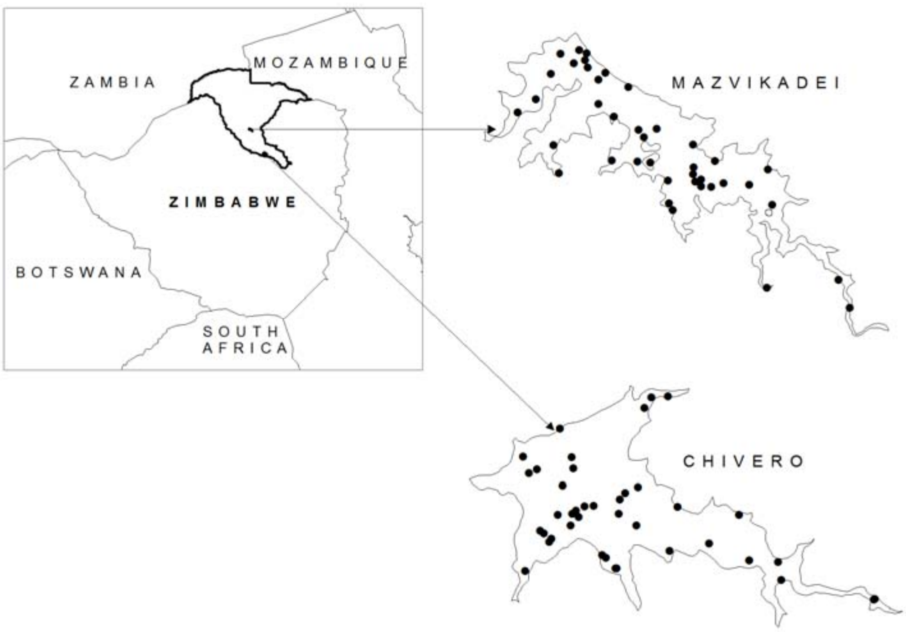


Figure 5: Map of lakes Chivero and Mazvikadei showing their location in Manyame catchment (black solid line) of Zimbabwe and the position of sample stations (solid circles).

The geographic coordinates of each sample station were transferred to a hand-held global positioning system (Garmin GPSmap 60CSx), which was used to navigate to sample stations in the lake. At each sample station, a water sample of ~1lin volume was collected from the uppermost water layer (top 40 cm). Water samples were stored in a cooler box and returned to the laboratory for analysis of chlorophyll-a, turbidity, total dissolved solids and other variables. Chlorophyll-a concentrations ($\mu g/l$) in surface water were measured spectrophotometrically in the laboratory after exposure to acetone using on samples filtered through 0.7 µm GF/F glass fibre filters (Tilzer 1988; Strickland and Parsons 1975). Turbidity was measured on unfiltered water samples using a standard nephelometer and results were expressed in nephelometric turbidity units (Brezonik et al. 2005). Secchi disk depth was measured on-site using a 20-cm diameter, black and white quadrated disk (Lanthrop 1992). Other variables such as pH, salinity and temperature were also measured at each sample station using standard calibrated portable water quality instruments.

3.2.4.2 Satellite image processing

Landsat 8 imagery (path 170 and row 72) covering the two reservoirs acquired on 6 and 22 June 2013 were downloaded from the freely available Landsat archives at http:glovis.usgs.gov. The images, which had less than 5% cloud cover, were registered to the Universal Transverse Mercator zone 36 south projection using the WGS84 as the global datum. A minimum of 15 ground control points were used during image registration. The nearest neighbour resampling method was used for image registration and a root mean square error less than 0.2 pixels (~ 6 m for Landsat 8 data) was obtained.

The uncalibrated digital numbers were converted to radiance and from this to a dimensionless top-of-atmosphere (ρTOA) as:

$$\rho TOA = \pi L_{\lambda} d^2 / ESUN_{\lambda} Cos\theta_s$$

where L_{λ} is the spectral radiance at the sensor, d is the Earth-sun distance in astronomical units, $ESUN_{\lambda}$ is the mean solar exoatmospheric irradiance for each band and $Cos\theta_s$ is the solar zenith angle in degrees (Irish 1998). Sensor calibration information such as solar zenith angle and Earth-sun distance were extracted from the header file of the imagery (Tebbs et al., 2013). Next, the images were converted to reflectance based on the equation provided by the United States Geological Survey (www.usgs.gov).

Three Landsat 8 bands in the visible regions of the electromagnetic spectrum, that is, band 2 (blue), band 3 (green), band 4 (red) and band 5 (near-infrared) were extracted from each image. Following Lillesand et al., (1983) and Sass (2007) at each sample station, the average reflectance value for a 3 x 3 window centred on these pixels was calculated to generate a satellite-based "sample" that corresponded with a ground-based sample. This spatial window was used to reduce the effect of scatter and account for locational errors that could have arisen due to boat drift. However, since previous research has shown that using reflectance values of pixels in the deep open area of a lake yields best calibration results (Kloiber et al., 2002), only average reflectance values for sample stations located at the lake centre were used in the calibration step to avoid spectral interference from the shoreline, aquatic vegetation and the lake bottom (McCullough et al. 2012). In the absence of bathymetric data, the lake centre was assumed to be the deepest part of the lake and hence sample stations located at the centre were considered typical of the open water. ENVI 4.6 software package

(ITT Visual Information Solutions, United States of America) was used for all image processing.

3.2.4.3 Calibration satellite data ground-based measurements

Landsat images were calibrated with ground-based measurements of chlorophyll-a, Secchi depth and turbidity made within 7 days of satellite overpass at sample stations. To avoid spectral interference from the shoreline, lake bottoms and aquatic vegetation, only field data from sample stations placed in the deepest regions of the lakes away from floating aquatic vegetation were used for statistical analysis. At each of the sample station not excluded from analysis, the average reflectance values for each Landsat 8 band and band ratios was paired with ground measurements of chlorophyll-a, Secchi depth and turbidity. Then, Pearson correlation matrices were computed to select bands or commonly used band ratios (such as band 2/4, band 4/2, and band 5/3) that were the most significantly correlated with each of chlorophyll-a, Secchi disk depth and turbidity. Following Kloiber et al., 2002, the strongest correlates were then regressed against chlorophyll-a, Secchi disk depth and turbidity. Least squares regression analyses were applied to the two datasets using the measured water quality parameters as the dependent variable and the reflectance recorded in single bands or band ratios as the independent variables. Regression equations developed were applied to corresponding bands or band ratios to produce surface maps of water quality parameter using the Spatial analyst tool in ArcGIS version 10.0 (Environmental Systems Research Inc., Redlands, CA, United States).

The coefficient of determination (R^2) which should approach unity, the standard error (s.e.) which should approach zero and the *F*-value were used to evaluate the significance of the regression models (Lavery et al. 1992). The three basic assumptions of regression analysis that: (i) regression residuals have constant variance; (ii) residuals are independent and; (iii) residuals are normally distributed, were tested and logarithm transformations of the response variables were performed where necessary to improve the distribution of the data and satisfy the assumptions of Pearson correlation and simple linear regression analysis (Crawley 2007). Outliers were identified and eliminated with the Bonferroni outlier test as well as case-by-case inspection of residuals (McCullough et al., 2012). Parsimonious regression models which are both easy to interpret and apply by other users were preferred. All statistical analyses were performed using the Hmisc package in R version 3.0.1 software (R Development Core Team, 2008).

Note, to ensure that the field data used to calibrate satellite were obtained within 7 days of satellite overpass as recommended in the literature (see Kloiber et al., 2012) for lake Chivero, satellite data acquired on the 6th of June 2013 were calibrated with field data collected on the 11th of June 2013 while satellite data downloaded on the 22nd of June 2013 were calibrated with field data collected on the 15th of June for Mazvikadei.

3.2.4 GIS-based expert system for rapid assessment of groundwater vulnerability

A GIS-based expert system was used to generate the groundwater vulnerability map. This map is based on an expert assessment of a variety of natural and anthropogenic factors that contribute to the vulnerability to pollution of the groundwater system. The factors assessed are:

- Rainfall
- Geology
- Soil
- Topographic wetness index

- Vegetation cover
- Land use

It is considered that these parameters control the vulnerability of groundwater to pollution, where vulnerability may be defined as the likelihood that groundwater pollution will occur for a given contaminant load applied at the land surface. There are a number of different tool to assess groundwater vulnerability, such as DRASTIC. In essence, these tools assess the likelihood of surface water reaching the aquifer. Some of the critical factors are the degree of confinement of the groundwater, the permeability of the unsaturated zone and the depth to the groundwater. This simple approach has been used to generate a Zimbabwe groundwater vulnerability map, given the data availability and the possibility to apply such data sets at a national scale.

For each of the individual parameters indicated above, a ranking has been applied between 1 and 0.1, where the maximum ranking (1) indicates that polluted water at the surface is most likely to reach the groundwater system and the minimum ranking (0.1) indicates that such water is least likely to reach the groundwater system.

For example, areas with the highest rainfall (> 1000 mm per annum) are ranked 1, and those with the lowest rainfall (< 400 mm per annum) are ranked 0.1. With regards to soil and geology, the most permeable materials are ranked higher than the impermeable materials. Geological formations that support shallow unconfined aquifers are ranked lower than geologies that give rise to deep confined aquifers. A spread-sheet provided in the appendix section (Appendix x) gives the details of the variations of rankings within and among the key factors.

These rankings are applied to a suite digital maps that record the parameter variations for each parameter; for example, each soil type is assigned a ranking value depending on its assessed impact on groundwater vulnerability. Similarly ranking values are assigned to different geologies, vegetation classes, land use classifications, topographic settings and rainfall values.

The digital maps are overlaid and the coinciding ranking scores are added together to compute the overall vulnerability. Dividing all the scores by the highest value score recorded normalizes this overall vulnerability score. The output is a vulnerability ranking from 1 to 0.1, with 1 being the most vulnerable to groundwater pollution and 0.1 being the least vulnerable. The result is presented as a national groundwater vulnerability map.

This vulnerability map may be overlaid with a '*contaminant load map*' that shows the contaminant hotspots, and a demographic map, in order to develop a '*groundwater quality risk*' map that shows the risk posed to the public by deteriorating groundwater quality. To a limited degree this has been done here. The major urban areas, the catchment boundaries and the EMA / ZINWA hotspots are shown on the groundwater vulnerability map. Where urban centres and hotspots coincide with vulnerable groundwater systems are the principal areas of concern.

To validate the results of groundwater vulnerability mapping, a total of 22 groundwater samples were collected and analysed. These came from the Manyame (11), Sanyati (7), Mazowe (3) and Gwayi (1) catchments. They included: potable groundwater for high density suburbs (4 samples); Urban Solid Waste Disposal sites (3 samples); Agricultural Impact (4 samples); Mining (3 samples); Industry (3 samples); Over-pumping in Urban areas (2 samples); and Geogenic Groundwater issues (3 samples). The location and detailed description of groundwater sample sites is presented in Appendix C.

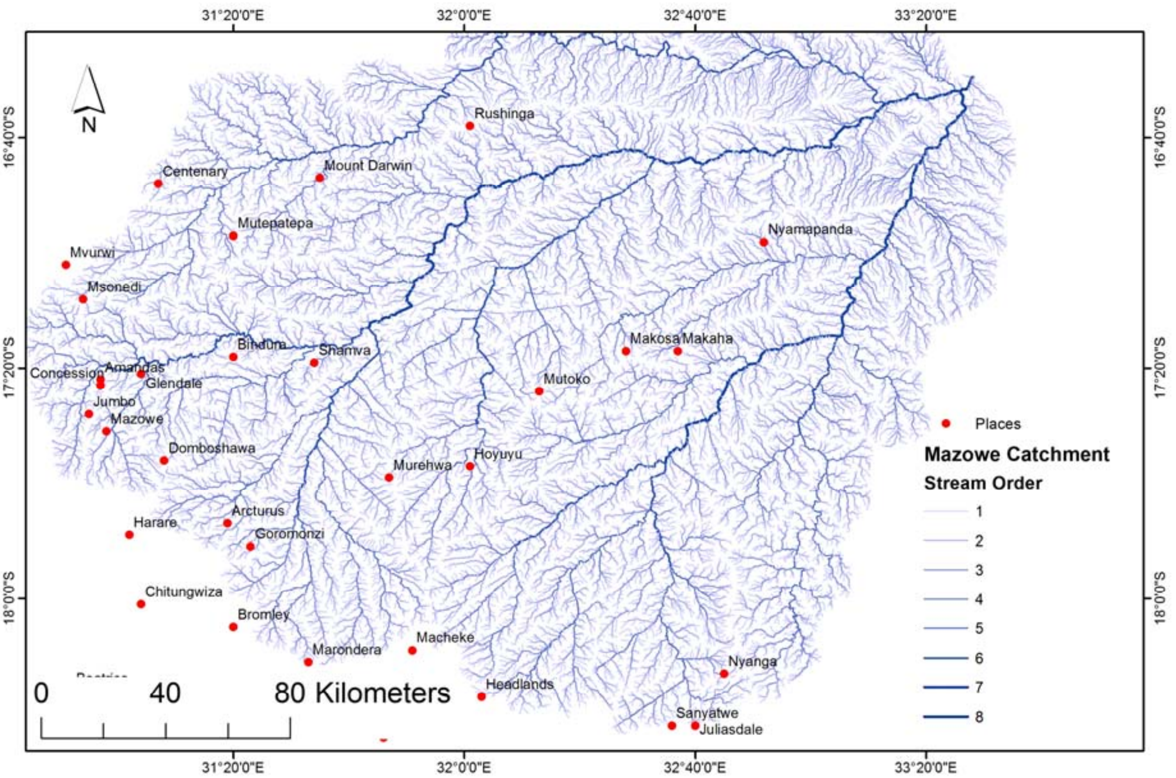
Neither ZINWA nor EMA were able to provide any groundwater quality data and the data from literature is scanty and without any laboratory certification. It was also found that to collect groundwater samples, permission had to be sought from the owner of the borehole. This required the location of the owner and made it difficult to just go out and collect samples.

The results of the groundwater sampling are presented in Appendices D, E and F. The spread-sheets have been arranged such that the 'hotspot types' are grouped together. This makes it easier to observe if there are specific issues related with specific hotspot types.

Chapter 4: Results- Rapid assessment of water quality and quantity

4.1 GIS-based estimation of hydrological catchment characteristics

Figure 6 shows that the entire drainage networks and stream orders of Mazowe and Runde catchments derived from a digital elevation model. These results indicate that using standard hydrological modelling tools in a GIS rapid assessment of surface water can be done. This eliminates the need of extracting the data on drainage network from analogue maps, which is time-consuming.



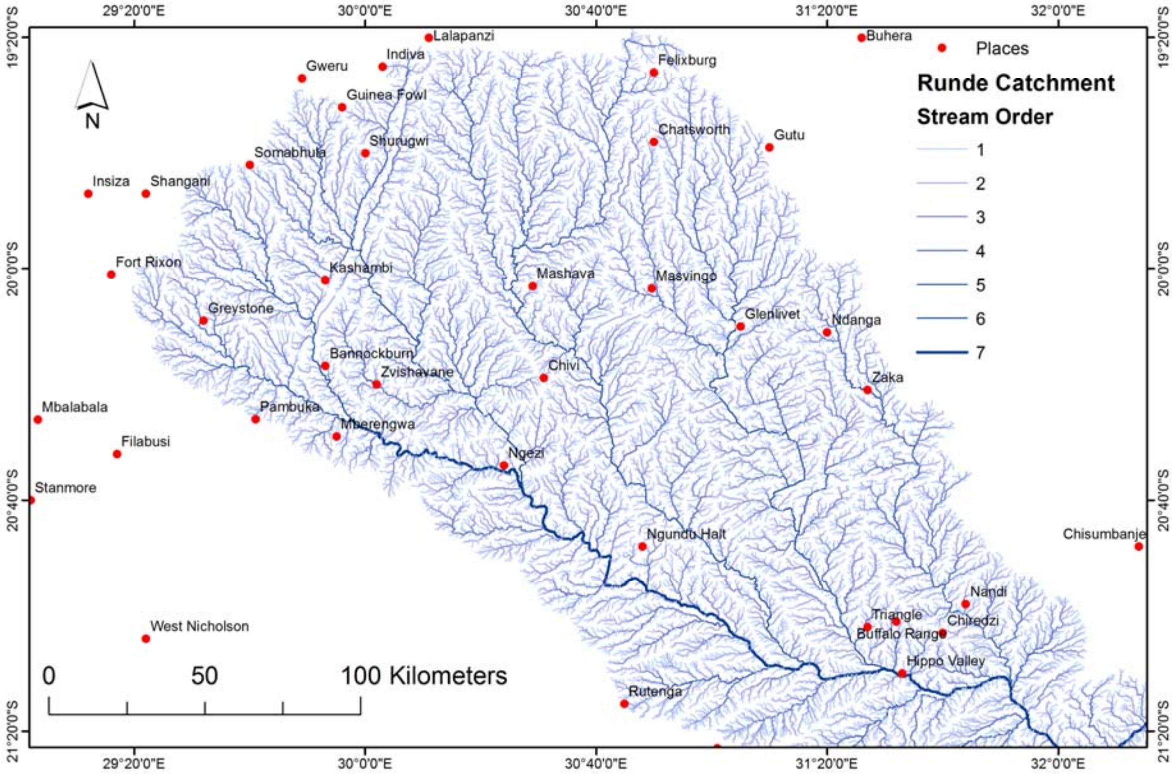


Figure 6: Maps showing the entire drainage network and stream order of Mazowe catchment (top) and Runde catchment (bottom) derived from a digital elevation model in a GIS.

Once the drainage network of the entire catchment has been mapped, statistics relevant to the quantity of surface water such as stream length and stream density can easily be derived as presented in Table 1.

Table 1: Drainage statistics for Mazowe and catchments calculated in a GIS

Catchment	**Strahler Stream Order**	**Total Stream Length (km)**	**Catchment Area (sqkm)**	**Stream Density (km/km^2)**
Runde	1	16198	41559	0.3898
Runde	2	8085	41559	0.1945
Runde	3	4216	41559	0.1015

Catchment	Strahler Stream Order	Total Stream Length (km)	Catchment Area (sqkm)	Stream Density (km/km^2)
Runde	4	2140	41559	0.0515
Runde	5	942	41559	0.0227
Runde	6	644	41559	0.0155
Runde	7	395	41559	0.0095
Mazowe	1	20518	53182	0.3858
Mazowe	2	10923	53182	0.2054
Mazowe	3	5492	53182	0.1033
Mazowe	4	2520	53182	0.0474
Mazowe	5	1163	53182	0.0219
Mazowe	6	769	53182	0.0145
Mazowe	7	462	53182	0.0087
Mazowe	8	8	53182	0.0001

4.2. Quantification and mapping of open water bodies

For Runde catchment, the Modified Normalised Difference Water index was able to detect all dams contained in the ZINWA database as shown in Fig 7. In addition, by using this satellite-based index wetlands as well as tailing dams can be detected and mapped. The main advantage of using this relatively new satellite-based index is that it is a physically-based index and time-invariant hence it can be used for monitoring the extent of surface water bodies throughout the year in all catchments.

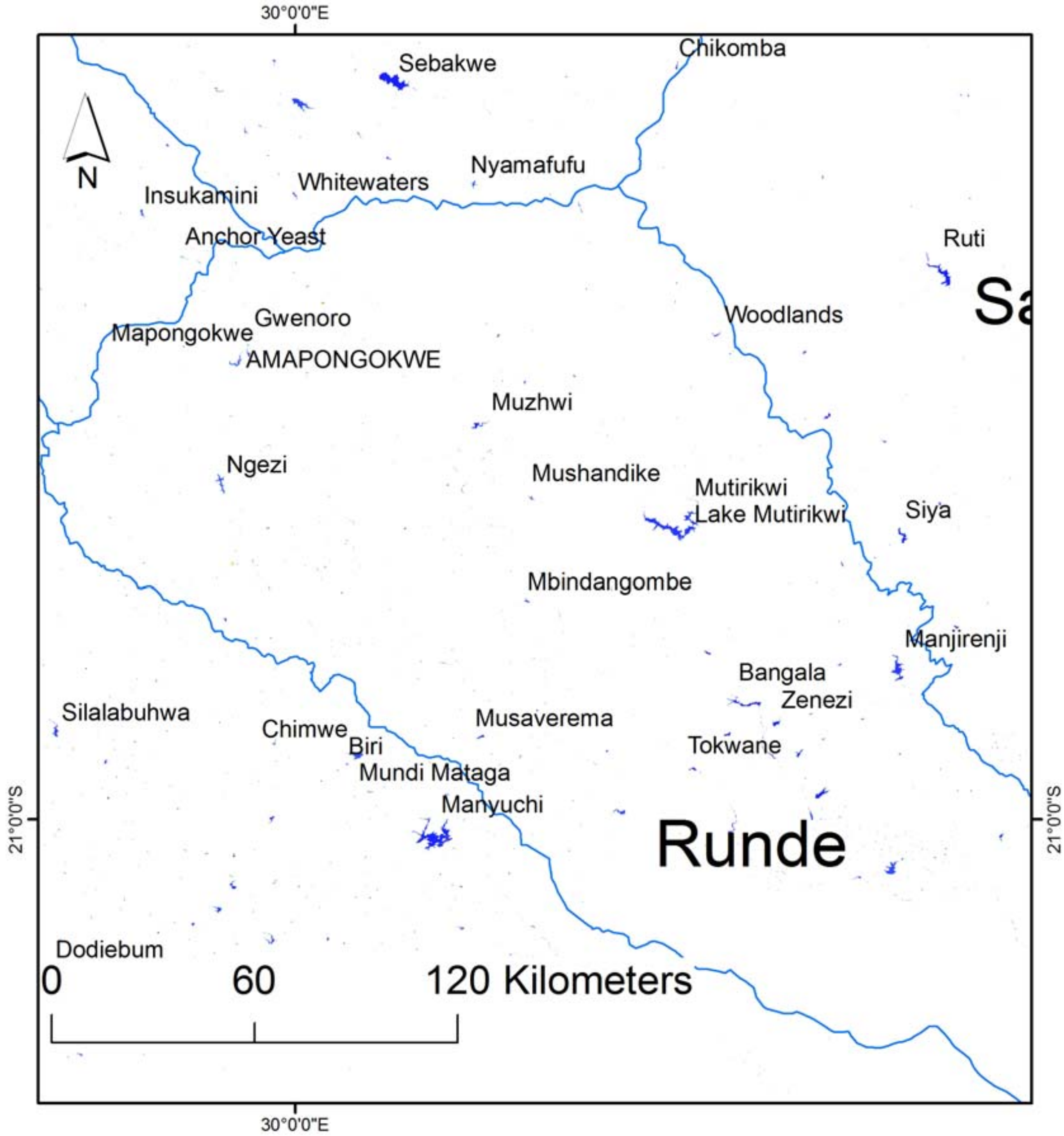


Figure 7: Map showing the distribution and spatial extent of all open water bodies in the ZINWA dam database detected using the Modified Normalised Difference Water Index (MNDWI) in Runde catchment.

4.3 Relationship between catchment condition, source degradation and water quality

Figure 8 shows the variation of catchment condition as predicted using the normalised difference vegetation index.

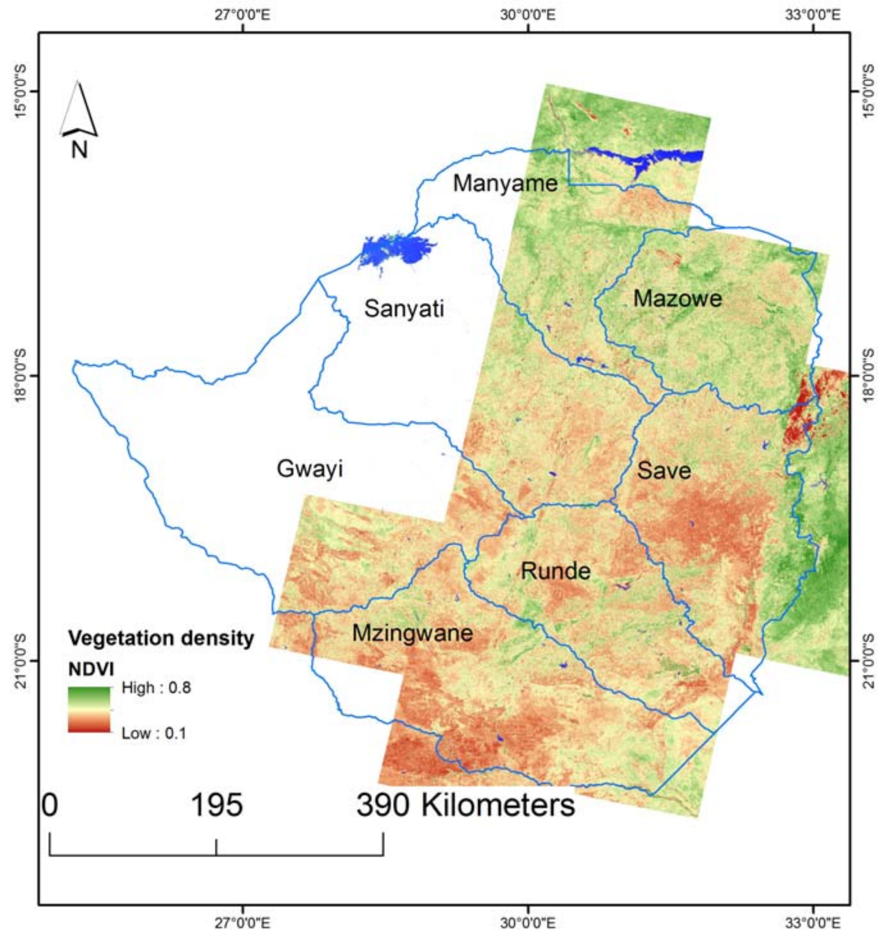
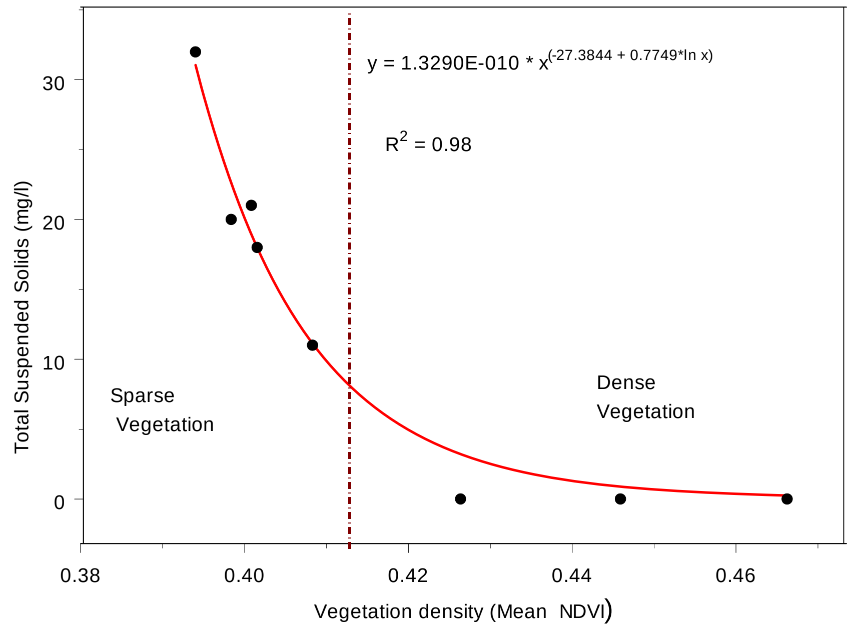


Figure 8: Map of source degradation and catchment condition estimated using the NDVI in Zimbabwean catchments. Green corresponds with high vegetation density while brown corresponds with low vegetation density.

Figure 9 shows that TSS decreased significantly as the mean vegetation density increased for both the drier (Sanyati and Mzingwane) and wetter (Mazowe and Manyame) catchments.



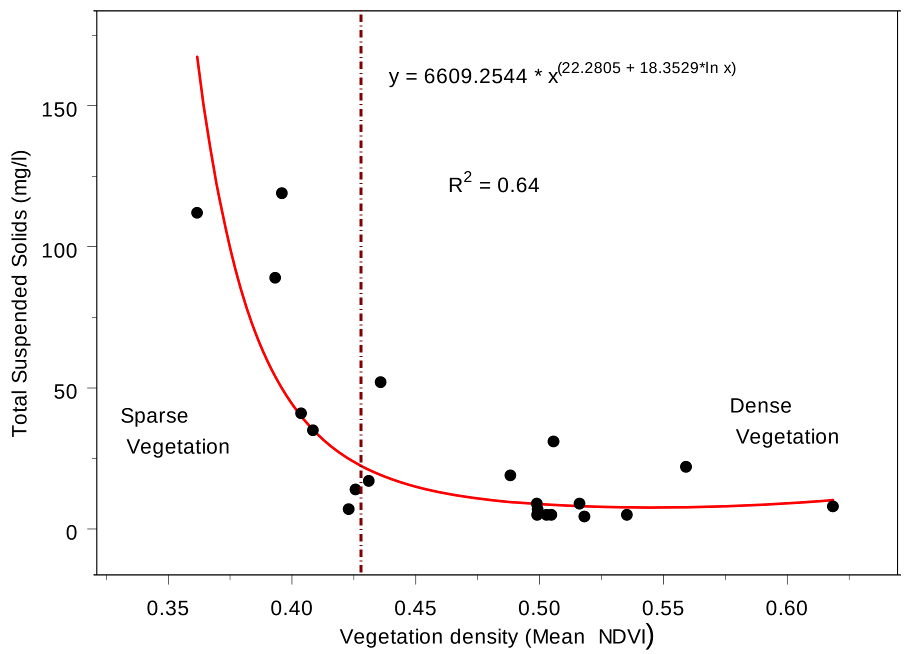


Figure 9: Relationship between Landsat 8 derived indicator of vegetation density and field measured total suspended solids (TSS) for Mzingwane and Sanyati (top) and Mazowe and Manyame catchments (bottom). The best fit non-linear regression line is displayed.

Figure 10 illustrates the hotspots derived from the equations in figure 9.

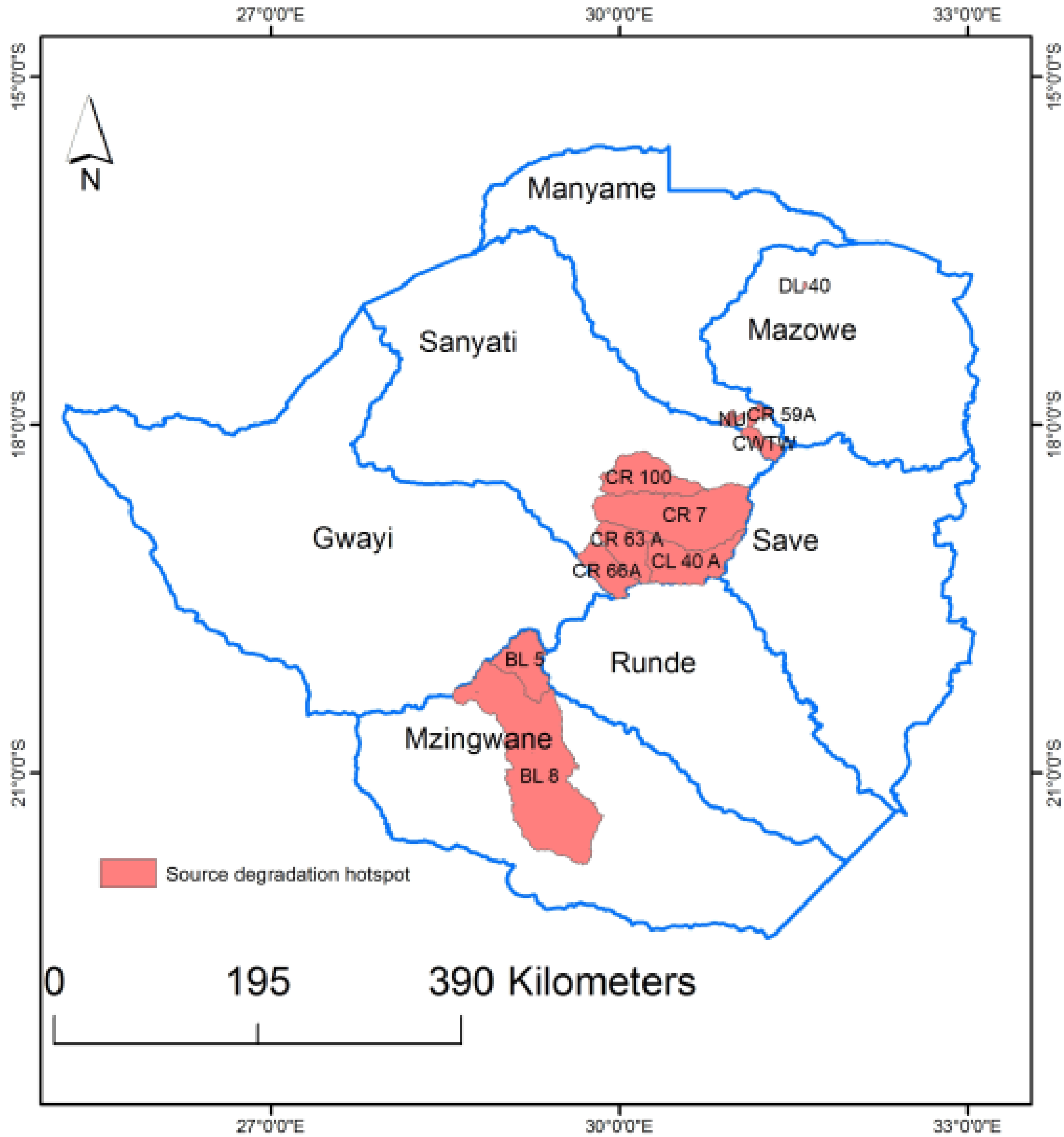


Figure 10: Source degradation hotspots based on the 4.2 NDVI threshold derived from the Mzingwane and Sanyati equation and the 4.25 NDVI threshold derived from the Mazowe and Manyame catchments equation.

4.4. Water quality in reservoirs

4.4.1 Relationships between ground-measured chlorophyll-a and satellite data

Pair-wise Pearson correlation analyses showed that field measured chlorophyll-a concentration in lake Chivero was negatively correlated with reflectance in the red band (r = -0.83) but in Mazvikadei the ratio of reflectance in the near infrared band to the red band yielded a strong positive correlation with chlorophyll-a (r = 0.92; Figure 11).

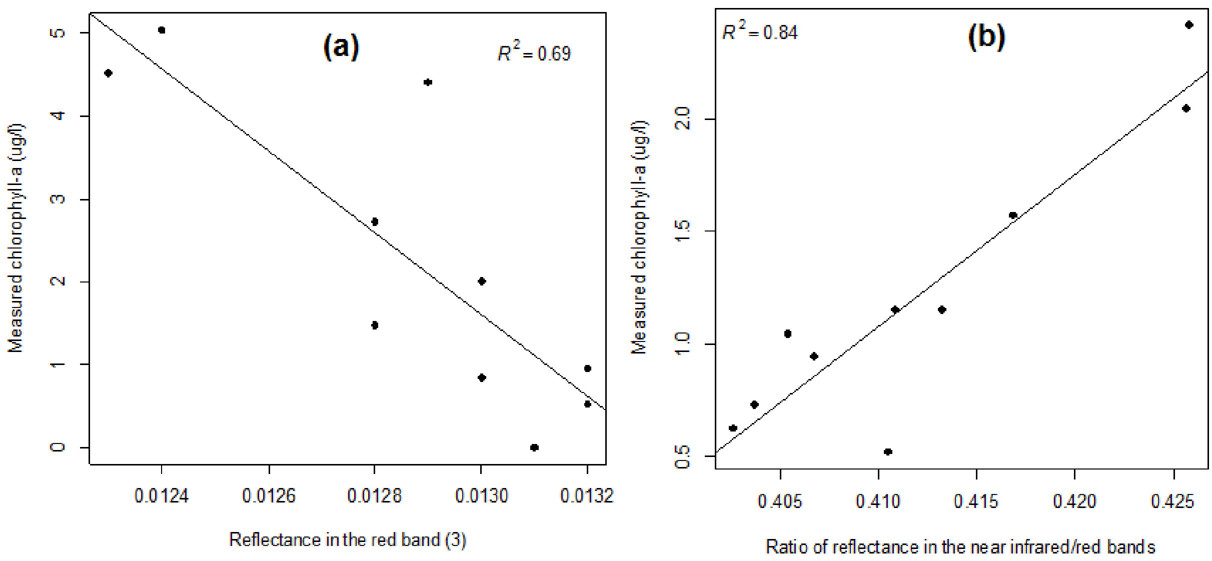


Figure 11: Scatter plots of (a) relationship of reflectance in the red band to field measured chlorophyll-a concentration in Lake Chivero and (b) relationship of the ratio of reflectance in the near-infrared to red bands versus field measured chlorophyll-a concentration in Mazvikadei. The regression lines for best fit linear models are displayed.

4.4.2 Relationships between ground-measured Secchi disk depth and satellite data

Ground measured Secchi disk depth was strongly positively correlated with the ratio of reflectance in the blue to the red bands in both lake Chivero (r = 0.87) and Mazvikadei (r = 0.88) as shown in Figure 12.

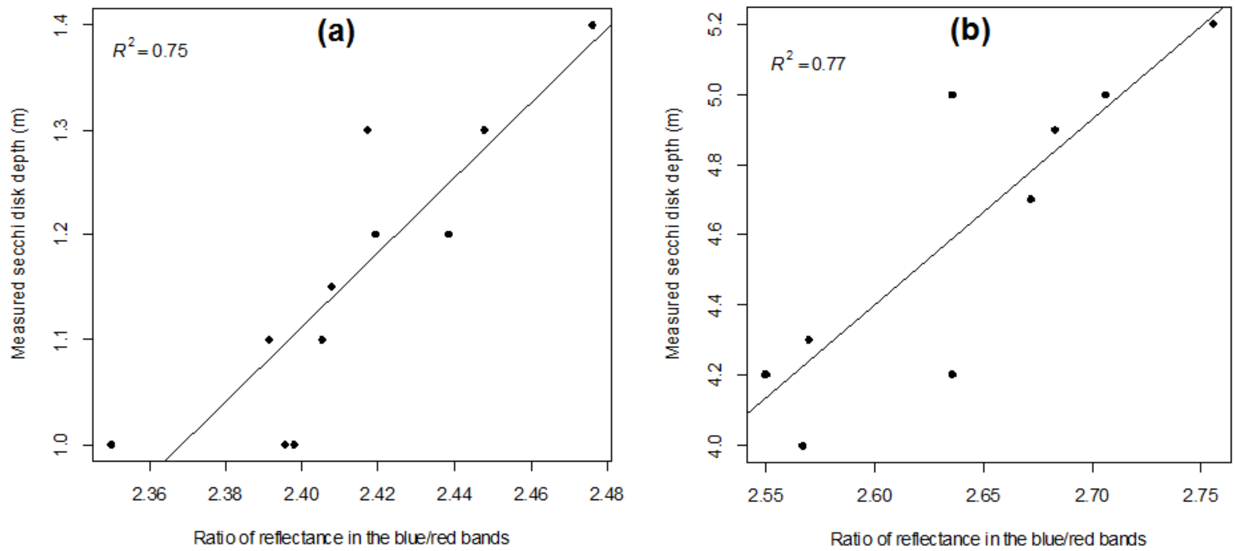


Figure 12: Scatter plots of the relationship of the ratio of reflectance in the blue/red bands to in-situ measured Secchi disk depth in (a) Lake Chivero and (b) Mazvikadei. The regression lines for best fit linear models are displayed.

4.4.3 Relationships between ground-measured turbidity and satellite data

Field-measured turbidity exhibited a strong positive correlation with the ratio of reflectance in the red band to the blue bands in both lake Chivero (r = 0.90) and Mazvikadei (r = 0.81) as shown in Figure 13.

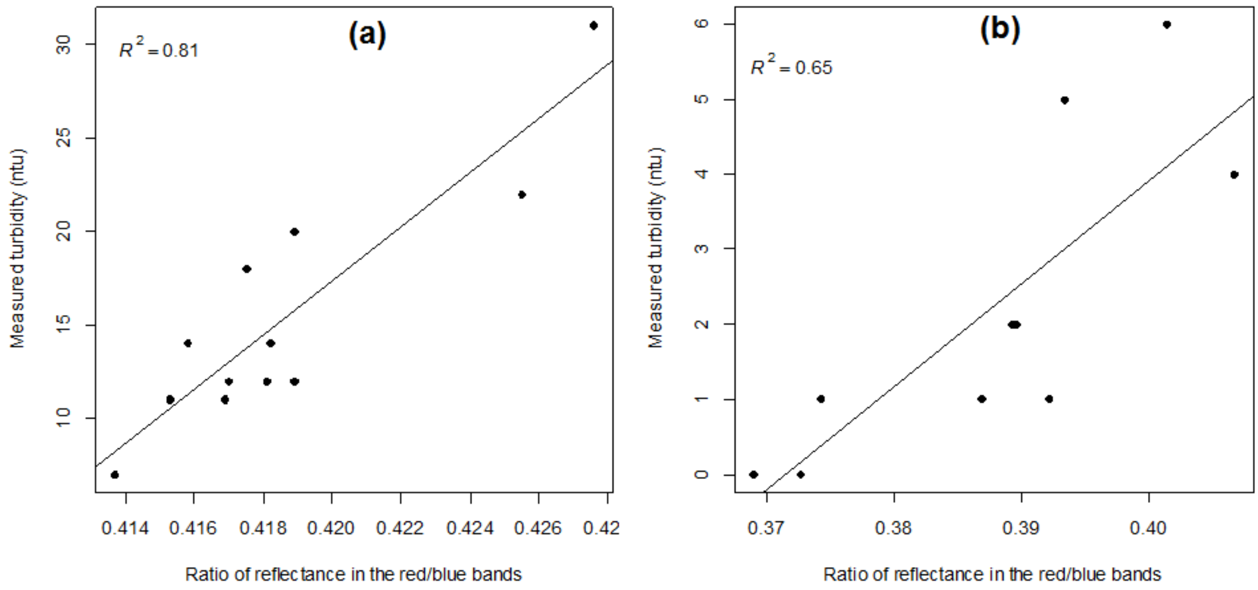


Figure 13: Scatter plots of the relationship of the ratio of reflectance in the red to blue bands versus field measured turbidity in (a) Lake Chivero and (b) Mazvikadei. The regression lines for best fit linear models are displayed.

4.4.4 Regression models for chlorophyll-a, Secchi depth and turbidly

Table 2 presents a summary of the six regression models that were developed by calibrating the most strongly correlated Landsat 8 band or band ratio with chlorophyll-a concentration, Secchi disk depth and turbidity measured in lakes Chivero and Mazvikadei. The fit of the six models is reasonably good (r^2 ranged from 0.65 to 0.84).

Table 2: Regression statistics of linear models used to predict chlorophyll-a concetration, Secchi depth and turbidity in lakes Chivero and Mazvikadei in Zimbabwe.

Water quality parameter	Reservoir	Equation	r^2	*s.e.*	*F-value*	*N*	*P-value*
Chlorophyll-a (µg/*l*)	Chivero	65.7 - 4932. 7 * Band 4 (1)	0.69	1.07	18.2	10	0.003
	Mazvikadei	-26.5 + 67.4 * Band 5/4 (2)	0.84	0.26	42.4	10	0.0002
Secchi depth (m)	Chivero	-7.4 + 3. 6 * Band 2/4 (3)	0.75	0.07	27.7	11	0.0005
	Mazvikadei	-9.4 + 5.3 * Band 2/4 (4)	0.77	0.22	26.5	10	0.0008
Turbidity (NTU)	Chivero	-590.0 + 1445.9 * Band 4/2 (5)	0.81	2.98	41.8	12	0.007
	Mazvikadei	-51.1 + 137.5 * Band 4/2 (6)	0.65	1.32	14.9	10	0.005

Equations are of the form $Y = a + bR_i$ where a is the intercept, R_i is the reflectance in the *i*th band or band ratio and *b* is the coefficient. *s.e.* indicate residual standard error of the model and *N* stands for sample size. Note the blue band (2), red band (4) and near infrared band (5) of Landsat 8 correspond with the bands 1, 3 and 4 of Landsat thematic mapper, respectively. Also note that only average reflectance values from sample stations located at the centre of the lake were used to calibrate Landsat data and those from shallower parts of reservoirs were not considered in the regression analyses to minimise the problem of spectral interference from aquatic plants, the shoreline and lake bottom.

4.4.5 Spatial predictions of chlorophyll-a concentrations

Figure 14 shows that chlorophyll-concentrations were higher in Lake Chivero than Mazvikadei Dam. The distribution of chlorophyll-a concentration in Lake Chivero and Mazvikadei Dam was generated by applying equations 1 and 2 on the respective band and band ratio, respectively (see Table 2).

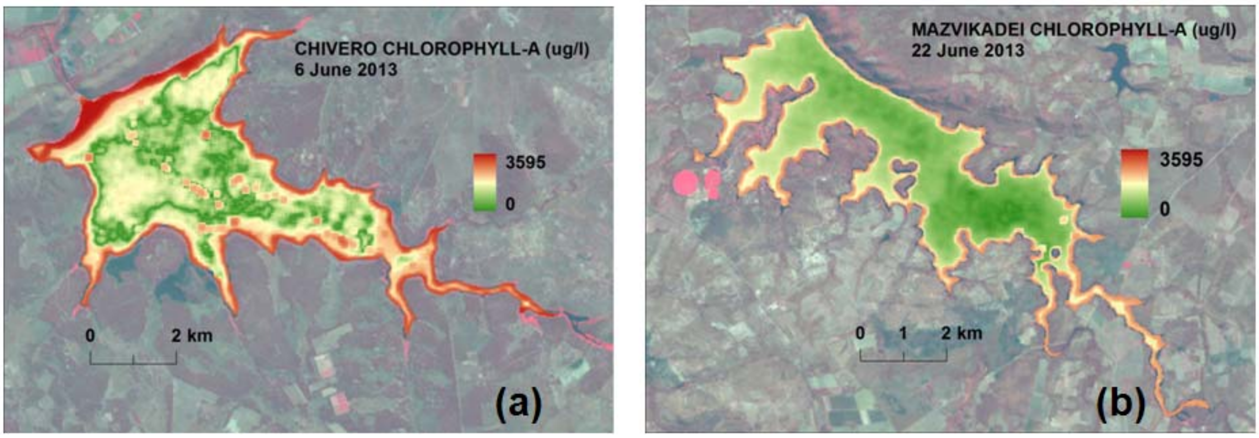


Figure 14: Maps of chlorophyll-a concentration in Lake Chivero (a) and Mazvikadei (b) reservoirs predicted from linear regression models developed from Landsat 8 satellite data calibrated with ground-measured data. The maps are overlaid on top of a false colour composite of consisting of Landsat bands, 5, 4 and 2.

4.4.6 Spatial predictions of Secchi disk depth

Maps of Secchi depth predicted from equations 3 and 4 (see Table 2) indicate that water transparency is higher in Mazvikadei compared to Lake Chivero (Figure 15).

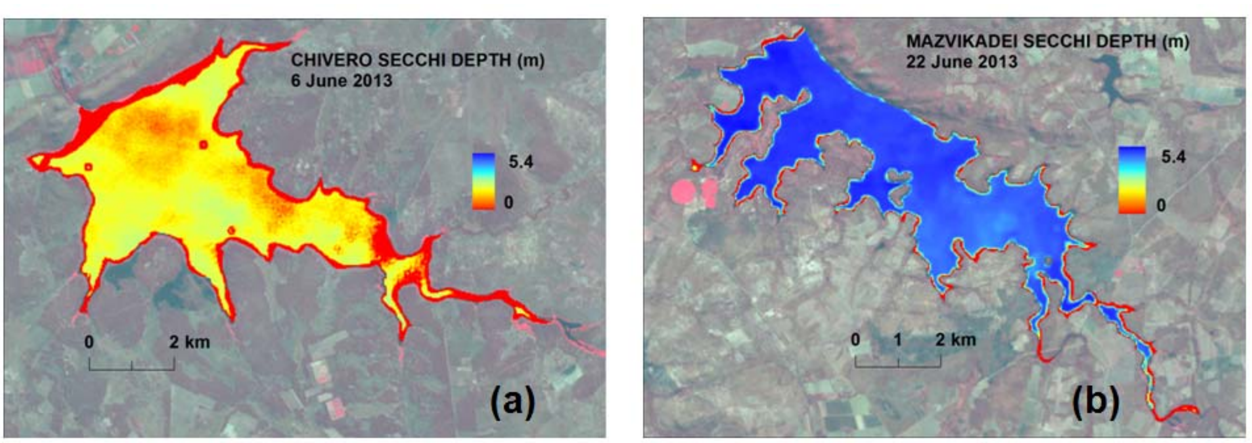


Figure 15: Maps of Secchi depth concentration in Lake Chivero (a) and Mazvikadei (b) reservoirs predicted from linear regression models developed from Landsat 8 satellite data calibrated with ground-measured data. The maps are overlaid on top of a false colour composite of consisting of Landsat bands, 5, 4 and 2.

4.4.7 Spatial predictions of turbidity

Maps of spatial predictions of turbidity suggest that the water in Lake Chivero is more turbid than that of Mazvikadei (Figure 16).

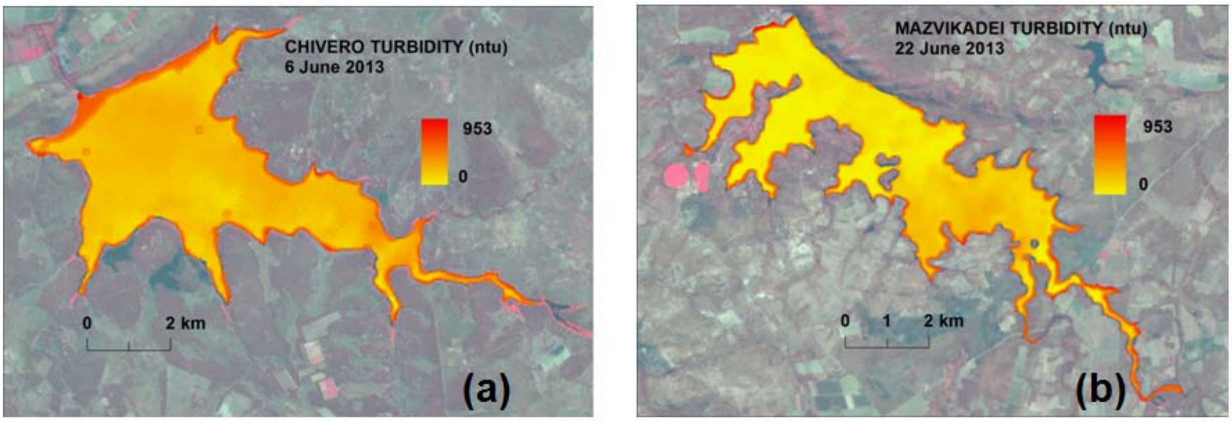


Figure 16: Maps of spatial variations in Chivero (a) and Mazvikadei (b) predicted from linear regression models developed from Landsat 8 satellite data calibrated with in-situ data. The maps (a) and (b) were produced by applying equations 5 and 6 (see Table 2) to Landsat 8 band ratio 4/2.

4.5 Groundwater vulnerability in Zimbabwe

Figure 17 shows groundwater vulnerability throughout Zimbabwe as well as groundwater samples that provide evidence for microbiological contamination. Most of these samples (57%) lie in areas with high vulnerability scores. Further, the results suggest that groundwater is more vulnerable to contamination in catchments with high urban sewerage especially Manyame and Mazowe. Aquifer vulnerability was predicted to be lowest in Mzingwane catchment. According to WHO standards no total coliforms should be present in the water if it is for domestic consumption.

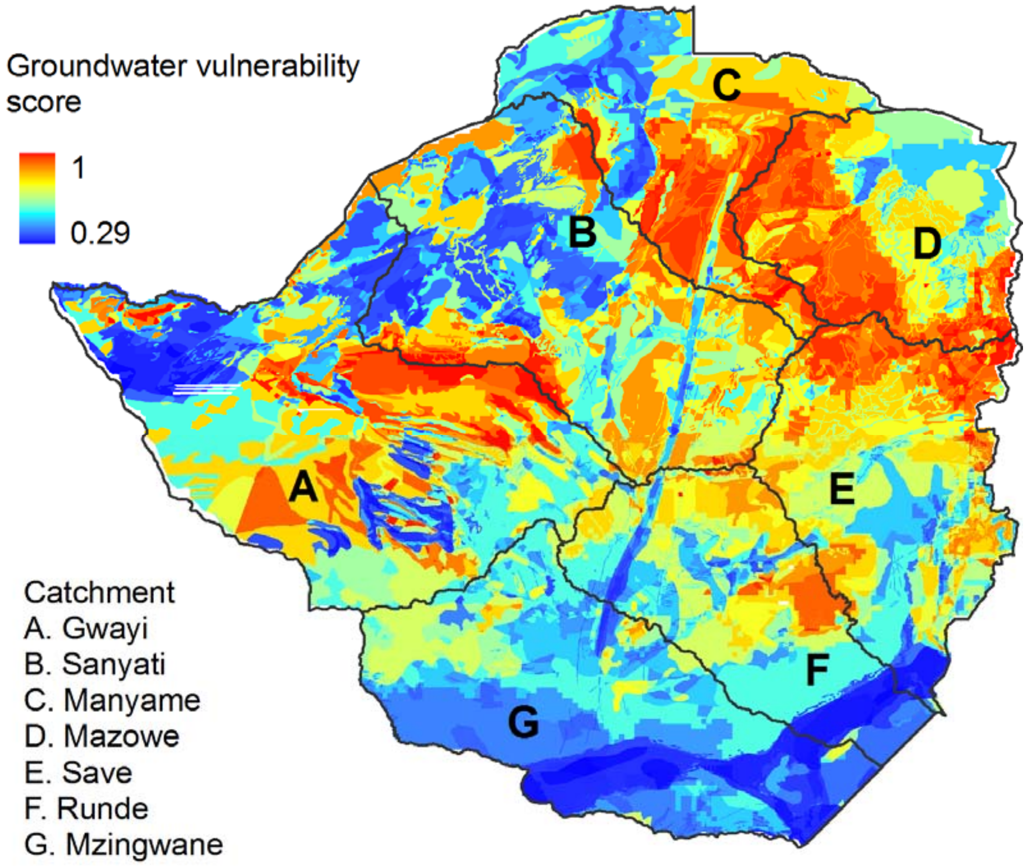


Figure 17: Aquifer vulnerability map of Zimbabwe produced using a GIS-based expert system. The expert scores used are presented in Appendix A.

Hotspots of microbiological contamination of groundwater

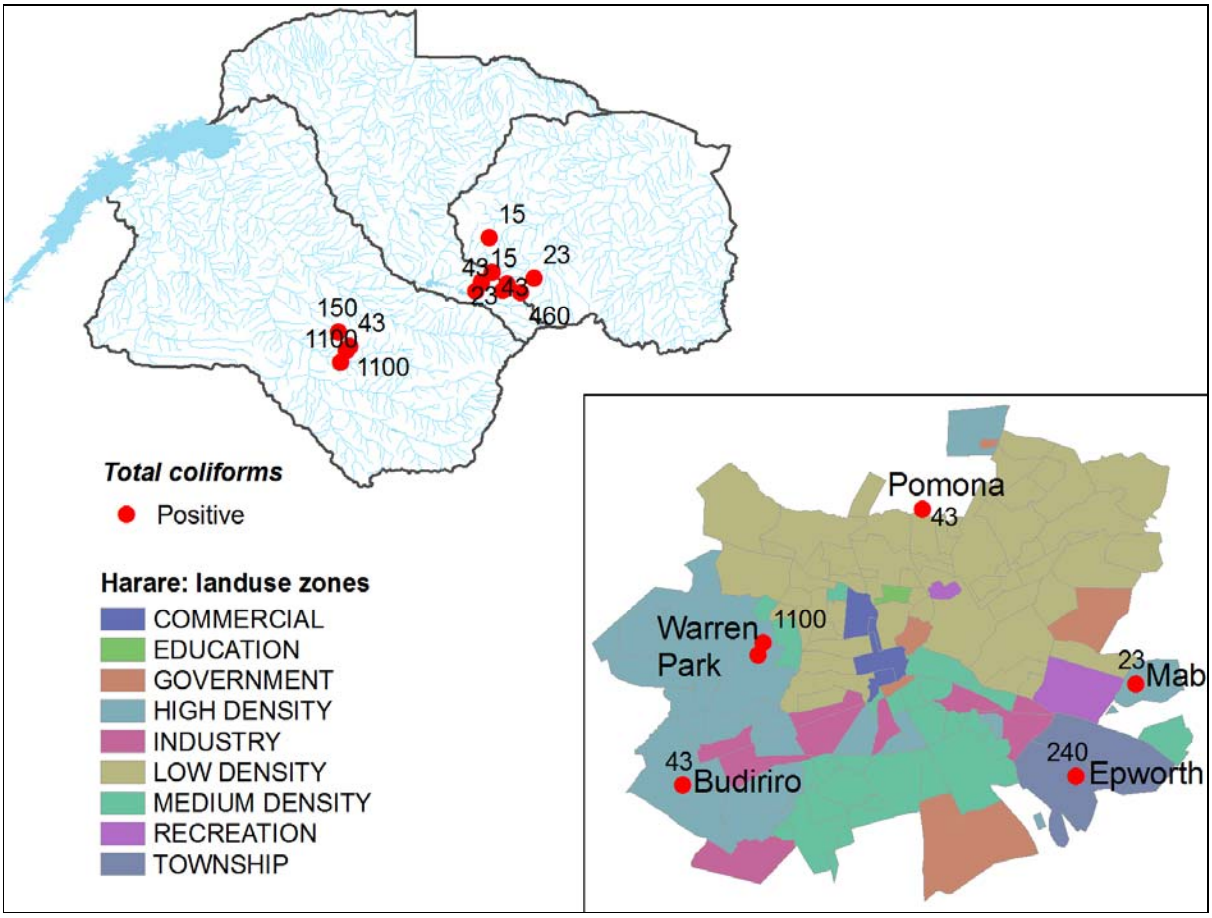


Figure 18: Map showing groundwater samples where total coliforms were detected in Zimbabwe. All 13 samples analysed for microbiological contamination tested positive. Most of these samples were located in the high density residential areas of Harare and Kadoma. Sampling was conducted between 6 June 2013 and 23 July 2013.

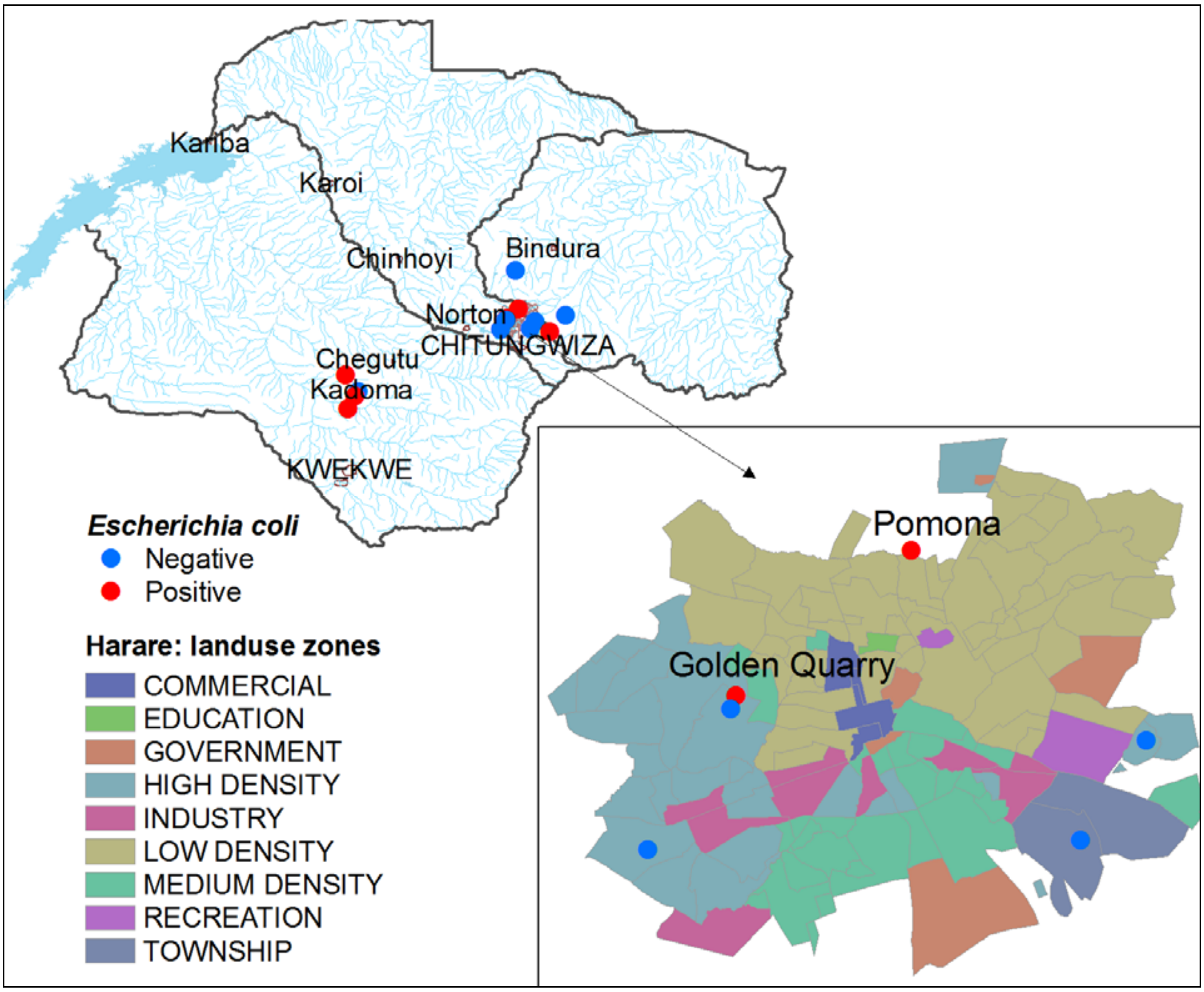


Figure 19: Map showing six groundwater samples that tested positive for *Escherichia coli* in Zimbabwe. Seven samples tested negative. Sampling was conducted between 6 June 2013 and 23 July 2013.

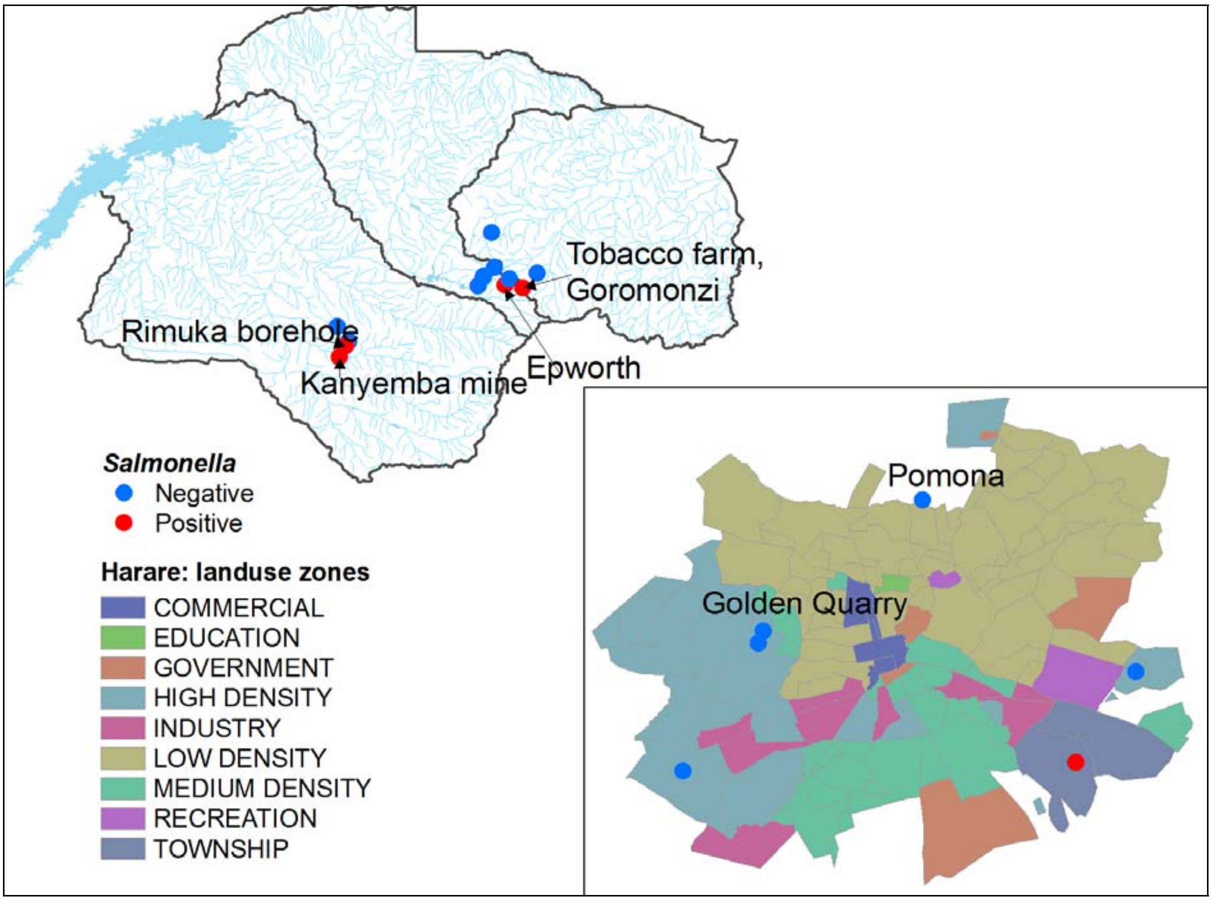


Figure 20: Map showing four groundwater samples that tested positive for *Salmonella* out of 13 samples tested between 6 June 2013 and 23 July 2013 in Zimbabwe.

Detailed results are presented in a spread-sheet (Appendix E). The results can be compared to the WHO drinking water standards at the base of the table. Values that exceed these guidelines have been highlighted in red if they greatly exceed the guidelines or in yellow if they are just above the guideline values. At a glance, the results summarised in Appendix F imply that there are many groundwater quality issues associated with all of these hotspot types. Many of these water quality issues can have a potentially serious impact on public health and the environment. However with this small sample number, caution is needed before any generalizations regarding the impact of various anthropogenic activities on groundwater quality can be made. This table can provide a general guide to the type of groundwater quality issues that may be anticipated at the different types of hotspots.

In addition, regular groundwater quality monitoring should be instituted at such localities, particularly where the risk to the public or the environment is high. The availability of timely water quality data allows the impacts of groundwater pollution to be ameliorated by appropriate adaptive management actions. Nevertheless it can still be stated that the groundwater quality at most of the 'hotspot' types does exhibit quality problems as indicated in Appendices E and F.

Chapter 5: Discussion and TORs for Phase 2

5.1. Discussion

In the introduction we painted a broad picture of the water quality and source degradation issues in Zimbabwe. However, Phase 1 was not designed to address all of these issues. The specific mandate of Phase 1 was to develop and test a methodology and carry out a rapid assessment of water quality using optical remote sensing and GIS calibrated with field data. In summary results of Phase 1 demonstrated that, using optical remote sensing and GIS, it is possible to undertake a rapid assessment of both surface and ground water quality in Zimbabwe at a fraction of the cost of the traditional methods. Phase 1 also demonstrated that a much smaller budget and infrastructure outlay is it required to accomplish this task. The results documented in this report are comparable to those in the literature by clearly demonstrating the utility of satellite remote sensing for rapid assessment of water quality. However, the methodology we used has two key limitations that may need to be addressed in the design of Phase 2, which should focus on a long-term monitoring and assessment framework that is needed for Zimbabwe waters.

First, as a quick first approximation of water quality from satellite remote sensing an empirical, regression type approach that related field measurements to satellite imagery was used to create maps of water quality. In other words, we used empirical algorithms to estimate water quality by statistically modelling relations between combinations of spectral bands and measured water quality parameters. The advantage of this empirical approach is that it is easy to implement as it does not require one to understand the underlying physics such as atmospheric and underwater light processes which influence the spectral properties of a water column. However, empirical algorithms struggle when the range of water column constituents fall outside of the range upon which the statistical relationship was based or when applied to other water bodies that may display different fractions of water column constituents. As such, empirical algorithms like the approach taken here are generally limited in transferability in space and time, in concentration range, and require ongoing coincident *in-situ* data. Inorder to mature, these algorithms need to be further tested with a range of parameter concentrations

Second, although the relations that we established between water quality variables and satellite data were based on reflectance data which is dimensionless, these may be Landsat 8 (i.e. sensor) dependent. This may be problematic for the goal of long-term time series where empirical algorithms would need to be re-parameterized for each new sensor used.

To address these limitations, we propose for Phase 2 physical-based models that use analytical or semi-analytical solutions of radiative transfer or bio-optical models to estimate water constituents based on forward optical or inversion models. Forward optical models are used to predict surface reflectance based on *in-situ* parameterization while inversion methods are used to match optical remotely sensed data to the spectra generated. These types of approaches provide advantages over empirical approaches, including reduced requirements for *in-situ* data, and sensor, space and time transferability. Sensitivity and error analysis can also be objectively determined. It is therefore clear that the much-needed long-term operational water quality monitoring and assessment systems developed for Zimbabwe rely on physical-based approaches.

With regard to the main findings, our report suggests that the urban sewerage and the mining sector are significant contributors to point and diffuse pollution despite the existence of effluent standards and legislation. Although we caution the generality of this finding given the small dataset used, there are some interesting policy and management implications that arise from this finding. This warrants future research which should tease apart whether the negative impact of mining and urban sewerage on water quality is due to the local urban authorities and the mining sector being compliant to the standards and legislation, or whether current standards and limitations need to be properly defined for successful control of point and non-point-source pollution of water.

The potential impact of harmful algal blooms, including cyanobacterial (blue-green algae) blooms in freshwater systems was not addressed in this report yet blue-green algal bloom is toxic and is known to pose a substantial health risk for communities accessing affected water for drinking, irrigation and recreation. The toxins can destroy cells in the liver and other internal organs, and may act on the nervous system leading to respiratory failure. Other health impacts can include gastric upsets, fever, headaches, skin irritations, and numbness and paralysis of the arms and legs. Exposure over time can lead to neurodegenerative diseases such as motor neuron disease and Alzheimer's-like dementia, and the toxins can be carcinogenic or tumor promoters. Human deaths have been associated with blue-green algal blooms, and deaths of livestock and wildlife are common. Therefore in Phase 2, a protocol for long-term monitoring of cyanobacteria must be developed and implemented.

Zimbabwe's water quality problems and sources of pollution

Results of this study showed that certain waterbodies have water quality problems, and others such as Lake Chivero and the Manyame rivers are well documented in the public domain as highly polluted systems. It is important for this study to identify the broad problems of water quality in terms of point and non-point source pollution as the design of any future monitoring programme will need to take that into consideration.

Point sources of pollution

The history of point source pollution is largely anchored in urban and industrial communities where wastewater is produced normally through a reticulated water supply and waste disposal system (Davis and Hirji, 2003a). Water supply in urban centres improves direct access to water which is an important benefit but it also creates the problem of having to process and safely discharge wastewater back into the environment (Davis and Hirji, 2003b). The planning of urban centres in Zimbabwe is based on a reticulated water supply and wastewater disposal system, and fully functional and efficient wastewater treatment facilities are essential. Hence, as observed in this study, urban centres were the primary sources of point source pollution followed by mining which is really a form of industrialisation outside of urban centres. Examples include malfunctioning sewage treatment facilities in most urban centres, sewer bursts, and industrial discharges into sewers and directly into waterbodies which in most cases are also water sources.

In Phase 2, water quality monitoring must consider issues related to point-source pollution in Zimbabwe as it has become a serious national issue. It is therefore important to establish water quality objectives as ambient and effluent quality objectives. EMA has already gazetted effluent standards (2007) while the municipalities have their own standards for waste and potable water. EMA uses these guidelines to punish polluters using the "polluter pays principle" although the sentiments are that a maximum fine of US$5000 is too lenient. Similarly, municipalities like City of Harare also charge polluters at point sources. However, polluters are content with paying fines and the effectiveness of such a strategy needs to be reviewed against the costs to the environment. The performance of sewage treatment plants needs to be assessed, and practical measures such as industrial pre-treatment can significantly reduce pollution loads in our rivers (Davis and Hirji, 2003b)..

Non-point sources

In this Phase 1 study, it was evident that Zimbabwe has problems with non-point source pollution which contributes to water quality problems the country is facing. Non-point source pollution by its nature is very difficult to attribute to an entity and is therefore very difficult to manage (Davis and Hirji, 2003c). A lot of activities in urban centres and rural areas contribute to non-point source pollution. The informal business sectors operating largely in urban centres like Harare include car breakers, oils, factory washes, illegal sand mining all contribute to effluent. Outside of urban areas, activities such as mining, agriculture and construction contribute to environmental degradation and hence water pollution. However, there is very little information on the monitoring of non-point pollution sources in Zimbabwe, in contrast to point sources often targeted for payment of penalties. Therefore, impacts and contribution on non-point sources is largely unknown and unquantified.

The future monitoring programme must also assess non-point source pollution but the exercise can be very expensive as the area involved can be large and a broad range of parameters may be involved (Davis and Hirji, 2003c). Water quality objectives are somewhat similar to those of ambient monitoring but they still have to be clearly defined particularly taking into consideration downstream beneficial uses (Davis and Hirji, 2003c). The first approach can involve physical and chemical monitoring where parameters such as nutrients, pesticides, salts, silt and sediment are measured. The second approach can involve biological monitoring which offers the advantage of detecting impacts especially if exposure to pollutants is chronic. Biological monitoring is also used for monitoring pathogens such as coliforms, and to also determine if there is acute toxicity normally measured as mortality. A case in point is the regular fish kills at Lake Chivero due to pollution of the water body.

The current status of Zimbabwe's water quality monitoring framework

In order to accurately define what needs to be done in Zimbabwe in terms of water quality monitoring which will lead to strategies for managing problems such as pollution, we need to understand more the current situation in relation to international best practices. Zimbabwe's water quality monitoring and management challenges are typical of most developing countries and the country needs to move towards modernizing this important aspect (Ongley, 1994, 1997). This process can be informed by studies done in other developing countries with similar problems such as Mexico (Ongley and Ordonez, 1997). The traditional paradigms of water quality monitoring programmes have not worked and the country will have to take a more adaptable approach that brings positive outcomes for its society (Ongley, 1994).

Institutional arrangements

First, it is necessary to highlight the institutional framework in place at the time the study was carried out. Phase 1 presented an opportunity to get some insight into the water quality monitoring systems that are currently operational in Zimbabwe, and to interface with the responsible authorities such as EMA, ZINWA and municipalities. The Environment Management Agency (EMA) is the statutory body responsible for environmental issues which also includes monitoring of surface water quality. This function was previously the responsibility of ZINWA before EMA was duly constituted under the Environment Management Act. ZINWA had put in place a comprehensive network of flow gauging stations on most rivers around the country, and also incorporated sampling stations for surface water quality monitoring and groundwater monitoring boreholes. Cooperation among these institutions and other stakeholders is vital for any water quality monitoring programme to be successful. Institutions tend to "defend their turfs" but this can prevent useful collaboration in data collection that in the long run will significantly reduce the costs involved.

ZINWA was responsible for both groundwater and surface water monitoring up to 2006. Thereafter, the responsibility for water quality monitoring was handed over to EMA in 2006. When ZINWA ceded the functions of surface water environment monitoring to EMA, the transfer of data was not done very well. However, EMA resumed the monitoring from then on but due to logistical and financial constraints discontinued the countrywide water quality monitoring and have instead focussed more on strategic areas that require intervention or in response to pollution incidents. This came out very clearly during attempts to compile previous data on the water quality monitoring programme. Where it was available, it had either many gaps or there was not much consistency in the parameters analysed or the frequency of sampling to really make any useful dataset. In some instances the data was in different formats as hardcopy or soft copy. The "polluter pays principle" has also hamstrung EMA as ambient monitoring now just becomes a cost.

When Phase 1 commenced, consultation was made within the Ministry of Water Resources Development (then custodian of ZINWA) and the Ministry of Environment (then custodian of EMA). Since September 2013, the two agencies have now been merged into the Ministry of Environment, Water and Climate, a move which provides opportunities for more harmonization between the two institutions, which is much in-line with our recommendations.

Water quality assessment and standards

A key requirement in any water quality monitoring assessments is to have clearly defined goals/objectives for the programme (Davis and Hirji, 2003a). It was not clear what the primary objectives of the ZINWA water quality monitoring programme were, but the extent of the programme suggests that it was a national data collection exercise intended to give information on water quality, land use impacts, water usage and regulation. Since ZINWA has the mandate for water management, this database was going to be pivotal for water resources management in the country. It was not clear what the objectives of EMA were as the data was not usable, and so the issue of water quality objectives is central to any future work to be done in Zimbabwe. If that is not in place the motivation to monitor water quality for objectives other than the "polluter pays principle" is difficult to institute. It must also be clear what the data will be used for, how it will analysed, what and where it needs to be collected.

The issue of water quality standards is also important so that there is sufficient and coherent guidance on the different uses of water. The WHO standards are used extensively in Zimbabwe along with local standards which include EMA Effluent Standards (2007), ZINWA standards, Standards Association of Zimbabwe, and municipal standards. The local standards attempt to address the various possible uses of water from potable to industrial. The presence of so many standards under different statutory bodies has its problems, and Phase 2 must critically look at the issue of coming up with unified national standards for the major types of water users. Typically, other functions such as environment, navigation, recreation or agriculture tend not to have any guidelines. Local standards should be simple and must take into account the limitations in the parameters that can be accurately measured in water quality monitoring (Davis and Hirji, 2003a).

Water quality monitoring network

As stated earlier, the purposes and objectives of the monitoring programme must be well defined in order to determine what sort of monitoring programme Zimbabwe requires. According to the The UN/ECE taskforce on monitoring and assessment, there are four main purposes for a water quality monitoring programme: basic/reference, effluent control and regulation, protection of functions and uses, and early-warning monitoring (Davis and Hirji, 2003a). In Phase 2, this must be resolved so that the different institutions involved in water quality monitoring can cohesively determine the objectives of their sampling programmes to reduce duplication and data that is not useful. It is now evident that inheriting a monitoring programme as the case with EMA can actually create more problems if its objectives are not well defined. At the same time, ZINWA's programme was disrupted as it had its water quality monitoring objectives linked to flow assessments when it initially designed the programme.

The next step would be to design the monitoring network itself based on the identified objectives. First step would be to identify the sampling sites for monitoring and here GIS & Remote sensing tools would be most useful. Then determine the frequency of sampling needed considering factors such as river flow dynamics, climate factors etc. and this being done in reference to the objectives. The third step would be to identify which parameters to sample and analyse, guided by sampling objectives influenced by statutory regulations, for example. These aspects were inherent weaknesses in the current water quality monitoring framework as parameters are sometimes measured because they can, but this tends to be costly. It is imperative to recognise that different approaches and parameters will be used depending on whether we are dealing with point or non-point sources of pollution. A monitoring programme must also consider the use of tools such as biological monitoring which can be very cost-effective in the long-term, but whatever approach is used must ensure that objectives of water quality monitoring are achieved (Davis and Hirji, 2003a)..

Sampling and analysis

Sampling involves the collection of a portion of water from a water body with the assumption that is representative of the conditions at that site and point in time. Primarily it involves field collection of samples of not just water, but any other medium such as sediment or organisms of interest such as macroinvertebrates, fish or riparian vegetation. All these parameters have techniques and a certain level of technical competency required by the person collecting the samples. Sample collection methods for surface and groundwater therefore need to be standardized to ensure that results are comparable even across institutions. At present, this does not exist in Zimbabwe which makes it difficult to confidently utilize data collected by another institution. In Phase 2, the aspect of sampling techniques will need to be addressed and training must be considered as sometimes tertiary institutions in Zimbabwe lack capacity to give potential water managers the necessary practical experience.

The next step after collection of samples is analysis for various parameters in the laboratory (Davis and Hirji, 2003a). Most developing countries, including Zimbabwe face severe constraints in this aspect because of the high capital outlay required to set up a laboratory. For example, EMA has one national reference laboratory situated in Harare, and this automatically determines the extent of any sampling programme in addition to the parameters that can be analysed. Laboratories tend to ignore parameters that they cannot analyse, and in Phase 2 critical thought has to be given to how the issue of laboratory analyses also taking into consideration the aspect of cost. Important to this also is the aspect of technical and professional competencies where training could be required for laboratory technicians (Davis and Hirji, 2003a). Laboratory procedures and methods need to be well defined and standardized across institutions in Zimbabwe, and in Phase 2 a way of achieving this needs to be determined (Davis and Hirji, 2003a).

Processing, interpretation, management and presentation of data

The way data is handled after collection is of great concern to many developing countries. The example given earlier where data collected by ZINWA in its monitoring programme can no longer be accessed as no one is certain who took what when EMA was formed highlights the seriousness of the issue. Ideally data should be entered and stored into a computerized database with key information such as sampling, measurement variables and sampling information (Davis and Hirji, 2003a). It will be most useful to also couple water quality monitoring data with hydrological data, and Zimbabwe had gone some way in trying to implement that but presently those two functions reside in two different statutory institutions. It is important to clearly determine by who and where the data are stored and ideally a unit must be responsible for data management in an entity so that there are adequate backups. Most importantly, other users and institutions should be able to access the data. The issue of access to data needs to be addressed in Phase 2 as it was apparent that accessing data in some regulatory institutions was a very difficult process. Data is collected so that it can be used, not stored and barricaded within institutions and parameters of how this can be best done need to be worked out.

Stockpiles of data are useless if that data is not analysed and interpreted in a way that gives clear management direction (Davis and Hirji, 2003a). This problem is also linked to a lack of clear objectives why the data were collected in the first place. What could be lacking in Zimbabwe's context is the capacity of staff in institutions like EMA and ZINWA to apply tools such as models in order to improve data interpretation. Phase 2 will need to implement capacity building trainings in order to increase the level of confidence in data treatment. This goes along with skills on how to present results to different audiences, as for example, some policymakers may not have the technical knowledge of water quality monitoring (Davis and Hirji, 2003a). The use of tools such as GIS mapping also can help in visually aiding understanding about water quality management to non-technical audiences.

5.2. Zimbabwe Strategy for Managing Water: Key questions relevant for developing the TORs for Phase 2

Based on the findings of this work, and experience in water quality assessment and management, we pose seven key questions that are critical for Zimbabwe's long-term strategy for monitoring its water quality in Phase 2.

5.2.1. Does the current policy and legislative environment provide for comprehensive water quality management?

Zimbabwe is regarded to have some of the finest legislation on environmental and water issues such as the ZINWA Act, Water Act and EMA Act and a national water policy. However, there is need to harmonise some sections of these different pieces of legislation to ensure efficient water quality management. In addition, what is lacking is also a proper implementation strategy that ensures maximum compliance by stakeholders and that derives maximum benefits for the government and the public. While the implementing agencies do have qualified personnel, there is need for continuous training of staff and capacity building to adapt to new challenges. There is also need for appointment of management staff with relevant technical qualifications and experience and whose performance is regularly monitored and evaluated. There is also a need for harmonization of activities of all units involved in law enforcement and for the judicial arm to decisively deal with offenders such that environmental protection becomes respected and prioritized by citizens and corporates. An application strategy for existing water-related legislative frameworks may need to be developed in Phase 2.

5.2.2. Does the institutional set-up promote efficient water quality management?

At least three parastatals are responsible for some aspect of water management in Zimbabwe. Despite the extensive network of institutions in water resources management, there is little coordination and cooperation between ministries whose decisions have major implications for water resources planning and management. There are also potential conflicts of interest in some institutions. For example, while the Environmental Management Agency has the legal obligation to monitor both underground and surface water, in practice ZINWA monitors underground water while EMA deals with surface water. Under this arrangement, ZINWA has to provide water quality data to EMA which may not be done timeously. In some cases there are no defined limits for each body and a lot of functional overlaps occur. Since each body manages the implementation of a different Act, there is need for harmonization of functions of each body in implementing water-related programmes to improve synergy. The recent promulgation of a single government ministry to oversee the environment, water and climate may be one such step towards harmonization (see "Discussion" under *Institutional arrangements*).

5.2.3. Do adequate technical skills exist within institutions to ensure efficient water quality management?

Institutions responsible for water quality management do not have adequately trained staff. The lack of adequate staff complement negatively affects the ability of the institutions to effectively carry out their mandate; yet human capital is a requisite skill to perform the water quality management operations. In this regard, the Consultant must implement a programme to promote new, and modern technical skills amongst the staff at the water management institutions. Areas that need attention include laboratory testing, field monitoring, biological monitoring, and the application of remote sensing and GIS tools to Water Quality management. This dire need must also devolve to the tertiary institutions where the requisite manpower is trained and ensure adequate resources are mobilized to produce this critical mass.

5.2.4. Are the technological resources (e.g. laboratories, geodatabases) and capacities adequate?

Traditional regular water quality monitoring systems comprising a dense network of ground-based monitoring stations and well-equipped laboratories are expensive and inefficient. Remote sensing offers relatively cheaper, repetitive and quantitative method for assessing and monitoring water quality (Lavery et al. 1993). There are several airborne optical and thermal sensors on satellites providing both spatial and temporal data needed for managing water. Zimbabwe can utilise remote sensing datasets such as Landsat and MODIS imagery which can be downloaded free of charge from the internet to monitor changes in water quality parameters and develop management practices to improve water quality. These datasets provide repeated measurements covering a large synoptic view of the earth making them suitable for national water quality monitoring.

To convert remotely sensed data into useful information specialised GIS software, hardware and skills are needed. It is this technical capacity that is currently lacking in organisations that are responsible for water quality monitoring and assessment in Zimbabwe. To address this problem in Phase 2, training is needed for EMA and ZINWA staff on how remotely sensed data, global positioning system (GPS), and GIS technologies can be integrated with in situ data to yield a valuable tool for monitoring and assessing water quality at different spatial and temporal scales across Zimbabwe.

5.2.5. Is data on water quality being collected based on clear water quality monitoring objectives? Is it adequate and of the right quality? Are there databases where data is stored and made accessible?

At present water quality monitoring objectives are fragmented and in general not clear why at times the data has to be collected. Typically this has led to the collapse of the extensive ground monitoring system initially established by ZINWA, as data collection must always be guide by clear management objectives. Data on water quality have not been collected consistently at least over the last 10 years. Numerous gaps exist, and the purposes for which they are collected are not clearly defined. There is no uniformity in the way data are collected making it difficult to assess for trends and other information. This implies that monitoring may not really be taking place. Water quality data are collected that are not adequate and methods of analysis produced some questionable data. There is need for a functional data collection system that also makes use of the newly developed remote sensing tools to ensure timely data collection. Phase 2 must develop and implement quality assurance/quality control (QA/QC) mechanisms to ensure that water quality data meet international standards. This will certainly require an investment in modern equipment and adequate capitalization of laboratory facilities. The establishment of a data management system is also imperative which will include databases with adequate backups. These will be key components to the development of an efficient water quality management system for Zimbabwe that can provide information for management decisions.

5.2.6. Are there sustainable financing mechanisms for a water quality management programme?

The Zimbabwean economy is still in a recovery phase after a period of hyperinflation. This has resulted in serious constraints on the ability of the Government fund programmes. Programmes such as water quality monitoring and management, are normally the first to lose funding especially when data collection objectives have not been well defined. This was very apparent from the lack of adequate water quality monitoring data from the institutions. Therefore, the issue of funding of a water quality monitoring and management programme is of critical importance. The Consultant must work with the Institutions to identify mechanisms of funding such a programme to ensure its sustainability in the future. Potential sources of revenue need to be identified, and thoroughly analysed with the assistance of the Consultant. This exercise can draw lessons from what other countries such as South Africa have done when funding water quality monitoring programmes.

5.3. Terms of Reference (TORs) for Phase 2

Given the issues raised in the Discussion, Zimbabwe will have to reconsider its approach to water quality monitoring focusing on what is relevant to the local context and also international best practices. Overall, there is need to change the entire data paradigm which was based on traditional approaches, to one with a clear rationale and is linked to the data needs of stakeholders all placed in the national socioeconomic context (Ongley, 1994). Based on our work in Phase 1, we propose that the consultant focus on the following work for Phase 2:

1. Develop or redesign both a long-term water quality monitoring and a short-term regulatory assessment framework for Zimbabwe's waters taking into account international best practices, but with clear and well defined objectives. The following must be taken into consideration:
   - Define water quality monitoring objectives for all statutory bodies with water quality monitoring functions, recognising the importance of point and non-point pollution sources.
   - In line with the objectives, identify sampling sites, appropriate parameters, and frequency of sampling. This can include the use physicochemical, biological monitoring protocols and GIS tools.
   - Train technicians and WQ managers at EMA and ZINWA in sampling procedures, methods, laboratory analysis and quality control. A comprehensive field and laboratory water quality sampling and assessment procedures manual/protocol for Zimbabwe must be produced.
   - Establish a data management unit that will be the custodian of all data collected in the field and laboratory. There is need to train and capacitate a unit on information

collection, data management and processing by responsible authorities (EMA and ZINWA).

2. Develop a capacity building programme (Nationals Strategic Training Programme) for providing adequate technical skills in water quality monitoring including laboratory testing, field monitoring, biological monitoring and their integration with remote sensing and GIS tools. The aim is to create a core group of professionals in order to sustain future monitoring programmes in line with the country's needs. Collaboration with university/polytechnic colleges in developing relevant curricular and research programmes will also ensure a consistent production of critical human capacity.
3. Conduct a review of different financing mechanisms for water quality monitoring management with an intention to identify a sustainable financing mechanism, especially the role of other stakeholders such as the private sector.
4. Evaluate the current water management-related legislative and policy framework for Zimbabwe to minimise duplication and conflicts among different agencies.
5. Review water quality standards for potable and effluent water and recommend possible approaches to developing unified, relevant and practical standards for point and non-point source pollution. Focus should also be on the reduction and simplification of parameters.
6. Set up quality assurance/quality control mechanisms for laboratory proficiency, calibration of equipment and standardisation of methods.

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Appendix A: Scores used to calculate groundwater vulnerability in Zimbabwe

Aquifer Vulnerability	ranking																**Relevance**	**ORDER**	ORDER
Geology type	granite/ gneiss	Bulawayan metavolcanics	Mashonaland dolerite	Great Dyke	Lomagundi dolomite	Deweras	Karoo esc. Grit & sandstone	Karoo mudstone	Kalahari sand	Batoka basalt	Cretaceous sandstones	Alluvial deposits	Umkondo formation	Sijarira	Shamvian	Tengwe Calcareous seds	conductivity		
vulnerability score	0.7	0.6	0.5	0.5	0.8	0.7	0.7	0.1	1	0.3	0.7	0.8	0.4	0.2	0.6	0.7	depth to water	4	3
Soil group	Arenosols (unconsolidated sands)	Luvisols (granite gneiss)	Litholsols (Karoo sandstone / Lomagundi)	Ferralsols (Umkondo / BIF Greenstone)	Nitosols (Great Dyke, Greenstone)	Cambisols (Karoo basalt)	Vertisols (Basalt)	Fluvisols (Alluvial)									vadose zone conductivity		
vulnerability score	1	0.8	0.6	0.6	0.4	0.1	0.1	0.5									degree of confinement	3	2

Aquifer Vulnerability	ranking																**Relevance**	**ORDER**	ORDER
Topographic wetness index (TWI) classes	Max TWI	2 TWI	3 TWI	4 TWI	Min TWI													
vulnerability score	0.9	0.72	0.54	0.36	0.18												depth to gw		
Rainfall	>1000 mm/yr	800-1000	600 - 800	400 - 600	<400												recharge		
vulnerability score	1	0.8	0.5	0.3	0.1												depth to gw	1	1
type / ranking																			
recharge rate																			

Aquifer Vulnerability	ranking																Relevance	ORDER	ORDER
Vegetation type	woodland	forest	savannah woodland	tree / shrub savannah	grassland												runoff / recharge		
vulnerability score	1	0.8	0.7	0.4	0.6												depth to gw	5	5
recharge																			
depth to GW																			
Land classification	Forest / Park / Safari / Sanctuary	Commercial Farmland	Communal Area	Small scale commercial / Resettlement	Urban												run-off/ recharge		
vulnerability score	1	0.8	0.4	0.6	0.1													6	6

Appendix B: Comparison of chemical parameters of surface water sampled in the seven major catchments of Zimbabwe to World Health Organisation Guidelines (WHO) for drinking water. Values highlighted in red exceed WHO limits.

Catchment	DATE	Sample	SITE CODE	River	longitude	latitude	Chloride (mg/l)	Sulphate (mg/l)	Nitrate (mg/l)	Ammonia_ (mg/l)	Fe (ppm)	Ni (ppm)
Gwayi	16/5/2013	5	AL 1	Upper Umguza	28.57	-20.06	7.1	136.9	0.024	0.103	N/D	N/D
Gwayi	16/5/2013	6	AL 2	Lower Umguza	28.53	-20.02	92.2	168.7	0.015	0.052	N/D	N/D
Mzingwane	16/5/2013	13	BR 22	Mtshabezi R	28.99	-20.95	7.1	50.0	0.002	0.012	N/D	N/D
Mzingwane	16/5/2013	15	EL 6	Impali	29.93	-19.67	7.1	15.2	0.001	0.011	N/D	N/D
Manyame	23/4/2013	6	CR 23 A	Mukuvisi River before Manyame confluence	30.90	-17.95	63.8	122.7	0.043	0.109	N/D	0.12
Manyame	23/4/2013	7	CR 23 AD	Mukuvisi/Manyame Rivers confluence	30.90	-17.95	49.6	130.0	0.004	0.109	N/D	0.09
Manyame	23/4/2013	9	CR 47	Mukuvisi River, Glen Norah	30.97	-17.91	63.8	150.6	0.102	0.100	N/D	0.05
Manyame	23/4/2013	11	CR 51	Crowborough Sewage Work	30.91	-17.86	63.9	197.9	0.090	0.096	N/D	0.12
Manyame	23/4/2013	17	CR 59A	Manyame River @ gauging weir below Harava dam	31.10	-17.99	0.4	27.7	0.042	0.022	N/D	N/D
Manyame	23/4/2013	12	DR 18 A	Manyame River, Chinhoyi bridge	30.22	-17.35	56.7	52.6	0.043	0.015	N/D	0.05
Manyame	23/4/2013	15	DR 33 A	Manyame River @ Mushumbi Pools	30.55	-16.17	44.6	29.0	0.160	0.019	N/D	N/D
Manyame	23/4/2013	13	FSTP	Firle Sewage Treatment Plant	30.93	-17.94	63.8	175.6	0.083	0.104	N/D	0.18
Manyame	23/4/2013	14	NSW	Norton Sewage Works, near L. Manyame	30.68	-17.87	141.8	272.3	0.016	0.078	N/D	0.04
Mazowe	23/4/2013	5	YJ	Yellow jacket River	31.04	-17.26	2659.5	717.2	0.028	0.019	89.90	N/D
Mazowe	23/4/2013	10	DL 1	Mazowe River, below dam	31.03	-17.25	14.2	59.1	0.002	0.020	N/D	N/D
Mazowe	23/4/2013	9	DL 2	Mwenje dam	30.99	-17.51	21.3	25.1	0.013	0.018	N/D	N/D
Mazowe	23/4/2013	15	DL 40	Downstream Mupfure dam	31.60	-16.77	7.1	9.6	0.027	0.015	N/D	0.03

Catchment	DATE	Sample	SITE CODE	River	longitude	latitude	Chloride (mg/l)	Sulphate (mg/l)	Nitrate (mg/l)	Ammonia_ (mg/l)	Fe (ppm)	Ni (ppm)
Mazowe	23/4/2013	3	DL 41 A	Mupfurudze River	31.42	-17.08	21.3	7.5	0.019	0.011	N/D	N/D
Mazowe	23/4/2013	7	DR 10		30.92	-17.36	21.3	48.7	0.013	0.016	N/D	0.10
Mazowe	23/4/2013	1	DR 12	Mazowe River, Freda Rebecca Mine T/off	31.28	-17.25	28.4	35.9	0.175	0.120	N/D	N/D
Mazowe	23/4/2013	8	DR 22		30.97	-17.24	28.4	13.1	0.236	0.011	N/D	N/D
Mazowe	23/4/2013	4	DR 31A	Fuse River	31.43	-16.78	35.5	17.8	0.009	0.011	N/D	0.03
Mazowe	23/4/2013	14	DR 32A	Mutwa River	31.41	-16.67	14.2	3.6	0.005	0.011	N/D	N/D
Mazowe	23/4/2013	16	DR 34	Mupfure River	31.59	-16.78	28.4	17.8	0.013	0.012	N/D	N/D
Mazowe	23/4/2013	12	DR 37	Mazowe River, Nyamapanda	32.76	-16.71	14.2	19.1	0.001	0.013	N/D	N/D
Mazowe	23/4/2013	2	DR 42A	Mazowe River, downstream Shamva bridge	31.73	-17.22	42.6	27.7	0.002	0.011	N/D	0.01
Mazowe	23/4/2013	13	DR29A	Ruya River	31.55	-16.72	35.5	44.4	0.019	0.012	N/D	N/D
Mazowe	23/4/2013	11	DR30	Sundu stream, flowing from Mwenje dam	31.08	-17.30	21.3	98.2	0.041	0.021	N/D	0.10
Runde	14/5/2013	5	EL 7A	Lake Mutirikwi	32.64	-19.88	7.1	23.4	0.024	0.011	0.10	N/D
Runde	13/5/2013	10	ER 118C	Mtshingane River	29.89	-20.42	7.1	24.2	0.007	0.014	0.11	N/D
Runde	13/5/2013	1	ER 1A	Mucheke River	30.80	-20.07	70.9	15.2	0.054	0.010	0.45	N/D
Runde	14/5/2013	8	ER 30A	Tokwe River	30.69	-20.39	14.2	0.0	0.009	0.010	0.55	N/D
Runde	13/5/2013	3	ER 3A	Shagashe River	30.84	-20.09	21.3	16.9	0.007	0.011	N/D	N/D
Sanyati	3/5/2013	3	CR 181 A	Biri River Musengezi	30.15	-17.97	7.1	35.4	0.003	0.023	N/D	N/D
Sanyati	3/5/2013	2	CR 43	Sebakwe Tributary flowing from Kwekwe town	29.84	-18.89	35.5	177.7	0.026	0.107	N/D	0.01
Sanyati	3/5/2013	4	CR 63 A	Sebakwe River below sewage works	29.83	-18.86	28.4	72.4	0.122	0.099	N/D	N/D
Sanyati	3/5/2013	6	CR 66A	Kwekwe River @ Redcliff	29.74	-19.01	35.5	101.2	0.025	0.105	N/D	N/D

Catchment	DATE	Sample	SITE CODE	River	longitude	latitude	Chloride (mg/l)	Sulphate (mg/l)	Nitrate (mg/l)	Ammonia_ (mg/l)	Fe (ppm)	Ni (ppm)
Sanyati	3/5/2013	5	CR 7	Munyati River @ Power station	31.10	-17.99	14.2	69.0	0.006	0.015	N/D	N/D
Save	5/4/2013	10	CHIPIN	Chipinge ponds downstream	32.63	-20.19	21.3	11.8	0.204	0.012	0.68	N/D
Save	5/4/2013	1	DTZ 1	Haruni River (DTZ Mine)	32.97	-19.78	7.1	112.8	0.003	0.014	0.53	N/D
Save	5/4/2013	7	EL 2	Rusape dam	32.08	-18.58	21.3	144.2	0.032	0.027	1.39	N/D
Save	5/4/2013	8	EPR 106	Nyamhingura River flowing into Pungwe	32.94	-18.37	7.1	74.5	0.041	0.025	1.50	N/D
Save	5/4/2013	2	ER 13	Dafi River	32.52	-19.08	14.2	48.3	0.007	0.015	1.67	N/D
Save	5/4/2013	3	ER 13 A	Sakubva River (Replaces ER 12)	32.62	-18.99	35.5	30.3	0.003	0.106	2.30	N/D
Save	5/4/2013	4	ER 49 A	Rusape River	32.13	-18.51	7.1	19.9	0.005	0.014	0.94	N/D
Save	5/4/2013	5	ER 56 A	Tributary to Haruni river	32.93	-19.79	7.1	12.6	0.034	0.015	0.37	N/D
Save	5/4/2013	6	ER 86 A	Dora River	32.53	-19.08	63.8	49.2	0.165	0.103	0.99	N/D
Manyame	23/4/2013	4	CWTW	Chitungwiza Sewage T. P., downstream	31.05	-18.03	56.7	104.2	0.002	0.103	N/D	0.13

N/D stands for not detected. Also note chromium, lead, cadmium, zinc, copper and cobalt were not detected in surface water samples based on the analytical methods used collected. A total of 49 samples out of 64 identified as hotspots by EMA and ZINWA were analysed between 5 March 2013 and 23 April 2013.

Appendix C: List of sampled groundwater hotspots suggested by ZINWA. The samples assessed the potential impact of human settlements (i.e., high density residential areas), solid waste disposal, commercial agriculture, industry and mining on groundwater quality in Manyame, Mazowe and Sanyati catchments.

Date	sample	longitude	latitude	catchment	ZINWA hotspot	description
06/06/2013	6	31.15768	-17.88614	Manyame	GW quality in high density suburbs	Epworth, Harare - 20m deep dug well
06/06/2013	7	31.19166	-17.83487	Manyame	GW quality in high density suburbs	Mabvuku Tafara public BH - heavily used
07/06/2013	12	30.93512	-17.89115	Manyame	GW quality in high density suburbs	Budiriro - Public BH with bush pump
23/07/2013	21	29.88788	-18.34519	Sanyati	GW quality in high density suburbs	Rimuka Borehole
09/06/2013	13	31.04786	-17.45521	Manyame	Harare GW - private pumping	Pvt low density Home BH
09/06/2013	14	31.08787	-17.46805	Mazowe	Harare GW - private pumping	Smallholder Irrigation BH 2.5 l/s
07/02/2013	1	31.07070	-17.73770	Manyame	Solid Waste Disposal	Brick factory at Pomona
06/06/2013	10	30.98084	-17.81217	Manyame	Solid Waste Disposal	Golden Quarry Solid Waste Dump
07/07/2013	11	30.97767	-17.81879	Manyame	Solid Waste Disposal	Westlea suburb next to Golden Quarry
04/06/2013	2	28.72732	-17.95023	Sanyati	Geogenic groundwater	Gokwe Artesian Water
04/06/2013	4	27.29923	-18.47055	Gwayi	Geogenic groundwater	Hot springs
23/07/2013	20	29.86325	-18.38019	Sanyati	Geogenic groundwater	Ingezi Well shallow GW
04/06/2013	3	29.76990	-18.84106	Sanyati	Agriculture impact	Agriculture - Cotton
06/06/2013	5	30.16653	-17.35154	Manyame	Agriculture impact	Lomagundi dolomite - commerical farming

Date	sample	longitude	latitude	catchment	ZINWA hotspot	description
06/06/2013	8	31.30215	-17.90551	Mazowe	Agriculture impact	Tobacco Goromonzi / Marondera
06/06/2013	9	31.41465	-17.78570	Mazowe	Agriculture impact	Goromonzi dairy
14/06/2013	15	30.97123	-17.88226	Manyame	Industry	Imponente leather
14/06/2013	16	31.12321	-17.85280	Manyame	Industry	Zimphos chemicals
14/06/2013	17	31.12945	-17.86546	Manyame	Industry	Zimphos chemicals
23/07/2013	18	29.93671	-18.45007	Sanyati	Mining	Tix Mine. GW sample replenished with surface water
23/07/2013	19	29.81148	-18.47430	Sanyati	Mining	Kanyemba Mine: water from mine shaft
23/07/2013	22	29.79515	-18.22564	Sanyati	Mining	Golden Valley Mine- underground water

N.B: GW stands for groundwater

Appendix D: Comparison of physical parameters of groundwater sampled in Mazowe, Manyame and Sanyati catchments to World Health Organisation Guidelines (WHO) for drinking water. Values highlighted in red exceed WHO limits.

Date	sample	longitude	latitude	Catchment	Zinwa Hotspot	Description	pH	Turbidity (NTU)	TDS (mg/l)
06/06/2013	6	31.16	-17.89	Manyame	GW quality in high density suburbs	Epworth, Harare - 20m deep dug well	5.1	30	173
06/06/2013	7	31.19	-17.83	Manyame	GW quality in high density suburbs	Mabvuku Tafara public BH - heavily used	5.2	3	112
07/06/2013	12	30.94	-17.89	Manyame	GW quality in high density suburbs	Budiriro - Public BH with bush pump	7.5	1	286
23/07/2013	21	29.89	-18.35	Sanyati	GW quality in high density suburbs	Rimuka Borehole	7.5	2	366
09/06/2013	13	31.05	-17.46	Manyame	Harare GW - private pumping	Pvt low density Home BH	6.8	0	128
09/06/2013	14	31.09	-17.47	Mazowe	Harare GW - private pumping	Smallholder Irrigation BH 2.5 l/s	6.8	0	101
07/02/2013	**1**	31.07	-17.74	Manyame	Solid Waste Disposal	Brick factory at POMONA	7.0	3	132
06/06/2013	10	30.98	-17.81	Manyame	Solid Waste Disposal	Golden Quarry Solid Waste Dump	7.0	6	272
07/07/2013	11	30.98	-17.82	Manyame	Solid Waste Disposal	Westlea suburb next to Golden Quarry	6.7	22	140
04/06/2013	2	28.73	-17.95	Sanyati	Geogenic groundwater	Gokwe Artesian Water	8.5	15	573
04/06/2013	4	27.30	-18.47	Gwayi	Geogenic groundwater	Hot springs	8.2	17	651
23/07/2013	20	29.86	-18.38	Sanyati	Geogenic groundwater	Ingezi Well shallow GW	7.5	5	414
04/06/2013	3	29.77	-18.84	Sanyati	Agriculture impact	Agriculture - Cotton	8.4	16	553
06/06/2013	5	30.17	-17.35	Manyame	Agriculture impact	Lomagundi dolomite - commerical farming	7.4	8	363
06/06/2013	8	31.30	-17.91	Mazowe	Agriculture impact	Tobacco Goromonzi / Marondera	5.2	1	55
06/06/2013	9	31.41	-17.79	Mazowe	Agriculture impact	Goromonzi dairy	6.5	6	225
14/06/2013	15	30.97	-17.88	Manyame	Industry	Imponente leather	6.6	8	1,089
14/06/2013	16	31.12	-17.85	Manyame	Industry	Zimphos chemicals	3.2	190	3,816
14/06/2013	17	31.13	-17.87	Manyame	Industry	Zimphos chemicals	4.3	253	3,572

Date	sample	longitude	latitude	Catchment	Zinwa Hotspot	Description	pH	Turbidity (NTU)	TDS (mg/l)
23/07/2013	18	29.94	-18.45	Sanyati	Mining	Tix Mine. Gw sample replenished with surface water	7.8	4	196
23/07/2013	19	29.81	-18.47	Sanyati	Mining	Kanyemba Mine: water from mine shaft	8.1	9	946
23/07/2013	22	29.80	-18.23	Sanyati	Mining	Golden Valley Mine- underground water	8.3	23	571
					WHO guidelines for drinking water		6.5-8.5	5	1,000

Appendix E: Comparison of chemical parameters of groundwater sampled in Mazowe, Manyame and Sanyati catchments to World Health Organisation Guidelines (WHO) for drinking water. Values highlighted in red exceed WHO limits. (Manyame = MN; Sanyati = ST; Gwayi = GW; Mazowe = MZ)

Date	Sample	longitude	latitude	Catchment	ZINWA Hotspot	Description	Chloride (mg/l)	Nitrate (mg/l)	TN (mg/l)	Ammonia	Sulphate (mg/l)	Mg (ppm)	Ca (ppm)	Na (ppm)	Fe (ppm)
06/06/2013	6	31.16	-17.89	Manyame	GW quality in high density suburbs	Epworth, Harare - 20m deep dug well	63.85	0.25	15.55	0.012	7.48	7.50	13.54	27.73	0.21
06/06/2013	7	31.19	-17.83	Manyame	GW quality in high density suburbs	Mabvuku Tafara public BH - heavily used	56.75	0.25	30.41	0.013	3.18	4.07	8.38	22.41	0.20
07/06/2013	12	30.94	-17.89	Manyame	GW quality in high density suburbs	Budiriro - Public BH with bush pump	56.75	0.25	7.48	0.014	135.16	14.76	36.80	14.98	0.36
23/07/2013	21	29.89	-18.35	Sanyati	GW quality in high density suburbs	Rimuka Borehole	120.60	0.13	0.15	0.016	75.54	25.58	31.01	32.52	N/D
09/06/2013	13	31.05	-17.46	Manyame	Harare GW - private pumping	Pvt low density Home BH	28.38	0.24	7.06	0.034	61.24	10.60	18.44	7.70	N/D
09/06/2013	14	31.09	-17.47	Mazowe	Harare GW - private pumping	Smallholder Irrigation BH 2.5 l/s	14.19	0.25	6.82	0.068	36.71	10.00	21.62	4.87	N/D
07/02/2013	**1**	31.07	-17.74	Manyame	Solid Waste Disposal	Brick factory at POMONA	14.18	0.26	0.63	0.052	52.62	14.14	13.09	11.75	N/D
06/06/2013	10	30.98	-17.81	Manyame	Solid Waste Disposal	Golden Quarry Solid Waste Dump	49.66	0.16	4.51	0.013	51.33	9.85	40.72	28.04	N/D
07/07/2013	11	30.98	-17.82	Manyame	Solid Waste Disposal	Westlea suburb next to Golden	28.38	0.1	4.21	0.02	89.59	8.58	14.54	22.20	0.7

Date	Sample	longitude	latitude	Catchment	ZINWA Hotspot	Description	Chloride (mg/l)	Nitrate (mg/l)	TN (mg/l)	Ammonia	Sulphate (mg/l)	Mg (ppm)	Ca (ppm)	Na (ppm)	Fe (ppm)
						Quarry		8		8					0
04/06/2013	2	28.73	-17.95	Sanyati	Geogenic groundwater	Gokwe Artesian Water	42.55	0.01	0.08	0.023	191.90	1.08	0.00	220.01	N/D
04/06/2013	4	27.30	-18.47	Gwayi	Geogenic groundwater	Hot springs	341.51	0.01	0.11	0.018	460.16	3.02	34.26	398.75	N/D
23/07/2013	20	29.86	-18.38	Sanyati	Geogenic groundwater	Ingezi Well shallow GW	78.03	0.03	0.23	0.025	95.61	26.24	44.39	35.35	N/D
04/06/2013	3	29.77	-18.84	Sanyati	Agriculture impact	Agriculture - Cotton	42.55	0.02	0.09	0.018	183.74	2.09	0.84	68.50	N/D
06/06/2013	5	30.17	-17.35	Manyame	Agriculture impact	Lomagundi dolomite - commercial farming	49.66	0.25	14.70	0.013	61.21	14.80	40.79	37.93	0.41
06/06/2013	8	31.30	-17.91	Mazowe	Agriculture impact	Tobacco Goromonzi / Marondera	14.19	0.27	20.89	0.013	39.29	2.59	4.41	7.77	N/D
06/06/2013	9	31.41	-17.79	Mazowe	Agriculture impact	Goromonzi dairy	35.47	0.25	25.19	0.012	58.21	13.65	26.25	6.35	0.05
14/06/2013	15	30.97	-17.88	Manyame	Industry	Imponente leather	482.39	0.00	24.01	0.016	139.31				
14/06/2013	16	31.12	-17.85	Manyame	Industry	Zimphos chemicals	106.41	0.02	18.96	0.061	353.55				
14/06/2013	17	31.13	-17.87	Manyame	Industry	Zimphos chemicals	177.35	0.01	9.19	0.033	312.71				

Date	Sample	longitude	latitude	Catchment	ZINWA Hotspot	Description	Chloride (mg/l)	Nitrate (mg/l)	TN (mg/l)	Ammonia	Sulphate (mg/l)	Mg (ppm)	Ca (ppm)	Na (ppm)	Fe (ppm)
23/07/2013	18	29.94	-18.45	Sanyati	Mining	Tix Mine. Gw sample replenished with surface water	35.47	0.01	0.74	0.018	90.88	19.34	21.38	25.80	N/D
23/07/2013	19	29.81	-18.47	Sanyati	Mining	Kanyemba Mine: water from mine shaft	56.75	0.02	0.25	0.018	654.48	31.83	110.69	40.78	N/D
23/07/2013	22	29.80	-18.23	Sanyati	Mining	Golden Valley Mine-underground water	56.75	0.26	2.44		500.14	27.61	64.75	35.20	N/D
					WHO guidelines		250.0	50.0	50.0	0.50	250.0	30.0	75.0	200	0.20

N.B.: GW stands for groundwater.

Appendix F: Comparison of chemical parameters of groundwater sampled in Mazowe, Manyame and Sanyati catchments to Zimbabwe Effluent Standards for discharge. Values highlighted in blue, green, yellow and red are within the blue, green, yellow and red limits, respectively.

Date	sample	longitude	latitude	Catchment	ZINWA Hotspot	Description	Conductivity (µS/cm)	pH	Suspended Solids (mg/l)	TDS (mg/l)
14/06/2013	15	30.97	-17.882	Manyame	Industry	Imponente leather	1,651	6.6	2	1,089
14/06/2013	16	31.12	-17.853	Manyame	Industry	ZimPhos chemicals	5,620	3.19	113	3,816
14/06/2013	17	31.13	-17.865	Manyame	Industry	ZimPhos chemicals	6,800	4.32	173	3,572
23/07/2013	18	29.94	-18.45	Sanyati	Mining	Tix Mine	332	7.76	3	196
23/07/2013	19	29.81	-18.474	Sanyati	Mining	Kanyemba Mine: water from mine shaft	1,604	8.06	7	946
23/07/2013	22	29.80	-18.226	Sanyati	Mining	Golden Valley Mine- underground water	968	8.33	15	571

Appendix G: List of Participants for the Water Quality Launch Workshop on the 17th of December 2012

Water Quality Strategy Launch Workshop
December 17, 2012: Holiday Inn, Harare

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Water Quality Strategy Launch Workshop
December 17, 2012: Holiday Inn, Harare

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