Manyame Catchment: A Risk Assessment

MDP | Zimbabwe

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Preface

R. van Dijk, F. van 't Klooster, J. Mc Gregor, L. Schuurman, I. Streefkerk
Harare, February 2019

We would like to express our sincere gratitude to the organisations and institutions that have provided their support and critics towards the accomplishment of this project. The lecturers and professors in the Civil Engineering Department of the University of Zimbabwe, VEI, the Royal Embassy of the Netherlands in Harare and the TU Delft. We are humbled by their assistance and pivotal roles which contributed to the success of this report.

Many thanks to our supervisors, Ir. Wim Luxemburg and Prof. Dr. Ir. Jules van Lier, for their academic support which has been helpful in both shaping and developing this work.

Abstract

This study investigates the many dynamics of the Manyame Catchment and comes up with recommendations on how to adapt or become more resilient to the risks at hand. The bad politics and forthcoming economic situation of Zimbabwe has led to instability and dramatic inflation over the last decade. This has resulted in a terrible investment climate, limited aid received from foreign countries and an outflow of educated population. Exploitation of water resources by industries, mines and urban centres located close to the rivers resulted in a decline in the quality and quantity of the environment [101]. Especially the Manyame River Catchment, that supplies the capital Harare and flows north into the Zambezi, has been greatly affected. The catchment suffers from several pollution sources such as agriculture, mining, industrial dumps and wastewater inflow. Poor management and the deterioration of the drinking water supply and sanitation infrastructure has led to the recent outbreak of cholera. Although the Manyame Catchment has enough water, another main issue is the spatial distribution of its water resources. In some areas there are dams, but no farmers to utilize the water. In other areas farmers are desperate for water, but don't receive any. The increasing dry spells due to climatic changes, has had disastrous effects for the non-irrigating smallholder farmers dependent on their maize production for survival, while floods created by the backwater curve from the Cahora Bassa Dam in the Lower Manyame sub-catchment have washed away the livestock, crops and infrastructure on the fertile areas in the flood plains. The situation stresses for better awareness, monitoring and guardance of the water resources. This will provide information for improvements in the planning, policy and management of water resources. Although the history of Zimbabwean governance would suggest it is purely acting on crisis management, proactive planning would be preferable to the alternative; to wait for the aquifers to dry up only for people to realize the real value of water.

Key words: Zimbabwe, water resources, Manyame Catchment, flooding, drought, water quality, groundwater, GIS, dam management

Abbreviations

AMSL	Above Mean Sea Level
ASIS	Agricultural Stress Index System
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
DEM	Digital Elevation Model
DO	Dissolved Oxygen
EC	Electrical Conductivity
EMA	Environmental Management Agency
EM-DAT	Emergency Events Database
GIS	Geographic Information Systems
GW	Groundwater
HSG	Hyrological Soil Group
LMCC	Lower Manyame Catchment Council
LMSC	Lower Manyame Sub-Catchment
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
MMCC	Middle Manyame Catchment Council
MMSC	Middle Manyame Sub-Catchment
MoU	Memorandum of Understanding
NDVI	Normalised Difference Vegetation Index
NGO	Non-Governmental Organisation
NTU	Nephlometric Turbidity Units
PET	Potential Evapotranspiration
RVE	Relative Volume Error
SCS	Soil Conservation Service
TCI	Temperature Condition Index
TDS	Total Dissolved Solids
TIR	Thermal Infrared
UMSC	Upper Manyame Sub-Catchment
UZ	University of Zimbabwe
VCI	Vegetation Condition Index
VHI	Vegetation Health Index
WWTP	Waste Water Treatment Plant
ZINWA	Zimbabwe National Water Authority

Contents

1

Introduction

“Water is life” is a principal that many scientists have written and discussed about. It’s the start of our origin, the driving system of our planet, and the most important reason we can survive. The spatial distribution and quality of our water sources however, have a strong influence on whether we can use it to our advantage. Especially in many regions in Southern Africa, rain is highly variable and with growing population in the region, the pressure to produce the necessary food has never been greater. This coincides with an increase in water demand and part of the increase will have to be accomplished under increasing water scarcity. The way water management is governed can therefore have an enormous impact on people’s lives and a regions agricultural productivity, welfare and food security.

This research project is a manifestation of the long academic cooperation between the Water Resource departments of the Technical University of Delft and the University of Zimbabwe. The universities have cooperated in academic papers and the hosting of PhD students, but cooperation between MSc Water Management students has never been realized. This research project is the first initiative, after a newly signed MoU between the two universities, in which a group of MSc students have been able to collaborate on a project in Zimbabwe.

Over the last decades, Zimbabwe has suffered from recurrent water problems in the form of droughts, floods and water quality. Especially the Manyame River Catchment hosting the capital of the country, Harare, experiences many challenges in all the respective sub-catchments. Polluted water resources that have to be cleaned by under capacitated drinking- and wastewater treatment plants and distributed by deteriorated water sanitation infrastructure threatens the safe water supply to the major cities in the catchment. Floods and droughts in the middle and lower sections of the catchment spark contradictory behavior to move to water bodies or not. The water problems have manifested themselves in terms of both time and spatial distribution patterns, and hence management of water resources is a fundamental undertaking in order to minimize risks and vulnerabilities that exist throughout the Manyame Catchment.

1.1. Research Objective

This study researches the many dynamics of the Manyame Catchment in Zimbabwe to come up with recommendations on how to adapt or become more resilient to the risks at hand. This is done in cooperation with the University of Zimbabwe through a regional and local risk assessment for flooding, drought and water quality.

1.2. Research Question

In order to reach the objective mentioned above, the general research question is formulated as the following:

What are the current water resource problems at hand in the Manyame Catchment, Zimbabwe and what can be done to create more resilience to flooding, drought and water quality problematics?

1.3. Reader's Guide

This research report consists of a total of 8 chapters. The chapters are divided into two parts.

Part I includes an overall analysis of the research area and the hazards exposed to it. Chapter 2 explains the general characteristics of the Manyame Catchment. Chapter 4 elaborates on the hydrological model and its applications. Afterwards, in Chapter 5, the flood risks within the catchment are discussed. In Chapter 3 the spatial probability of a drought is determined for the entire Manyame Catchment. The water quality issues which are present along the river are assessed in Chapter 6. Chapter 7 includes various topics all related to the future water supply of Harare. It elaborates on the dam management and groundwater drought risk in the surroundings of Harare.

Part II focuses on two specific case study areas which are high in risk. In Chapter 8 Case Study 1, situated in the Middle Manyame Sub-Catchment, is presented. The case includes droughts, dam management and water quality as the main risks. The main topics of Case Study 2, presented in Chapter 9, are floods, droughts and dam management.

Chapter 10 concludes the research findings and gives recommendations on how future management of the water resources in the Manyame Catchment could be improved.

Overall Analysis

2

Research Area

The Manyame Catchment, one of the seven catchment areas in Zimbabwe, is situated in the north of the country (see Figure 1) and has a total catchment area of 40,497 km^2 [102]. Topographically, the Manyame Catchment slopes generally towards a northern direction as evidenced by the direction of the Manyame River, from which it earns its name. They Manyame flows into the Zambezi river basin, between the Kariba and Cahora Bassa Dam. The other two major rivers in the catchment are the Musengezi River to the east and the Angwa River to the west of the Manyame Catchment.

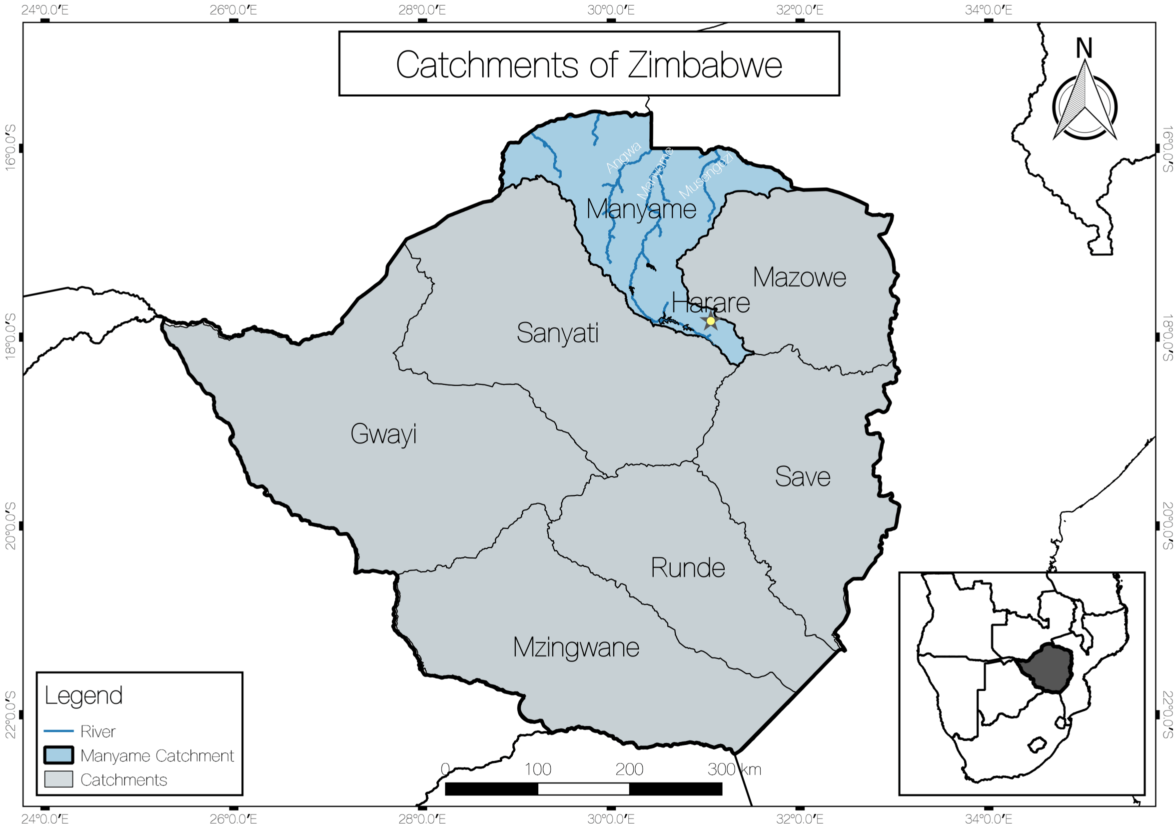


Figure 1: The seven catchments that constitute the Zimbabwean hydrological water management systems

The Manyame Catchment was chosen in consultation with the University of Zimbabwe (UZ), because it is a relatively well gauged catchment. This should enable a more realistic and in-depth analysis of apparent drought and flood issues. The gauging structures depending on the flows vary from notches, flumes to simple stage measurements. Some gauges have automatic data loggers whereas others are manually recorded [101]. However, some gauges have not been operational for some time or have significant data gaps.

The Manyame Catchment is also characterized by various hazards that can be taken into account in the risk assessment. These include natural hazards like drought and flood. Moreover, the Manyame Catchment suffers from several pollution sources such as agriculture, mining, industrial dumps and wastewater inflow and houses the capital of the country, Harare. Poor management of the drinking water supply and sanitation infrastructure has lead to the recent outbreak of cholera in the Upper Manyame sub-catchment.

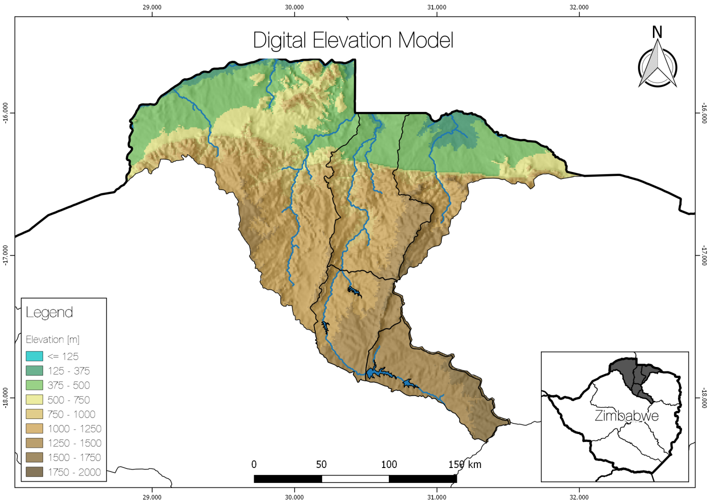


Figure 2: Digital Elevation Model for the Manyame Catchment

The Manyame Catchment has an elevation ranging from 300m in the Zambezi Valley to 1800m above mean sea level (AMSL) in the region of the capital of the country, Harare (see Figure 2) [101]. The southern Zambezi Escarpment can be found halfway the LMSC. In this section of the catchment it only takes a couple of kilometers for the elevation to fall from 800m to 300m (see Figure 2).

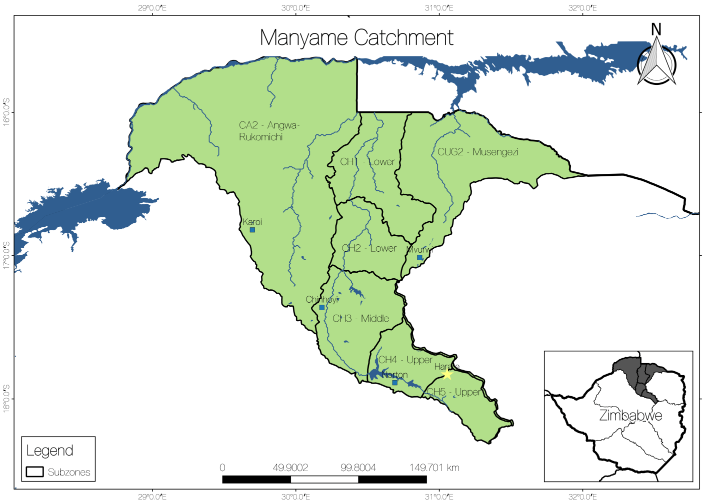
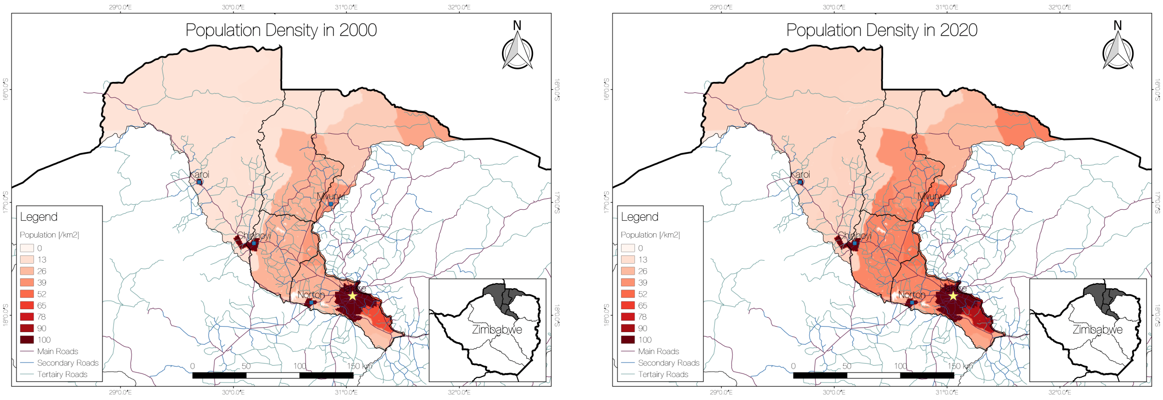


Figure 3: The five subzones of the Manyame Catchment

The Manyame Catchment is divided into 5 sub-catchments (see Figure 3), the Upper Manyame sub-catchment (UMSC), composed in subzones CH5 & CH4, the Middle Manyame sub-catchment (MMSC) CH3 subzone, the Angwa-Rukomichi‘s CA2 subzone, the Musengezi’s CUG2 subzone, and the Lower Manyame sub-catchment (LMSC) composed in CH2 & CH1. In this research we will only be considering the Upper, Middle and Lower Manyame sub-catchments. This means we are only following the Manyame River, which eventually drains into the Zambezi River.

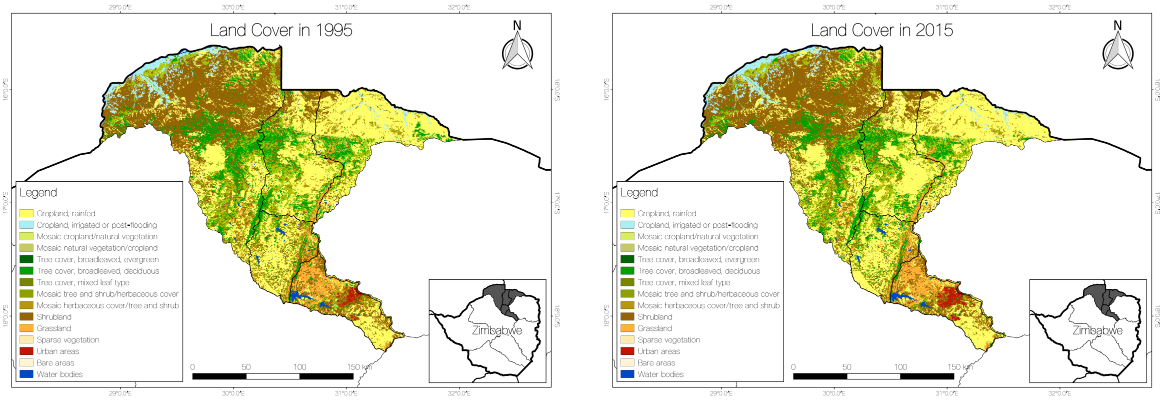
As can be seen from Figure 4, both the UMSC and MMSC have a high population density area around respectively Harare (the capital of Zimbabwe) and Chinhoyi. The LMSC does not have such big cities and is less densely populated, especially in the northern part. Looking at Figures 4a and 4b, the entire Manyame Catchment is experiencing rapid increase in population and urbanisation between 2000 and 2020. Harare, for example, experienced population growth from 310,000 people in 1961 to approximately 3 million in 2010 [87].



(a) 2000 (b) 2020

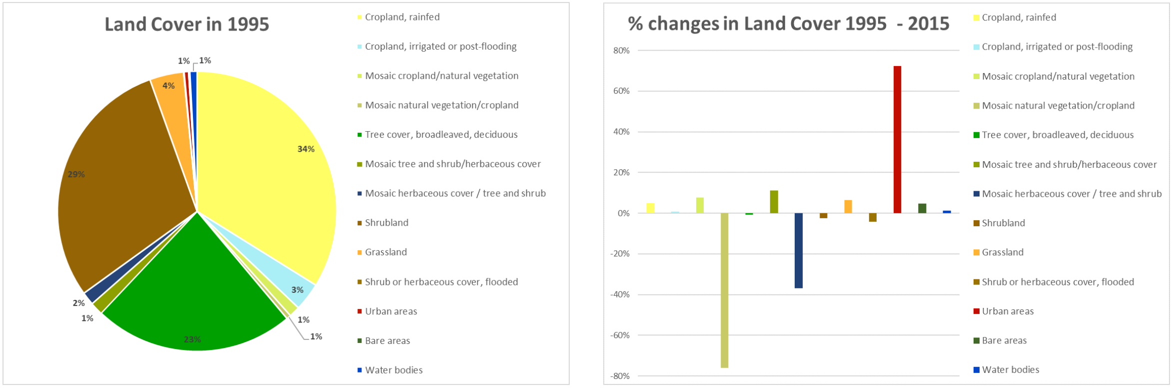
Figure 4: Population per km^2 for 2000 and projected for 2020

This can also be seen when looking at the land cover and land cover change in the catchment (see Figures 5 and 6). The figures shows a significant increase of roughly 70% increase in urban areas, mostly to the expense of shrub, vegetation, tree and cropland.



(a) 1995 (b) 2015

Figure 5: Land cover for 1995 and 2015 in the Manyame Catchment



(a) 1995 (b) 2015

Figure 6: Land cover change in percentage from 1995 till 2015 in the Manyame Catchment

In the part below a situational analysis will be presented for the respective Upper, Middle and Lower Manyame sub-catchments.

2.1. Situational Analysis Manyame Catchment

2.1.1. Upper Manyame Sub-Catchment

The UMSC area is the most urbanized area in Zimbabwe and harbours the country's capital city, Harare. It contains four major towns, namely Harare, Chitungwiza, Ruwa and Norton. To supply these cities from water two dams were build, which created two big lakes, being Lake Chivero and Lake Manyame. Harare, Chitungwiza and Ruwa are located directly upstream of both lakes, whereas Norton is located downstream of Lake Chivero and upstream of Lake Manyame. Besides these two big lakes, there are several rivers flowing through the UMSC. The most important ones are the Manyame River, Mukivisi River and Marimba River. The elevation in the UMSC ranges between 1321 to 1668 m AMSL. The area is 3,786 km^2, and mainly consists out of heavy textured clays to sandy clay loams. Most of the UMSC experiences very low erosion rates [62].

The most important socio-economic activities in the UMSC range from industrial manufacturing, engineering, farming, mining, recreation and tourism [101]. In the past decades, the four major towns have experienced rapid population growth, without matching growth of infrastructure and socio-economic activities [87]. This has negatively impacted the catchment's natural resources in the form of increased pressure on surface and groundwater aquifers and deteriorated water quality of surrounding lakes and rivers. Most pollution problems are due to partially treated sewage effluent and sewer overflows which are discharged into the river systems. Due to financial constrains the Waste Water Treatment Plant (WWTP) could not be expanded to cater for the population growth resulting in overloading of sewage treatment plants [101]. Especially in Harare, the sewerage systems are overloaded and the distribution systems are so old that sewage bursts and blockages are quite common [85]. Also industrial waste is discharged into the rivers on daily basis. During the rainy season, when surface runoff comes into play, non-point sources, such as urban agriculture, solid waste dumps, sewer blockages and uncollected refuse, are more pronounced. In addition, the natural geology of the area contributes to some of these water quality pollution parameters, such as iron, manganese and suspended solids in the catchment's river systems [62].

Located southwest and downstream of Harare, Lake Chivero is a reservoir created to be the main supplier of drinking water to the city of Harare, Chitungwiza and Ruwa in 1952. However, this geographical positioning is such that all the catchment activities directly or indirectly influence the drinking water quality in Lake Chivero [101], since the sewage effluents of the cities are again discharged into Lake Chivero via the Mukuvisi and Marimba River. This causes the lake to be highly eutrophic. Lake Chivero experienced issues with eutrophication, algal blooms and mass fish killings as early as 1967. After these initial issues, the lake was successfully remediated with stricter discharges and using sewage effluent on agriculture land to reduce nutrients polluting the lake. This remediation was successful till the late 1970s, but studies show that by the 1990s the high concentration of phosphorus was again recorded in Lake Chivero [39]. This most like due to the increased urbanization and lack of upgrading the WWTP, resulting in an increasing discharge of poor sewage into the Manyame River [62].

Lake Manyame is built as back up for when Lake Chivero cannot satisfy Harare's water demand. As it is located downstream of Lake Chivero, it receives the water discharged from Lake Chivero and has therefore experienced high levels of phosphorus and nitrogen (especially ammonia) since 1991. It is clear that the process of eutrophication has also begun in this lake [62].

2.1.2. Middle Manyame Sub-Catchment

The MMSC is located in Mashonaland West Province and Mashonaland Central Province and has a total area of 4,245 km^2. The major urban centre is Chinhoyi. Besides the Manyame River, there are three other main rivers that drain the catchment, namely Mukwadzi, Muzare and Munene [29]. The most important dams are the Mazvikadei Dam and Biri Dam located on the Mukwadzi River and Manyame River, respectively. The Biri Dam is an important source of irrigation water and also supplies drinking water to the city of Chinhoyi [29]. The elevation in the MMSC ranges between 1098m to 1590m AMSL, with the highest area located in the east of the sub-catchment.

The major socio-economic activities in the MMSC involve industry, fishing and most importantly intensive farming and mining [101]. The MMSC has been an important agricultural area for Zimbabwe.

However, due to the fast track land reform in 2001 white-owned large-scale farms have been extensively allocated to two types of agricultural resettlement for black farmers: A1 - village based farms and A2 - commercial farms [47]. These farms were not able to undertake such intensive farming for several reasons. Where the transition should have broadened access to water, in practice irrigation water usage has remained low because of a depressed agricultural sector, shortage and high costs of electricity, and lack of capital needed to restore damaged or stolen irrigation equipment. This explains why there is underutilization of water and an overall decline in water usage from both the Mazvikadei and Biri Dam. This, in turn, has resulted in a situation where most dams are almost full at the end of the dry season. Mazvikadei Dam, for example, was almost 90% full in August 2016 despite the drought. This was not the case before fast track land reform when most dams would be less than 50% full by October because of irrigation by commercial farmers (this will be further discussed in Chapters 7 and 8) [29].

Not only water quantity issues are significant in the MMSC but also water quality issues play an important role. This is because the MMSC is located downstream of the UMSC and therefore receives the polluted water from Lake Chivero. Other sources of pollution in the MMSC are agricultural runoff into the dams and the disposal of untreated sewage into the Manyame River [47]. In a study by Norah et al. [64] it was found that the concentration of nitrates, phosphates, DO, total dissolved solids (TDS) and biological oxygen demand (BOD) did not meet acceptable water quality standards for the sites downstream of the sewage discharge. The sewage effluent from the Municipality of Chinhoyi WWTP was the major contributor to the poor water quality. In addition, the MMSC includes small-scale and large-scale mines of chrome, gold and dolomite. Some A1 farmers are complaining that they are no longer able to use water from Mukwadzi River because of cyanide contamination from these mines [29].

2.1.3. Lower Manyame Sub-Catchment

The LMSC is located in the most northern part of the Manyame Catchment with an area of 6308 km^2 and an estimated population of around 263,000. The area is divided into the CH1 & CH2 hydrological zones and elevation ranges between 380-1470 AMSL. The LMSC is characterized by water competition among the major using sectors such as the mining and smallholder floodplain cultivation [101]. An increase in population has resulted in increasing domestic and agricultural water demands. The usage of inefficient irrigation systems such as overhead sprinklers and furrow irrigation also contribute to the high water demand. This rising water demand has resulted in an increase in boreholes, which have been known to dry out in the middle of the year. An even more apparent issue in the LMSC however, is the degradation of water quality. Due to discharge of domestic, agricultural and industrial waste from the upstream sub-catchments into the Manyame River the water quality of both surface water and groundwater has significantly decreased. In certain times the conditions have worsened to the extent that the water was unfit for human consumption. Locally open defecation and leaking septic tanks were identified to be a contributing source of pollution that is taking place on a large scale through sparsely distributed settlements. Mostly the agricultural river bed cultivation in the LMSC were also found to contribute to the pollution of riverine systems and environmental degradation in the area.

In addition, problems regarding drought and gully erosion are increasing. The soils are increasingly eroded due to the highly erodible characteristics of the sodic soils, seasonal river bank cultivation, clearing of land through deforestation and burning as well as poor grazing management.

Additionally, in this rural area, the governmental institutions like the Lower Manyame Catchment Council (LMCC) and the Zimbabwe National Water Authority (ZINWA) have insufficient capacity, revenue collection and state support to maintain essential services. The ineffective institutional arrangements, weak legislation implementation and enforcement add up to the catchment's problems.

2.2. Climate Zimbabwe

Zimbabwe is a semi-arid country that is characterized by dry winters and wet summer (see Figure 7), with the rainfall ranging from 450 mm to 650 mm in the low rainfall areas and from 750 mm to 1000 mm in high rainfall areas [34]. Temperatures in the high-lying areas vary from 12–13°C in winter to 24°C in summer. In the lower lying areas the temperatures are usually 6° C higher on average. Summer temperatures in the Zambezi and Limpopo valleys average between 32°C and 38°C [7].

The Manyame Catchment is located in an area of Zimbabwe that is characterised by relatively high to moderate rainfall of 750mm/year [101] and moderate temperatures ranging from from 24°C to around 32°C. These temperatures increase in the northerly direction [101, 102]. Within the catchment the total rainfall variation is negligible as can be seen in Figure 8. The Mean Annual Runoff (MAR) of the catchment tends to vary following the seasonal rainfall trend and further decreases in the northerly direction towards the escarpment and is lowest in the LMSC, which has low laying areas. The MAR is further reduced by evaporation, which is relatively high in the Manyame Catchment due to high temperatures [101].

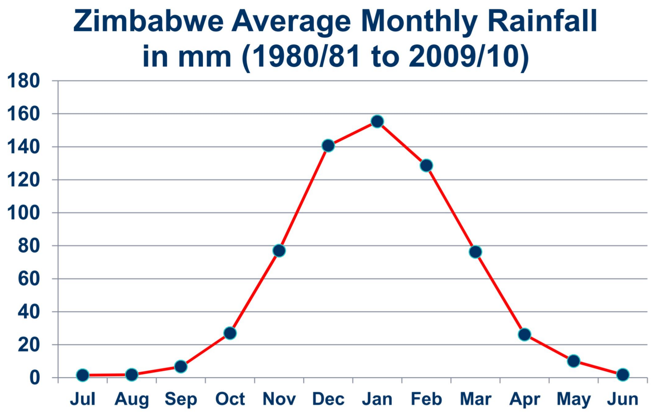


Figure 7: Zimbabwe Monthly Rainfall averaged from 1980 to 2009

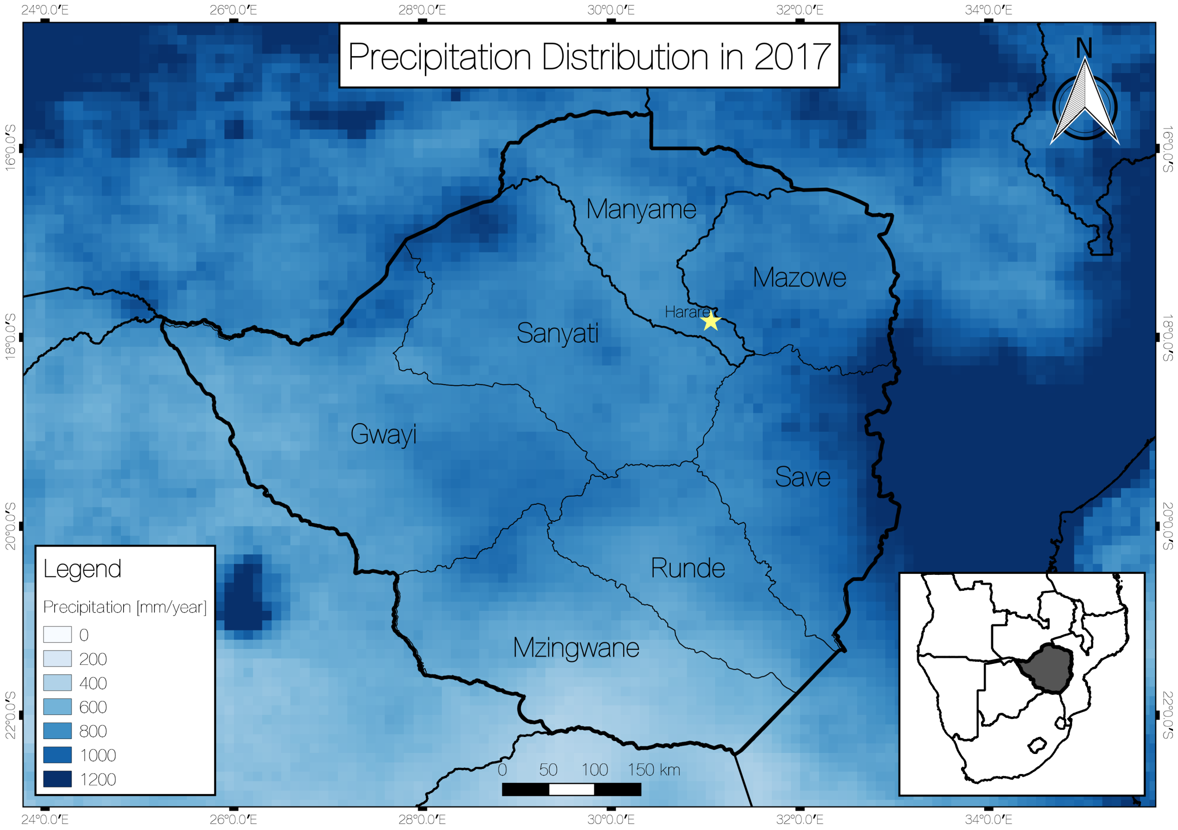


Figure 8: Zimbabwe rainfall distribution in 2017. Image developed in QGIS with monthly NASA Precipitation data from 2017

2.2.1. Climate Change in Zimbabwe

Climate change effects are evident in Zimbabwe as they are all over the world [99]. The 2050 projections on the climate change effects in Zimbabwe consist out of the following:

- A modest decrease in total amount of rainfall
- Erratic rainfall distribution throughout the country
- More droughts and floods
- Reduced groundwater recharge

- Changes to the onset and end of the season
- More frequent and longer mid-season dry periods
- Temperature increase of between 1°C and 3°C

2.3. General risk assessment

Zimbabwe is one of the countries in Africa most prone to natural hazards of hydro-meteorological origin. Its complex climatic and varied geological conditions result in multiple natural hazards. Among them, floods, droughts, and tropical cyclones cause the greatest economic losses. The past disasters which have happened in Zimbabwe (and other countries) have been monitored by the Emergency Events Database (EM-Dat). Table 2.1 shows the Emergency Events Database for Zimbabwe between 1990 and 2019 (present). Of all the natural disasters occurring regularly in Zimbabwe, droughts have the greatest potential impact and affect the greatest number of people. On average, drought is Zimbabwe's most costly natural hazard in economic terms, as well as in frequency of occurrence. In addition to droughts, also floods are among the most costly natural disasters in terms of total affected and economic loss [41].

Besides natural disasters, Zimbabwe also has a high rate of epidemic disasters. The annual numbers of people who die from these disasters is relatively small compared to those who die from natural disasters. For example, although drought is one of the biggest natural disasters of the country, there is no record of even a single death due to drought induced famine. Cholera is perhaps the most contagious of the entire range of common epidemics experienced in Zimbabwe. Due to deteriorating water quality around urban areas the most severe cholera outbreak took place in 2008 with more than 4000 deaths [8].

Disaster Type	Disaster Subtype	Events Count	Total Deaths	Total Affected	Total damage ('000 US$)
Drought	Drought	6	0	19122618	550000
Epidemic	–	2	71	10102	0
Epidemic	Bacterial disease	17	4900	111349	0
Epidemic	Parasitic disease	1	1311	500000	0
Epidemic	Viral disease	3	67	6502	0
Flood	–	1	13	30000	3600
Flood	Flash flood	1	3	1002	20000
Flood	Riverine flood	9	271	313020	272900
Storm	Tropical cyclone	3	259	113023	190200

Table 2.1: Past disasters in Zimbabwe [26]

3

Droughts

Droughts are one of the most relevant climate-related hazards in the African continent. They can have devastating consequences for food production, livestock and water supply. The economic losses due to droughts have the greatest impact on the agricultural sector. The so-called phenomenon ”Agricultural drought” is a climatic phenomenon that slowly develops and impacts the crop production. Since it prevents optimal food production and access to resources, it endangers the livelihoods and lives across the country. The most affected crops are grains like corns, maize, beans, wheat, sorghum and rice, which are basic to the daily diet of the worlds population [19].

The International Disaster database of the Centre for Research on the Epidemiology of Disasters (CRED), reports more than 19 million people are affected over several drought events during the last 30 years (1990–2019) in Zimbabwe [26]. Table 3.1 summarizes the frequency and severity of droughts for Zimbabwe during the last three decades (1990-2019) [58].

Extreme Drought	Severe Drought	Mild Drought
1992	2004	1991, 1995, 2002, 2003, 2007
	2016	2010, 2014, 2015, 2018

Table 3.1: Past droughts in Zimbabwe [58]

A drought, especially in the case of Zimbabwe, is mostly caused by a seasonal precipitation variability (see Figure 7) than by the total amount of rainfall [15]. The distinction between meteorological and agricultural drought is therefore important. A meteorological drought is characterized by below average precipitation over a region for a prolonged period of time which normally results in total crop failure [91]. Agricultural drought however, can happen during seasons with higher precipitation totals than those defined as meteorological droughts. It happens when the cumulative soil moisture available for plants is greatly lower than the cumulative water requirements for crops [66]. Although the cumulative precipitation may be enough to produce a crop, there is a shortage of moisture available for plants, resulting in yield reduction or total failure of crops [15]. Another type of drought which is elaborated on in this report is groundwater drought. Groundwater drought is characterized by persistent decline in groundwater recharge, levels, storage and discharge, see section 7.2.

Peter Morgan, a groundwater expert in Zimbabwe, has noticed the distinct changes in the pattern of rainfall within the rainy season in the last few years. These greatly affect the harvest as well as water supplies in general. He stated:

“Zimbabwe’s well-being is much dependent on water - the staple diet of the population, maize, depends on a good consistent rainfall season. But in recent years the pattern of rainfall during the growing season has changed, with dry spells occurring during what was once an almost continuous rainy season.” (Morgen, 2016)

Identification of droughts prone areas is essential for programmes aiming to increase the food and water security. In order to develop drought management policies and plans, it is important to have real-time geo-reference information that allows to make timely decisions given a drought risk. FAO's Global Information and Early Warning System (GIEWS) and the Climate, Energy and Tenure Division has developed an information system which allows countries to monitor vegetation and crops using satelite data. The tool is called Agricultural Stress Index System (ASIS) [18].

The method that is applied to the Manyame Catchment to indicate droughts risks is based on the ASIS tool. ASIS is established, because reliable rainfall data is very scarce in many regions in Africa. However, vegetation abundance and development data is strongly related to rainfall and can therefore be used as drought indicators [73].

3.1. Methodology

ASIS Method

The Vegetation Health Index (VHI) together with Normalised Difference Vegetation Index (NDVI) data is used to derive the probability of drought at a certain location. The data products are produced by the Center for Satellite Applications and Research (STAR) of the National Environmental Satellite, Data and Information Service (NESDIS). The final data products, consists of weekly VHI tif-files at 4 km resolution for the period of 1991 to 2018. The years 1995 and 2004 are incomplete and therefore not included in the analysis.

VHI is an index developed by Kogan (1995) which combines the Vegetation Condition Index (VCI) and the Temperature Condition Index (TCI). VCI is a proxy for soil moisture condition and was designed to separate the weather related component with the ecological component of NDVI. It is scaled by the minimum and maximum of NDVI value of a certain pixel, expressed as the following relation:

$$VCI_i = 100 * (NDVI_i - NDVI_{min})/(NDVI_{max} - NDVI_{min})$$

TCI relates to the brightness temperature estimated from the thermal infrared (TIR) band. The advantages of using the TIR band over a visual light band is that it is less sensitive to water vapour in the atmosphere. The algorithm is similar to VCI; the temperature in every pixel is compared to its maximum and minimum. TCI is composed as follows:

$$TCI_i = 100 * (T_{max} - T_i)/(T_{max} - T_{min})$$

TCI and VCI are combined to establish the VHI and is expressed as:

$$VHI_i = w_1 * VHI_i + w_2 - TCI_i$$

W1 and w2 are weighted value and set to be equal (0.5) by the Center for Satellite Applications and Research. The step-by-step approach used to translate VHI to a probability of agricultural drought is explained in the next section.

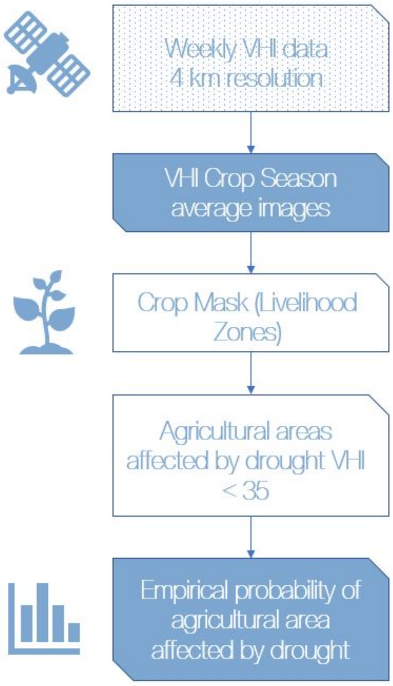


Figure 9: Process of Developing Agricultural Drought Risk

Step-by-step approach

The method is explained by a step-by-step approach to make the process more clear (see Figure 9). It consist of five steps of which two are intermediate outputs of the method. An overview of the approach can be seen below.

1. First of all a temporal selection of the VHI data is made. Weekly data is gathered online for the period of 1991-2018. The analysis is solely performed for the agricultural season. Maize, wheat and sorghum are indicated as the main crops in the catchment and their corresponding growing seasons can be seen in Figure 10.

2. The season for maize and sorghum start in November/December and ends in April/May. In general, the rainy season is the crop growing season which lasts from week of 48 to week 17 of the next year. All smallholder and urban farmers are depended on the rainy season to grow their

crops as they do not have the resources to irrigate. This exposes the group to the highest risk for droughts. For this reason, only the crop harvest in the rainy season (week 48 to 17) is taken into account in the analysis.

For every year, the weekly VHI is averaged along the crop season. Drought is considered 'Exceptional' if the VHI is between 0-5; 'Extreme' 6-15; 'Severe' 16-25; 'Moderate' 26-35; 'Abnormally dry condition' 35-40. The result of the average VHI for every year is illustrated in Figure 11.

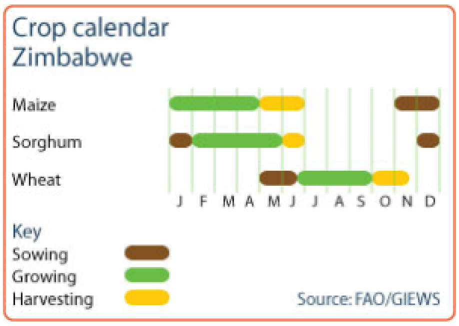


Figure 10: Crop Calender of Zimbabwe

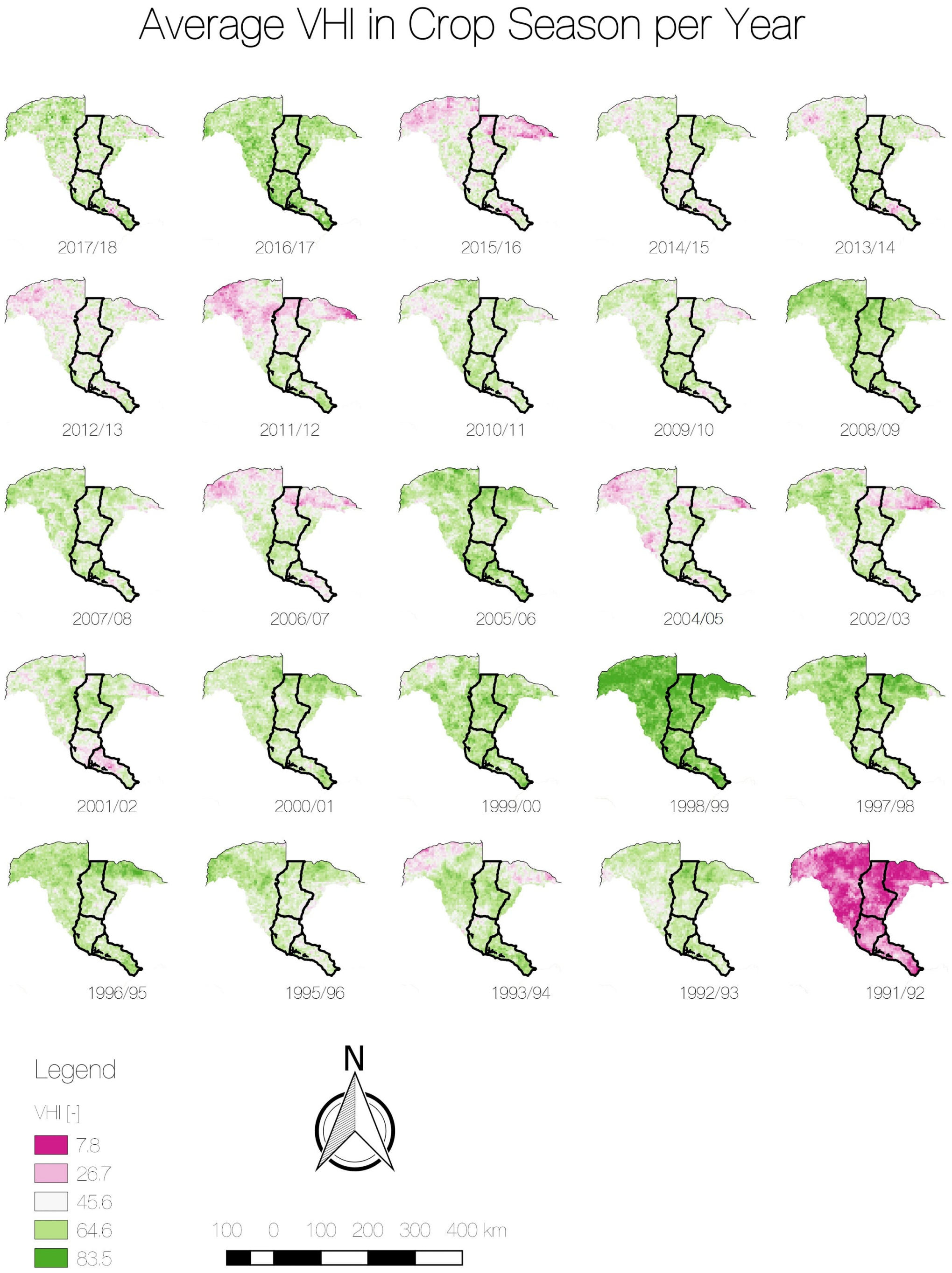


Figure 11: Average VHI per Year during Crop Season

3. Afterwards, a spatial selection of the data is made. The analysis is solely performed for the agricultural areas (see Figure 12). The Livelihood Zones from FEWSNET are used to indicate the agricultural areas. The national parks, urban and mining areas are manually removed.

4. Afterwards, for every pixel the percentage of VHI which is under 35% is computed for the entire period. The 35% limit is considered to be the threshold when the population experience socio-economic consequences from the drought. In other words, failure of crops resulting in some degree of food insecurity and the consequences related to that [38].

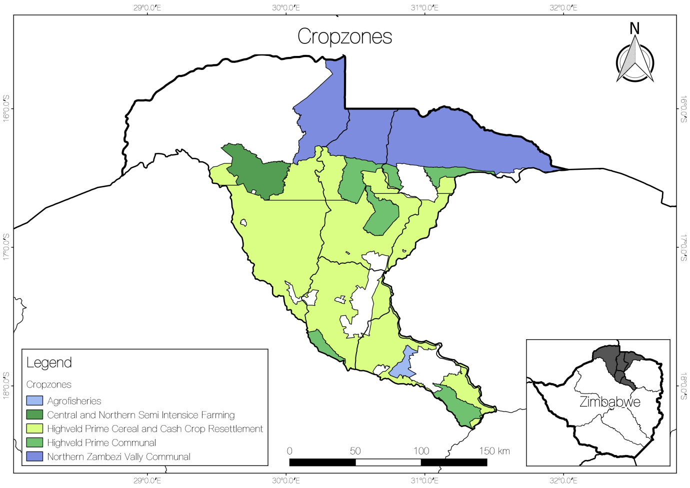


Figure 12: Cropzones in the Manyame Catchment

5. As a final step, the probability of agricultural area affected by drought is computed by a binomial distribution [73], where P is n/N with n is number of times that VHI is below 35 and N the total amount of years.

$$Probability = P + 2\sqrt{P(1-P)/N}$$

3.2. Findings

The final result of the probability of a drought, in every pixel, can be seen below.

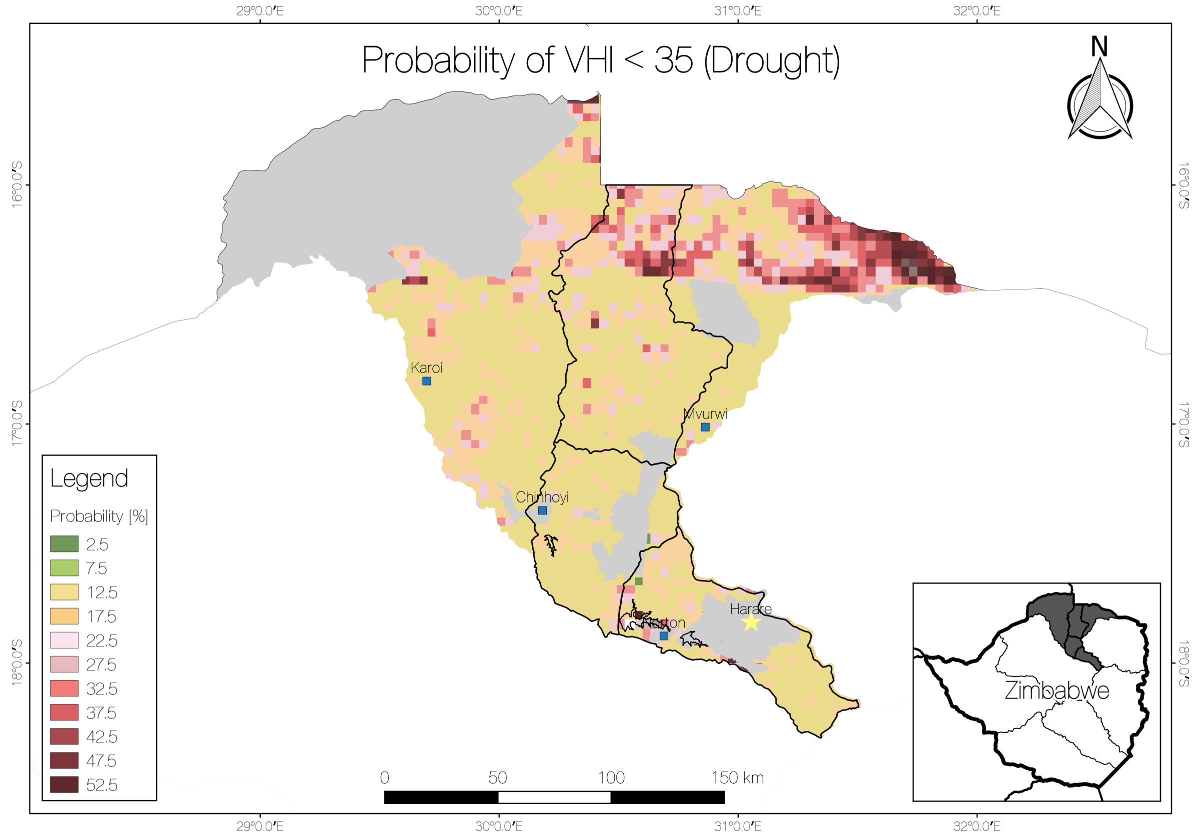


Figure 13: Probability of a Drought

By comparing the average VHI for the 25 years with Table 3.1, it can be seen that the results of the method coincide with the drought years and severity of the known droughts. Especially the extreme drought of 1991/92 can be seen very clearly. Unfortunately, because 2004 data was unavailable, it is not possible to see a severe drought. Mild droughts can also be seen, as well as good years. The probability of a drought is about 15% on average as can be seen in Figure 13. The Manyame Catchment is therefore not considered to be extremely prone to droughts.

However, the method used to compute the probability of droughts does not take into account the variability of the rainfall pattern. The VHI values are averaged out in the process by averaging the VHI along the crop season. However, due to the high variability of the rainfall pattern low VHI values can occur, indicating dry spells. Dry spells occur as short periods of water stress that last for a few weeks during crop growth causing the crops to fail [66]. As mentioned by Peter Morgan, there have been distinct changes in the pattern of rainfall within the season in the last few years, with dry spells occurring during what was once an almost continuous rainy season. In the Manyame Catchment, the critical period of dry spells is often in January. This is acknowledged by the Lower Manyame Catchment councilor, Tafireyi Dzomba:

”The drought these days is of a very long scale which usually happens particularly in January. That’s the time where there is normally a long, long dry spell. So when that happens there normally is no other alternative for the farmers than to see their crops wilting. There are no other means of trying to irrigate the crops. Normally there’s nothing they can do. They will just be watching their crops wilting.” (Appendix A.6. Interview Tafireyi Dzomba – LMCC).

The VHI values of a dry spell in January are therefore considered more critical than the averaged VHI along the crop season of that same year. For this reason, the same method was applied to compute the probability of a dry spell. As January is the most critical month for a crop to fail or succeed, the period of January 1992 to January 2018, excluding 1995, is analysed. By following the same steps of the ASIS method, the VHI in January of each year is summarized in Figure 14.

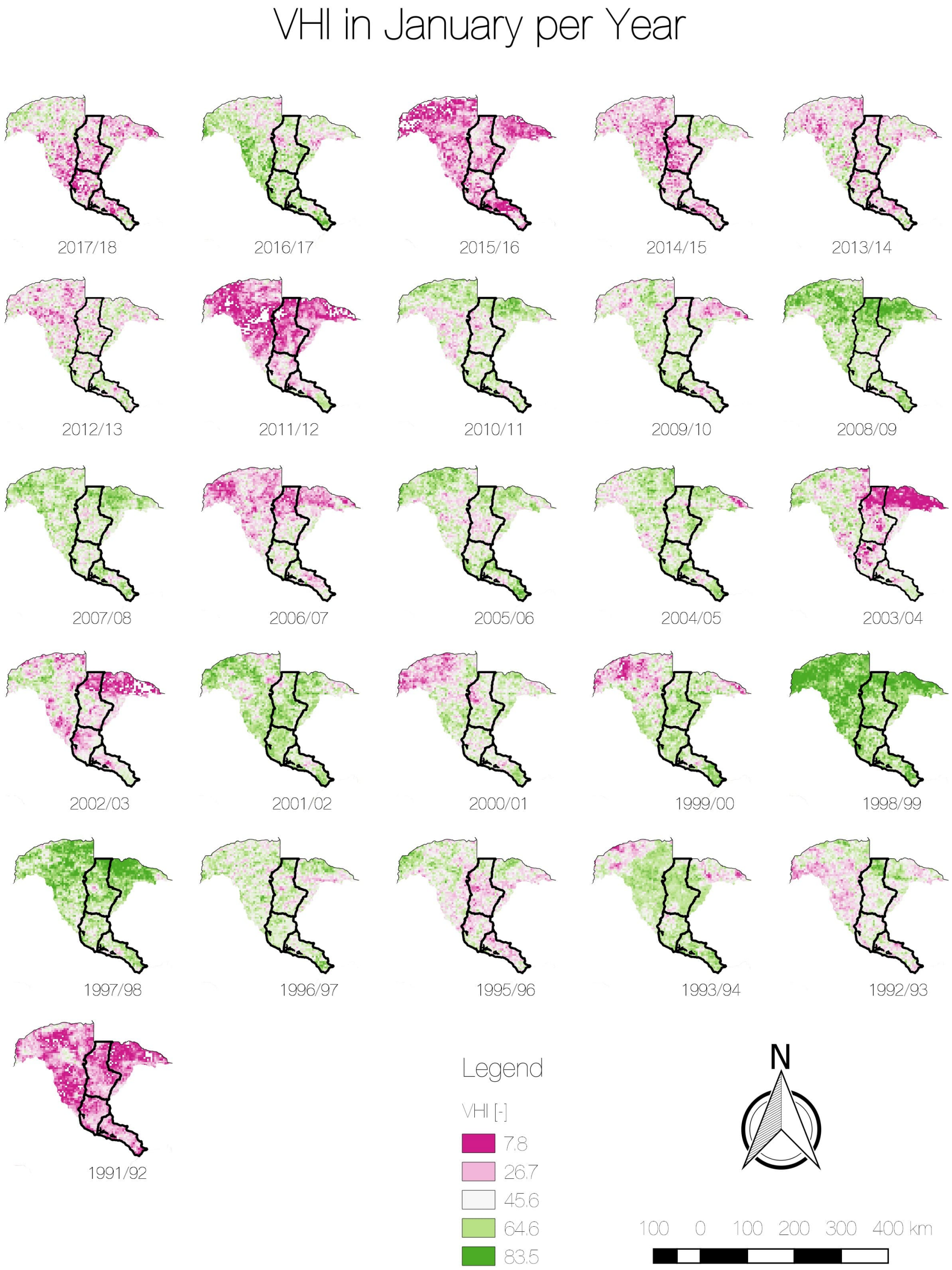


Figure 14: Average VHI per Year during Crop Season

The final result of the probability of a dry spell can be seen below. It can be clearly observed that the risk for dry spells are extremely high, especially in comparison to the risk for a drought. The map shows that some areas are more prone to dry spells than others. The probability of having a VHI <35 in a season, has a mean value of just over 30%. In other words, on average, the chance of having a mid-season dry spell is one out of three years.

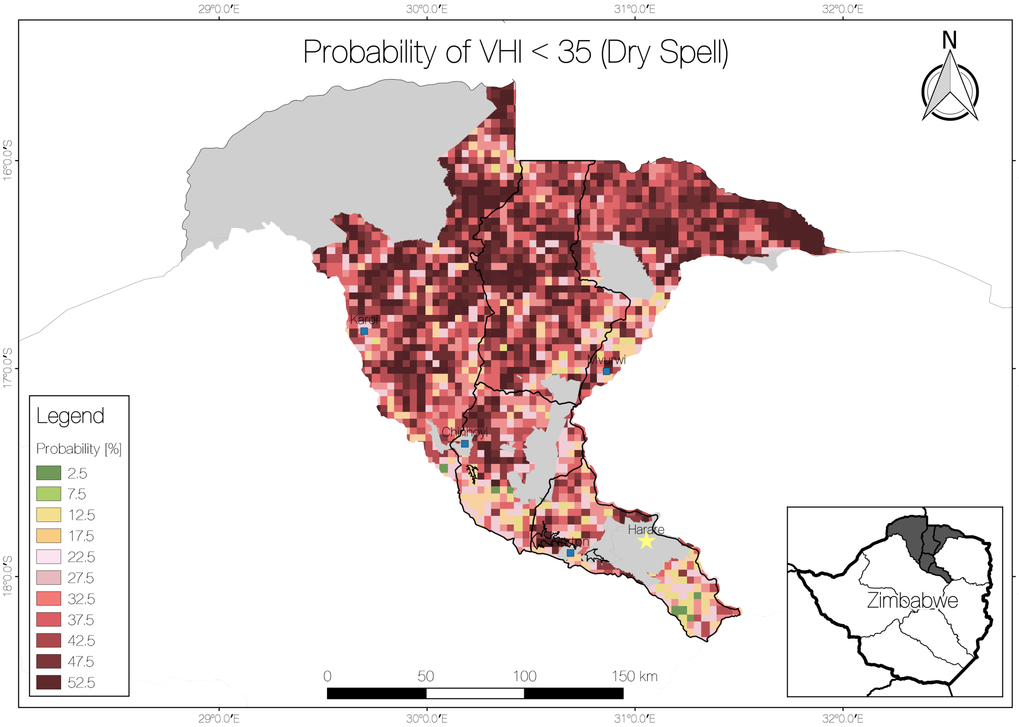


Figure 15: Probability of a Dry Spell

3.3. Conclusion & Recommendations

The results show that the Manyame Catchment is prone to both droughts and dry spells. This will enable organizations to focus on areas prone to dry spells to allocate and concentrate their resources. Final conclusions and recommendations are given in Chapter 8 & 9, where specific case studies are examined.

In order to improve the food insecurity across the country, the ministries of Agriculture and Environment could implement risk management strategies for drought. Risk management involves developing plans to be prepared, mitigate and respond to drought. The plans must consider activities when a drought warning comes. Such as using technologies for harvesting rainwater. Plans must also consider drought mitigation actions such as including short-cycle varieties of seeds when the drought is expected. Finally, when drought reaches critical levels, plans should include response measures such as food aid or agricultural insurances. Monitoring drought is a key to establishing a successful management scheme for making timely decisions. The country level ASIS tool could be of great contribution to that [19].

4

Hydrological Model

Rivers have significant influences on many environmental studies. Understanding the behavior of a river is required for some of these studies such as flood modelling, river morphology and water resources. Depending on the goal and methods used, other research fields also require either a hydrological model or the output of a hydrological model (e.g. hydrographs and amounts of surface runoff). Some of the subjects of these studies are erosion, drought and water quality. Furthermore, knowledge about water resource availability can help policymakers and stakeholders to develop an area [13].

So far, no study has yet attempted to establish a hydrological model specifically for the Manyame River Catchment [27, 28]. For this reason, a hydrological model for the Manyame River Catchment is established using the program HEC-HMS. The HEC-HMS model is selected because of its suitability for ungauged catchments and its successful application in previous studies performed in the UMSC [27, 28].The methods that are used in the model are chosen from the methods available in HEC-HMS, more information on specific methods can be found in the manual of HEC-HMS 4.3 [79].

The first 'Assumptions and Methodology' section of this chapter is used to describe the assumptions made and the methods used regarding the input data of the model. In the second part the calibration and validation process are described. Followed by a chapter about the findings. Concluding with a chapter containing the recommendations and conclusions.

4.1. Assumptions and Methodology

4.1.1. Ungauged catchment

The Manyame Catchment can largely be regarded as ungauged. Ungauged basins are catchments with insufficient, inadequate or questionable data [30]. For modelling purposes, the catchment was divided into 27 sub-catchments. In the Manyame Catchment area there are only two sub-catchments that are gauged. These are called Marimba and Mukuvisi. Other gauging stations have either outdated or missing data. Besides this, some of the gauging stations produce questionable data. Some gauges for example show the same flow for weeks during the rainy season. For some of these stations this is caused by dams upstream discharging steady outflows, but due to a lack of data on dam discharges these gauges are not useful for calibration and validation of the hydrological model.

The two gauged sub-catchments, the earlier mentioned Marimba and Mukuvisi, also contain some gaps in the data. These few minor gaps (of a few days) were filled with the average discharge of the 7 days before and after the gap. This method is assumed to be of sufficient quality, since the gaps in the data were small and the gradient of the gauging data of the 7 days before and after was approximately zero and showed little fluctuations around the average. The two gauged sub-catchments are located in the UMSC and highlighted with a red color in Figure 16.

The Manyame Catchment contains several big and small dams (see Figure 16). An attempt was made to put the major dams into the model. However, the quality of the discharge data was insufficient for some of the dams. Furthermore, this data is not available for some of the dams such as the Mazvikadei Dam, which is one of the major dams. Basin parameters (e.g. the area of each sub-catchment) were acquired with QGIS, sometimes combined with literature and google satellite. Some of the parameters that were used as input data of the model are listed in the appendix (Appendix A.9. Hydrological model input data).

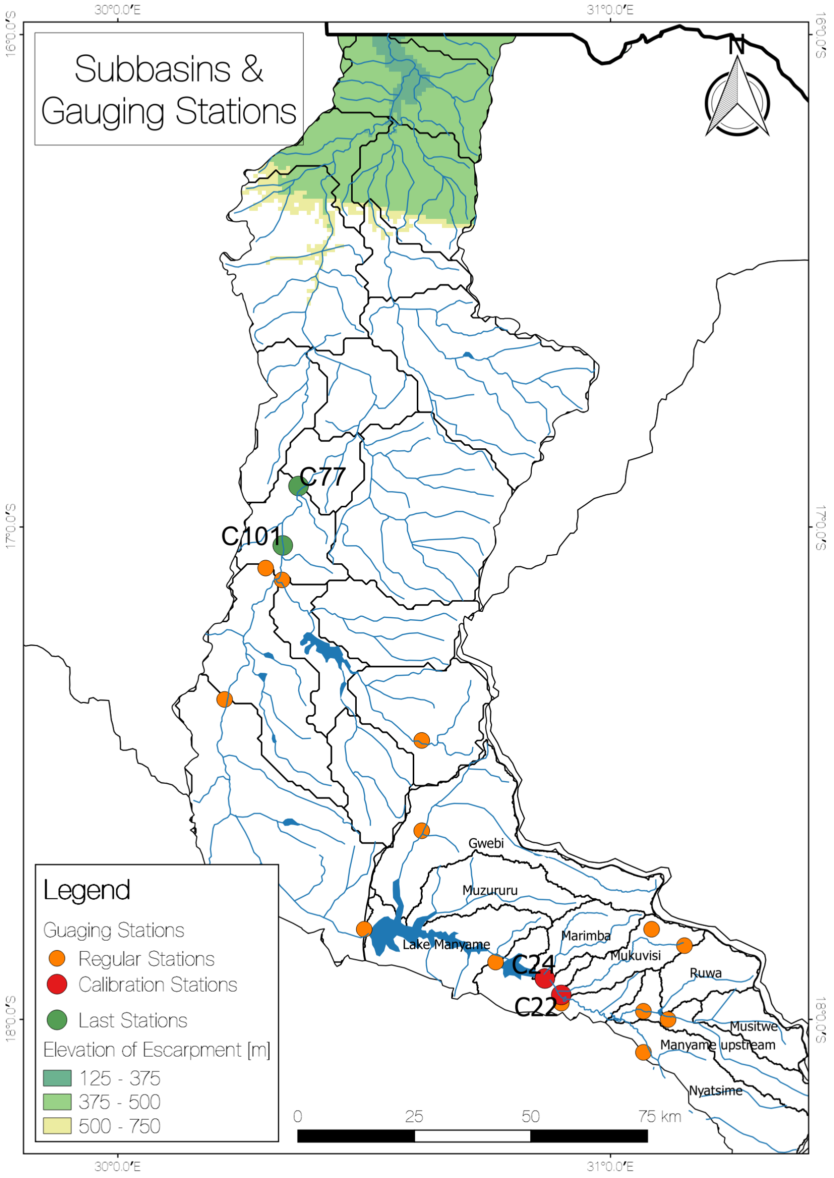


Figure 16: Sub-basins and gauging stations in the model

4.1.2. Meteorological data

Satellite data was used to obtain rain and evaporation data. There are several reasons why the satellite data was preferred over the data of local weather stations. One of them is that there are only a few weather stations in the Manyame Catchment. This would require interpolation over large area's of approximately 100 km or more. An approximation like this would not do justice to the large temporal differences (especially for rainfall), observed in the satellite data. Besides that, the gauged rain data has quite some gaps (e.g. due to the crisis in 2008 or power cuts). Lastly obtaining data from other parties in the catchment has proven to be a tedious and long process in some cases.

Rain

In order to obtain spatial and temporal precipitation data for the Manyame Catchment, satellite data was downloaded. The satellite data was downloaded in tiff format from Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) [24]. Daily precipitation data for the years 2008 till 2015 was used. However HEC-HMS does not take tiff files as input data. Therefore, to be able to implement the rain data into HEC-HMS, the tiff files were imported in QGIS. Sample points were added to QGIS, after which the point sampling tool was used to substract the data of the tiff files at these specific points. These points work like weather stations that measure rain and evapotranspiration. Using the satellite data relatively big differences in rainfall within one sub-catchment were observed. Therefore, to keep most of the resolution of the data, two sample points for each sub-catchment were added (more would require a lot of work as it is implemented manually). After this the average precipitation for the two points was calculated for each of the 27 sub-catchments. In this way, the spatial resolution is retained as good as possible.

Evapotranspiration
HEC-HMS calculates the actual evapotranspiration using potential evapotranspiration (PET) and the soil water limitations present in the sub-basins. The latter is calculated by the model using rain and potential evapotranspiration data.

From NASA two datasets that provide PET were downloaded; the GLDAS NOAH dataset and the MOD16A2 dataset [76]. However, both datasets gave PET fluxes for the Manyame Catchment that were 2 to 3 times as high as PET fluxes that were reported by local weather stations. According to a contacted NASA employee (Hiroko Kato), the NOAH dataset is indeed overestimating PET, which is probably due to a bug in the code. NASA has performed a preliminary comparison on the NOAH dataset over some sites in the US and found 2 to 3 times higher PET values than that of a published study. Trambauer et al. (2014) found that PET values from MOD16 are 2 to 3 times higher in Africa compared to other methods that calculate the PET, especially for arid and semi-arid areas [86].

However, the PET data that was received from Belvedere weather station (located in Marimba sub-basin) was a monthly average obtained from averaging several years. Idealy, data of a better temporal resolution and preferably also spatial resolution is needed to accurately simulate the flows in the catchment.

In order to obtain such a dataset, the data from the local weather station and the satellite data were combined. From both datasets, the data of a few time series of pixels close to the weather station were plotted in anomalies. The GLDAS NOAH data produced anomalies that looked nothing like the anomaly produced by the local weather station data. The anomalies of the MOD16A2 dataset matched the pattern of the local weather station data relatively well, except for the amplitude. Therefore, instead of using the anomaly, the whole dataset was scaled with the local weather station data (i.e. the satellite data was multiplied with the average PET of the local weather station and divided by the average PET of the pixels close to the weather station). Hereby the spatial and temporal heterogeneity of the satellite data, which is 500 meter and 1 month respectively, is retained.

Subsequently a canopy method was added to enable the model to link the PET to the water availability in the sub-basin. Also, the method requires a specified amount of canopy storage. The total storage was assumed to be 1 mm over the whole catchment.

4.1.3. Groundwater flow
As mentioned by Dr. Richard Owen (Appendix A.2. Interview Dr. Richard Owen - GW expert) the base flows in the Manyame Catchment is relatively small. However, along the 2 gauged sub-catchments there are some small industries. These produce an unknown amount of discharge which makes the calibration of the model difficult. Moreover a large but unknown amount of the groundwater is pumped out. Therefore, the linear reservoir concept is inappropriate to model the base flow, because it conserves mass within the sub basin.

However, the inclusion of baseflow in the model is likely to produce a better simulation of the flow and will hereby also contribute to a better calibration of other input values of the model. Therefore, the recession baseflow method was implemented in the model (for the gauged catchments only) and its input values will be optimized based on the gauging data.

4.1.4. Loss method
The loss method controls the partitioning of the water that infiltrates and the water that leaves the catchment as direct runoff. Some models such as the 'Green and Ampt' require some unknown and

unavailable input data (e.g. hydraulic conductivity and wetting front suction) for the Manyame Catchment. Both the soil conservation service (SCS) curve number method and the 'initial and constant loss' method seem appropriate for this catchment. Firstly, the SCS curve number method was chosen since more input data was available for this method in this catchment and therefore less parameters need to be calibrated. However, due to bad performance (total runoffs were twice as high as observed) the 'initial and constant loss' method was chosen subsequently. This method requires a percentage of imperviousness and infiltration rates per sub-catchment. It also requires an initial water deficit. Because there is no data about the water deficit in the soil, this parameter has to be calibrated.

An attempt was made to estimate the soil cover, and hereby the percentage of impervious area needed for the 'initial and constant loss' method, using NDVI and false color composite maps. Unfortunately the algorithm used in QGIS (i.maxlik) could not distinguish bare soil (with a few shrubs) from urban area. Subsequently maps for February (relatively wetter month) were downloaded for a more pronounced distinction between the two classes. Unfortunately a high percentage of cloud cover made classification impossible.

Subsequently, a land-cover map was downloaded from the European Space Agency (ESA) [16]. Per sub-basin the percentage of each cover class was calculated. Subsequently the extend of impervious area was calculated using the urban cover class with an impervious cover percentage of 80%. This factor was determined by comparing the pixels of the urban cover class with google satelite pictures and by using impervious estimates of Washburn et al. (2010). However, some of these estimates were much lower than estimates that were made based on Google Earth pictures. Consequently, the percentage of imperviousness in these catchments were estimated based on the Google Earth pictures. To increase the accuracy of these arbitrary estimates, the percentage imperviousness was also optimized (within a range around the estimated values) in the calibration process.

There was no data available on infiltration rates, therefore these were estimated with satellite data on soil characteristics. For this a gridded dataset produced by Ross et al. (2018) was used. Based on soil texture, groundwater and bedrock depth Ross et al. created a 250 m spatial resolution dataset. In total they made 8 different classes called hyrological soil groups (HSG's). The classes are based on factors such as runnof and infiltration processes.

In the downloaded maps urban areas were indicated as soil with high runoff (soil group D). However, the average infiltration rate should only be calculated for the pervious areas. For the impervious area, which is another input variable, no infiltration is allowed. Therefore, the percentage of impervious area had to be subtracted from the total percentage of soil group D. Subsequently the average infiltration rate per basin were calculated using a table provided by Minesota Stormwater [52].

Routing method

Routing methods are used to predict changes in the shape of a hydrograph as water moves downstream. Routing can also be used to predict the shape of a hydrograph subsequent to multiple rainfall events in different sub-basins of the catchment. Multiple methods can be used as routing methods for HEC-HMS. Some of these methods however, are too simple. 'Lag routing' for example can only model translation of the wave and not the attenuation. Other models such as the 'kinematic wave routing' and the 'modified pulse routing' are too extensive for a catchment which is largely ungauged. Therefore, for this hydrological model the Muskingum method is chosen. This method requires 3 parameters as input. The number of small rivers flowing into the main river, the Muskingum K which is a factor proportional to the travel time of the flood wave in the river and the Muskingum X which is a weighing factor dealing with the streams shape. If Muskingum X is zero than the reach is modeled as a reservoir and if Muskingum X is 0.5, the wave travels through the reach without attenuation.

The gauging data received from ZINWA is a daily averaged discharge. Therefore, it is inadequate to use for estimating the parameters X and K. However it is known that the Muskingum X = 0 to 0.3 in natural streams, the average Muskingum X in natural streams is approximately 0.2. Because the attenuation of the floodwave is relatively insensitive for this parameter, greater accuracy is not absolutely necessary [37].

A good approximation of the Muskingum K is shown in the formula below:

$$K = \frac{L}{c} \tag{4.1}$$

With:
L = length of mainstream (m)
c = flood wave velocity (m/s)

For the basins upstream of all the big dams, the attenuation of the flood wave is damped out by the dams before the water reaches the flood prone LMSC. The last big dam is the Manyame Balancing Weir (see Figure 17), which is located just upstream of gauging station 101 (see figure 16). Therefore attenuation, and thus routing, in the part of the catchment upstream of the dams, is not needed. To remove all possible attenuation upstream of the Manyame Balancing Weir, this sub-basin was assigned a Muskingum X of zero. After the major dams however, attenuation of the flood wave is possible. According to a LMCC manager water in the LMSC can reach levels that are 10 to 20 meters higher during the big floods that approximately occur ones every 5 year (Appendix A.6. Interview Tafireyi Dzomba – LMCC). Therefore, it is reasonable to assume that the main channel is at least approximately full everywhere, even further upstream in the MMSC. By observing pictures and videos of our field trips, we approximated the average depth of the channel to be 5 meter during flood occurrences. Assuming that the wave can be approximated as a low wave (i.e. the height of the wave is much smaller than the depth of the water) [2]. The following formula can be used:

$$c = \sqrt{g * d} \tag{4.2}$$

With:
c = flood wave velocity (m/s)
g = gravitational acceleration (m/s^2)
d = average depth in the main channel

With an average depth of 5 meter during flood occurrences, the flood wave velocity below the Manyame Balancing Weir can be estimated at 7 m/s.

Quite some assumptions were made for the derivation of the Muskingum K. However, a rough estimation is sufficient in a small scale hydrological model as the routing method is needed for the model to run but does not have a major influence on the output of the model [35].

Figure 17: The Manyame Balancing Weir located in the MMSC

Transformation method

The transformation method controls the time it takes for the water in the basin to reach a channel. The Snyder unit hydrograph method is a transformation method that was developed for analyzing ungauged basins ([81]). Therefore, this method is the most suitable for this basin. Moreover, this method has already been successfully applied in the UMSC by Gumindoga (2016) [27]. The parameters needed for this method are the lag time and the peaking coefficient. Studies performed by the soil conservation service (SCS) have found that the lag time, can in general be approximated by taking 60% of the time of concentration [79]. The lag time is defined as the length of time between the centroid of precipitation mass and the peakflow of the resulting hydrograph. The time of concentration can be calculated with the following equation [89].

$$t_c = 60 * (\frac{11.9 * L^3}{H})^{0.385} \tag{4.3}$$

With:
t_c = time of concentration (minutes)
L = length of longest watercourse (mile)
H = elevation difference between divide and outlet (feet)

The elevation difference between the divide and outlet, and the length of the longest watercourse have been calculated using a DEM model in QGIS. However, another program such as 'GEO HMS' would be recommended as calculating the longest watercourse in QGIS was quite a tedious process.

The other required parameter for this method is the peaking coefficient. It represents the steepness of the hydrograph that results from a unit of precipitation. Lower values represent a steep rising hydrograph [79]. Because the resolution of the gauging data is in days, an estimation of this parameter is not possible. Therefore, this parameter will be optimized in the calibration process. The parameter can however not be transferred to the other sub-basins because the two sub-basins that are gauged are by far the two most urbanized basins in the whole catchment. These catchments have a high percentage of imperviousness and are characterized by many anthropogenic features such as preferential pathways (e.g. gullies on the side of the road) and consolidated soils caused by human activity. Therefore, the peak coefficient of the two gauged sub-basins will differ from the peak coefficient of the two gauged sub-basins. The peak coefficient of the other sub-basins can be estimated by measuring the discharge in an unurbanized catchment, and timing the time difference between the centroid of precipitation mass and the peakflow [79]. For this report such a measurement could not be performed due to time restrictions.

4.1.5. Calibration and validation

Rain data was retrieved for the period 2008 till 2015. Runoff data was retrieved from ZINWA up until 2014, with some gaps in the data especially around 2008 and 2009 because of the situation of hyperinflation in the country. Therefore, the data from 2008 was left out of the simulation. Subsequently the calibration of the model was performed between 2009-2013 and validation in 2014.

Calibration

The optimalization function of HEC-HMS was not working, therefore calibration was done manually. Firstly the 'recession constant' and 'ratio' parameters from the recession baseflow method were changed. However, the hydrograph was not improving and the performance indicator, Nash-Sutcliffe was decreasing. Moreover, the amount of baseflow volume was a lot lower than 1% of the total volume. Subsequently, a constant baseflow for each month was put into the model. The performance of the model was again not increasing, therefore baseflow was removed from the model. The inability of the model to simulate the baseflow is partly caused by industrial effluents that discharge into both the Marimba and Mukuvisi river. The model could not account for these flows because of the unavailability of such data [27].

The percentage of imperviousness were estimated based on estimations using google satellite pictures. Because this method is arbitrary, the choice was made to calibrate the two gauged basins also on imperviousness. The initial estimates were 35% and 45% for the Marimba and Mukuvisi subcatchment respectively. Subsequently the model was run for several percentages within a range of 10%

of the initial estimate. After calibration the imperviousness was estimated on 40% and 55% for the Marimba and Mukuvisi sub-basin respectively.

The third parameter that was calibrated is the ‘initial deficit’ parameter of the loss method. However, varying this parameter did not result in changes of the output performance. Subsequently the infiltration rate was varied to check if the model was sensitive to this parameter. However, varying the infiltration rate did also not result in changes of the performance output. However, changing the percentage of imperviousness did have effect. Even after several changes in the model, including adding a surface method (a ‘simple surface’), the results did not change. It is still not clear what is the cause for the misfunctioning of the loss method.

Lastly the peaking coefficient was calibrated. The determination of this parameter was a trade off between correctly modelling the low peaks and the high peaks. Eventually a value in-between was chosen. For both catchments the peaking coefficient was estimated to be 0.1.

Calibration and validation results

The figures below show the observed discharge at the outlet of either the Marimba or the Mukuvisi sub-basin and the simulated discharge of both sub-basins. In the top of the graph the precipitation and the precipitation loss are plotted. The precipitation loss is a summation of evaporated water and infiltrated water.

Figure 18 shows the calibrated hydrograph of Marimba. The baseflow of the hydrograph is not simulated, which is the case for all the hydrographs, as already explained in the calibration paragraph. Some of the peaks are simulated quite well, but especially the big peaks are underestimated. The performance indicator Nash-Sutcliffe of the calibrated hydrograph is 0.125, which indicates that the predictive power of the model is not high. A model would perform suffiently if the Nash-Sutcliffe is bigger than 0.5 or 0.65 (both are used as treshold values) [72]. One of the main reasons for the Nash-Sutcliffe being so low is the difference between the baseflow of the observed and simulated data.

The relative volume error (RVE), which is the relative difference between the observed and simulated total discharge, is 4.33%. A possitive RVE means that the simulated output estimated a larger total discharge than the observed.

In the validation hydrograph of the Marimba basin (Figure 19) the simulated hydrograph is able to model the large trends. However the model is not able to simulate the sharp peaks and declines. The Nash-Sutcliffe is just above zero and the RVE is 17.32%.

In the calibrated hydrograph of Mukuvisi basin (Figure 20) it can be observed that the discharge after large rainfall events is highly underestimated. The Nash-Sutcliffe is -0.043 and the RVE is -31.63%. An additional reason for the bad correlation between the observed and simulated data might be due to errors in the observed data. For example, in the validation hydrograph of the Mukuvisi basin (see Figure 21), there is quite some excess rain in Februari. However, the observed discharge is decreasing the whole month. Moreover, in November there is only a little excess rain. However, a large peak was observed in the data. The RVE for Mukuvisi in the validation year is -15.10% and the Nash-Sutcliffe is only -2.34.

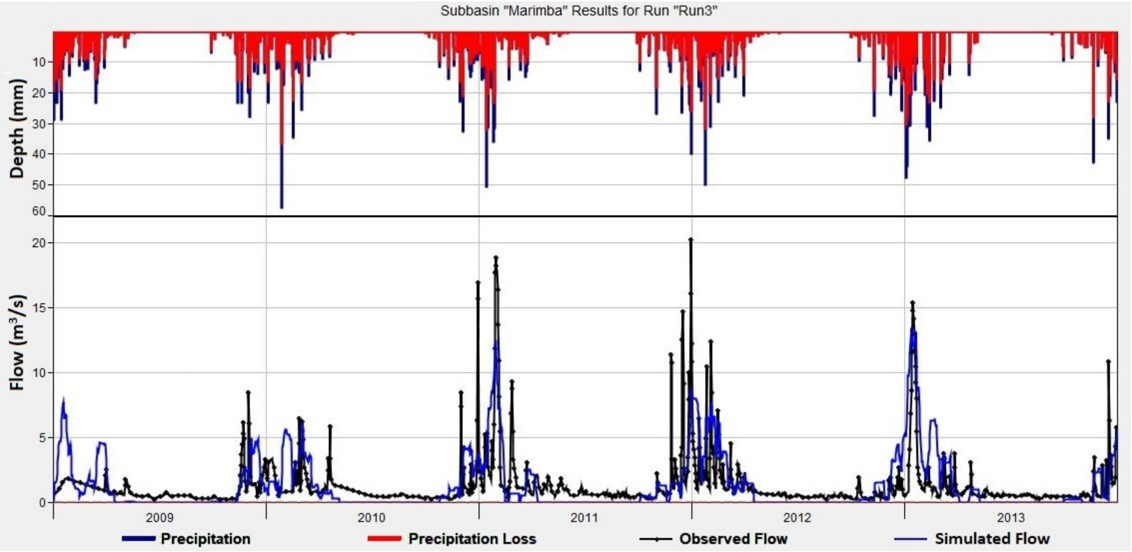


Figure 18: Calibration Marimba sub-catchment

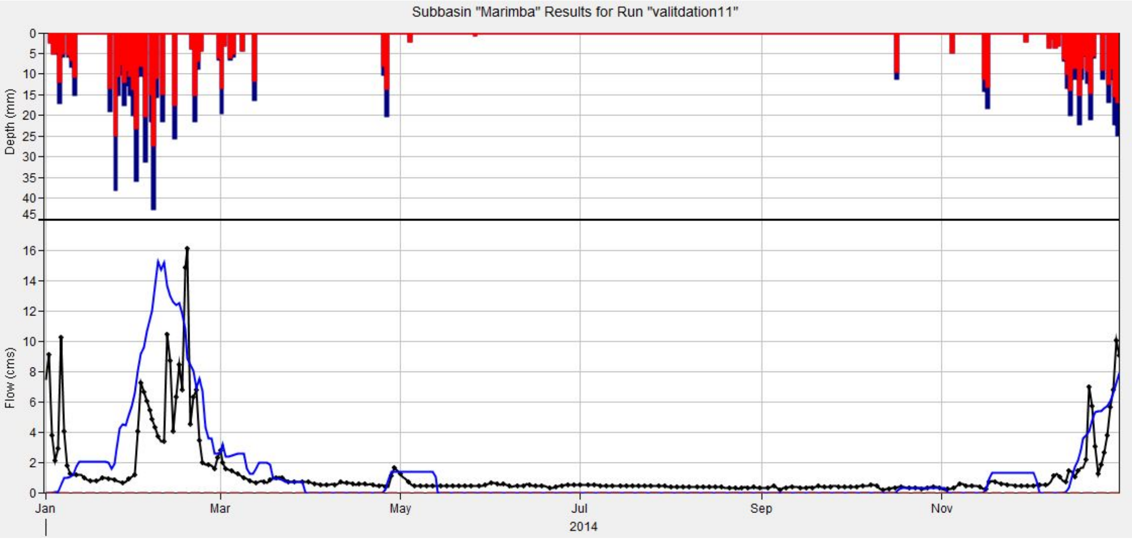


Figure 19: Validation Marimba sub-catchment

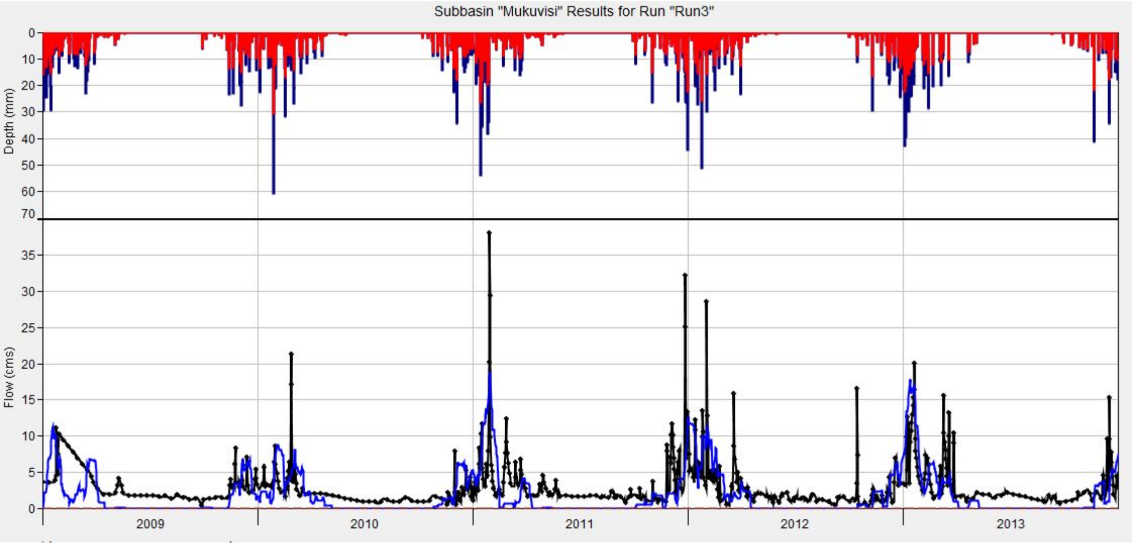


Figure 20: Calibration Mukuvisi sub-catchment

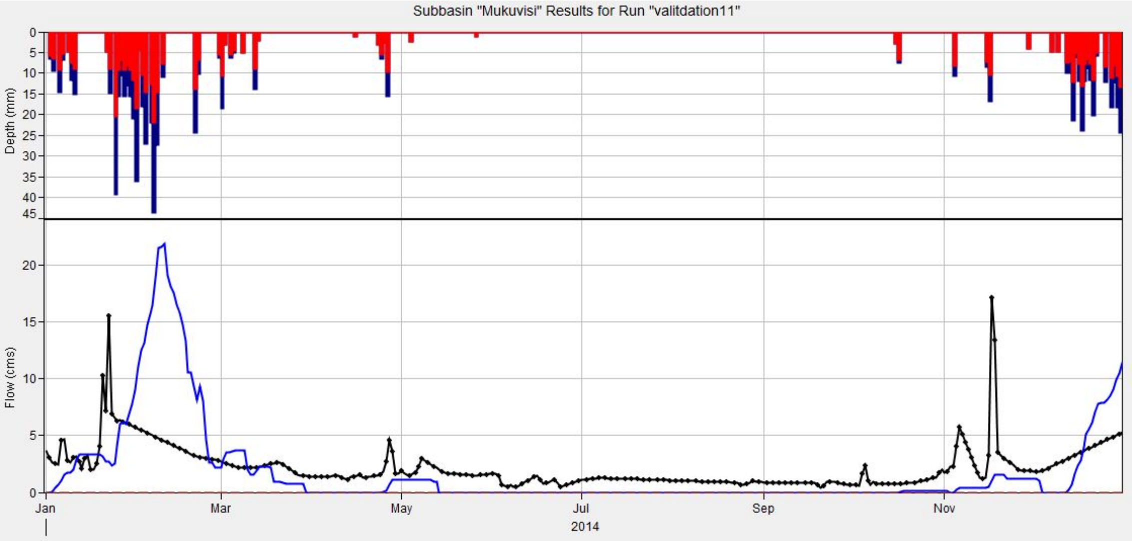


Figure 21: Validation Mukuvisi sub-catchment

4.2. Findings

Both the calibration and validation of the Marimba basin show quite promising results. The expectation is that, after some fine-tuning and the implementation of baseflow data, the simulated hydrograph is of sufficient quality (i.e. near or above a Nash-Sutcliffe of 0.5). The results of the Mukuvisi basin are however less promising. This is probably caused by several reasons such as the insufficient quality of the input data, assumptions made in the methods and possibly inadequate (numerical) approximations of the model (e.g. the bad simulation of the infiltration process).

These errors also apply largely for the Marimba basin. However, the quality of the observed data of the Marimba basin is presumably a lot better as the amount of excess rainfall and observed discharge seem to correlate quite well. For the Mukuvisi basin this correlation is not that good (see figure 21) as was already mentioned in the result section. Therefore, a quality check of the observed discharge data needs to be performed. Before that, the observed discharge data, or data derived indirectly from it, cannot be used for the model.

The total amount of discharge leaving the catchment differed a lot between the observed and modelled discharge in the Mukuvisi basin. A possible explanation for the large volume difference in this basin might be because of groundwater that does not end up in the river, but instead percolates further down into the soil to replenish the overutilized aquifer (more on this in chapter 7.2). Reasoning like this would however not explain the slight over prediction of total discharge in the Marimba basin. Nevertheless, it is important to note that some large fluxes of water in the basin are not determined by natural processes, but caused by human activities, causing problems in the modeling process.

4.3. Conclusion & Recommendations

Recommendations

One of the main recommendations would be the installation of an extra gauging station. Concerning the location of the gauging station, the following conditions are suggested: The gauge would preferably be located at one of the rivers that flow into the Manyame river and that have no (big) dams upstream. This is recommended as these conditions make calibration possible. Another suggestion for the location of the gauging station would be upstream of the escarpment in the LMSC or in the downstream parts of the MMSC, as these two catchments are only gauged in the main Manyame river. A last suggestion would be to choose a location with (almost) no urban area located upstream of the gauging station. This would make it possible to calibrate the hydrological model on an unurbanized area, which is of big importance as the major part of the catchment is not urbanized. Calibration of the model for the less urbanized areas in the catchment might also be done in another gauged catchment, with approximately the same basin characteristics and the same climate.

The other major recomendation is to improve the estimates of imperviousness. The landcover map did a poor job on estimating the amount of urban area. Therefore, this was (partly) done by looking at google satellite pictures, which is of course an arbitrary procedure. It is strongly recommended to improve these estimations. For example, by using the method, described in the 'Loss method' paragraph, which uses NDVI and false color composite maps to estimate the urban extent. However, a bit of luck is needed to get maps in the rainy season without cloud coverage.

For better calibration of Marimba, it would be strongly recommended to gather data about the effluents of the industries discharging in the river, as this might not only improve the modelling of baseflow but might also improve the estimation of other calibrated parameters.

The received data of the gauging stations was only registered per day. For the estimation of parameters, in this case especially the lag time and peaking coefficient, it would be useful if the discharge was (temporarily) registered per hour or even minutes. This is currently already possible because the data is noted on a chart by an autographic recorder, which is a semi-manual measuring device. The prefered alternative however, is to replace the autographic recorders with automatic loggers.

More knowledge on the model, which could not be found but can be requested from the HEC-HMS makers (U.S. Army Corps of Engineers), might prove to be useful. This will improve the appreciation on the possibilities and limitations of the model. Such knowledge is for example needed to understand what the model does with the rain data compared to the infiltration rate which is given per hour while the rain data is per day.

Conclusion

The main goal of this hydrological model was to provide input for a flood model. As one of the inputs required by a flood model is a hydrograph. This hydrograph has to, at least partly, be provided by a hydrological model. This is because the last good working gauging station is more than 70 km upstream of the area that is most prone to flooding (see figure 16). In addition, a significant part of the catchment is draining its water downstream of that point.

The hydrological model was supposed to be done in a few weeks, however due to several setbacks such as delayed availability of data, tedious procedures in data processing, several errors found in the data and problems encountered due to the crisis situation in Zimbabwe, the goal to use the hydrological data as input for a flood model was unfortunately too ambitious.

However, the hydrological model can still prove to be useful. Especially the results of the Marimba basin are quite good for a basin as urbanized and populated as Marimba. This emphasizes the potential of the model for the whole catchment. Due to time constraints there was not a lot of time to fine-tune the model further. However, with the bigger temporal and especially spatial resolution of the rain and evapotranspiration input in this model, there is a lot of potential for its usability. Moreover, both at the University of Zimbabwe and the UMCC interest was shown in the model. An additional benefit is that these institutions use HEC-HMS as their hydrological model program.

After implementation of (at least) the main recommendations stated above, the model can for example be used to model the extent of floods more accurately. Or it could be used to model how sensitive the severity of the floods in LMSC is to both the backwater curve of the Cahora Bassa (which is a big hydro dam downstream of the Manyame Catchment) and the water coming from upstream. Furthermore, as already mentioned in the introduction of this part, other studies such as water quality, water resource management and erosion studies can make use of either the model itself or its outputs. On top of that the model can be used to run multiple scenarios such as different climate scenarios.

5

Floods

In the Manyame Catchment, and the LMSC in particular, one of the big water related problems is flooding. This concerns fluvial as well as river flooding. One of the reasons for river flooding is that this area is affected by the backwater curve of the Cahora Bassa Dam. Also, this downstream river section is characterized by high erodibility of sodic soils and cultivation close to the riverbank, resulting in high sediment loads. The high sediment loads have resulted in a raised river bed (Appendix A.6. Interview Tafireyi Dzomba – LMCC) and morphological changes in the river segments. The extent of the flooding can be modeled with floodplain zoning. This is usually done with a complex hydrodynamic flood model, with applications that can vary widely depending on the methods and the amount of inputs. Unfortunately a good analysis on the risk of fluvial flooding with the help of a hydrodynamic and flood is not possible, because it has proven to be out of the scope and time span of this research.

5.1. Methodology

Determining the floodplain boundaries however, is critical in the risk and resource management in the area. In areas with high flood risk it is the first step for urban development or an environmental protection plan. It can support many applications like flood hazard mapping, policy development, development studies, and the analysis of human-flood interactions. Fortunately, the increased availability of remote sensing data and technologies, have now made it possible to use an alternative to hydrological flood models. With access to long, high-resolution datasets of the Earth's surface properties, scientists have recently developed a high resolution global floodplain raster in the Nature journal [60].

The GFPLAIN250m (accessed via figshare [59]) is the first, comprehensive, high-resolution, gridded dataset of Earth's floodplains at a 250 meter resolution (at the equator). GFPLAIN250m uses a DEM and a geospatial analysis algorithm to produce a gridded floodplain layer all over the world (see Figure 22). The method identifies low-lying cells along river corridors and "recognizes the floodplain extent as formed by those cells, draining to the selected channel location" [60]. "Observing any aerial image of fluvial corridors, one can clearly distinguish floodplain boundaries by their unique shapes and colors," explained lead author Nardi in an interview with the Arizona State University [90]. The newly developed technology gives us in this research the opportunity to gain a better understanding of the complex floodplain-urban interactions in the relatively data-poor LMSC.

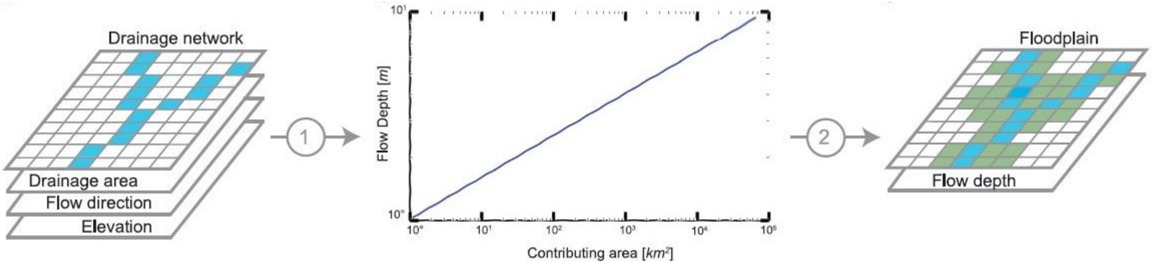


Figure 22: Flow chart describing the DEM analysis and geomorphic scaling law processing for floodplain delineation [60]

5.2. Findings

In Figure 23 the GFPLAIN250m floodplain of the whole Manyame Catchment is presented. As can be seen the floods mainly occur downstream of the escarpment in the lower section of the LMSC. Floodplains are also visible in the area between Lake Chivero and Lake Manyame. A problem of flooding in this area was however never mentioned by any of the people we spoke to. The flooding in the LMSC will be further discussed in Case Study 2, Chapter 9.

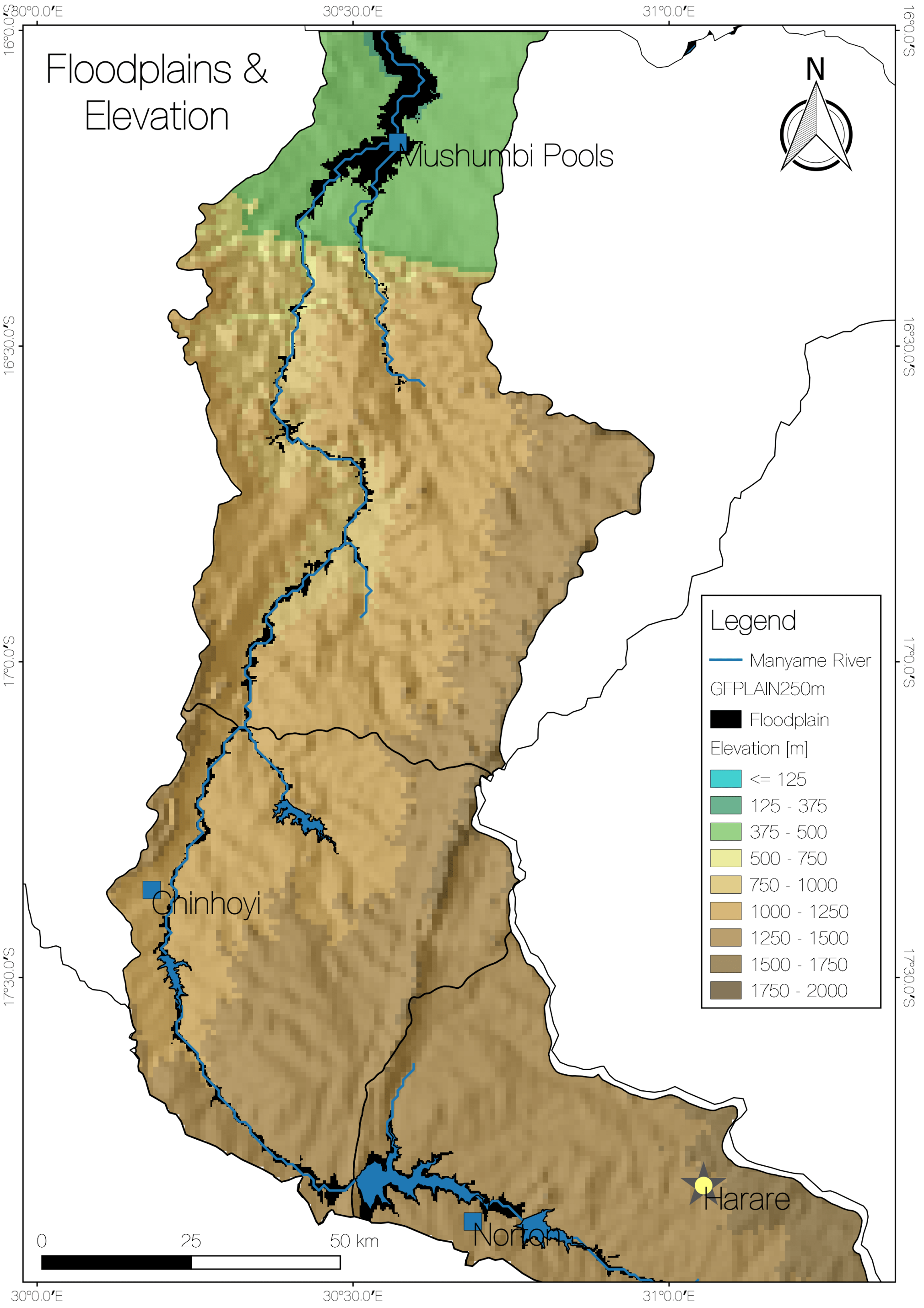


Figure 23: The GFPLAIN250m floodplain is presented in blue color. The DEM of the catchment is presented on the background with the escarpment clearly visible.

6

Water quality

Water quality refers to the physical, chemical, biological and radiological characteristics of water and is usually characterised with respect to its suitability for a specific purpose [10]. Furthermore, water quality is also used to assess the survival of the aquatic ecosystem with respect to the water quality. In addition, the water quality can be used for improved management of natural water bodies to ensure the environmental impacts of pollution are kept to a minimum.

6.1. Literature Study

Before the water quality was assessed in the Manyame Catchment, a literature study was performed to determine the major factor influencing water quality. This influenced the necessary water quality tests to perform.

Upper Manyame sub-catchment

In the UMSC, there are non-point sources of water pollution such as agriculture and mining and point sources such as sewage and industrial effluent. Urbanisation and population growth has lead to an overloading of the sewage treatment plants due to lack of capital investment to expand the WWTP. This results in an increasingly greater portion of untreated sewage being disposed into surface water. In particular in the rainy season, the non-point runoff increases and results in increased nutrients in and turbidity of the surface water. In addition, there are mining activities such as gold and chrome in the UMSC. However, in comparison to the untreated sewage effluent, this contribution is small in terms of affecting water quality [101].

Middle Manyame Sub-Catchment

Agriculture runoff, mining and sewage effluent are all sources of pollution in the MMSC. In terms of agricultural runoff, commercial farming results in a greater risk to the contamination of rivers compared to subsistence farming on communal lands. This is mainly due to the lack of finances in the subsistence farming sector, which makes it difficult for them to buy and use fertilizers. However, overgrazing and vegetation clearing is a common issue amongst subsistence farming. This results in increased soil erosion, wetland loss and loss of river banks and results in the increased siltation of rivers and subsequent dams downstream [57]. An increase in the nutrient concentration due to agriculture and sewage effluent has resulted in an increased invasion of alien species such as the water hyacinth weed (Eichhornia Crassipes) [45].

In terms of mining, a study by Murwira [57] stated there are roughly 20 gold mills present in the whole Manyame Catchment, and mainly in the MMSC and UMSC. This is due to many of the large-scale mines being replaced by small-scale and artisanal due to the economic crisis in Zimbabwe. These small-scale mines do not use the sophisticated extraction technologies of the large-scale mines and these mines are commonly associated with being informal and unregulated leading to poor management of the processing and waste. This has lead to heavy metals such as lead (Pb), cadmium (Cd) and chromium

(Cr) polluting the rivers downstream of the mines. Another contaminant associated with mining are sulphate ions [20]. Acid mine drainage seeping from tailings is another issue that affects the water quality, this is indicated by a decrease in the pH of the surface water.

Agriculture and mining affect the water quality in the MMSC, another major contributor to pollution in the Manyame River is direct discharge of sewage effluents. The problem with the sewage effluent is that it is poorly treated due to overcapacity and poor maintenance and development of the WWTPs. The discharge leads to eutrophication problems in the water bodies due to the high content of nitrogen and phosphorous. Furthermore, this discharge also impacts downstream users as the river water is often used for household activities such as cleaning, bathing etc. In the past, the town of Chinhoyi, situated along the Manyame River, has been found to discharge poorly treated sewage from the Mpata Treatment Plant (MTP) and the Hospital pump station [64].

Lower Manyame Sub-Catchment

The activities influencing the water quality of the LMSC are predominantly agriculture and mining. The sewage effluent is adequately treated and does not pose a threat to the water quality [101]. There is both chrome and gold mining in this sub-catchment, which induces the potential for both heavy metal pollutants and acid mine drainage. Other non-point polluters of the surface water through runoff are both large-scale and small-scale farmers. However, due to land reform, the number of large-scale farming has decreased considerably and as mentioned before in the MMSC, small-scale farming results in increased vegetation clearing and overgrazing. The upstream pollutants could also have a significant impact on the water quality if there is little self-recovery and the dilution of pollutants due to tributaries is poor.

6.2. Methodology

The water quality was analysed using two methods, namely using QGIS techniques and point sampling.

Turbidity

The first method is a remote sensing analysis of turbidity. Turbidity is visually determined by means of QGIS. An empirical formulation is derived by Chawira [4] and expressed as follows:

$$Turbidity = 5.0819 \frac{B1}{B3}^{-1.0125} [NTU]$$

Images of Landsat 5 and 7, band 1 and 3, are used to obtain the turbidity images. The results can be seen in Figures 28 and 29 for Lake Manyame, Lake Chivero and Biri Dam respectively.

Point Sampling

Based on the literature study and the availability of water quality testing kits the following parameters were tested using water quality kits: nitrite/nitrate, phosphates, ammonium, sulphates, free chlorine, total iron, total hardness (as $CaCO_3$), pH, DO and EC. In order to assess the impact of mining on the water quality of the Manyame River, more heavy metals should have been tested, however testing kits for these contaminants were difficult to obtain and the University of Zimbabwe is unable to test for heavy metals in their laboratories. Therefore, the heavy metal tests are limited to testing total Fe, which is still an indication for mining pollution [20]. These parameters are further explained in the Appendix (see Appendix A.7. - Water Quality Parameters).

To obtain an overview of the water quality in the Manyame Catchment area, samples were taken at various points along the river and in some cases tributaries and neighbouring dams were tested. These sample points were chosen based on information from local students, Professors and Working Professionals that are managing the catchment. However, some of the sample points were limited to the accessibility of the river in that area. Therefore in certain areas the sample points had to be adjusted due to lack of access. Where possible, samples were taken straight from the sewage discharge to assess whether the WWTP is treating the effluent adequately.

In order to fully assess the water quality and the influences of point and non-point discharges on water quality, a survey was developed using Akvoflow. This survey includes information on the communities surrounding the sample point, discharge points and land-use. The survey was developed to analyse the risk associated with the water quality as it is also important to obtain a better understanding how the water is used, if it requires further treatment and if there were any water related health concerns in the communities using this water. Unfortunately, it was difficult to obtain information about the areas as often the sample points were taken in rural areas. Therefore, only the water quality data was recorded using Akvoflow (see Appendix A.7 for the layout of the app).

Limitations of the water quality samples

The water quality samples are point samples taken at various points along the river. All samples were taken in situ, however there are some limitations with the data collected. Due to lack of time it was not possible to do more than one sample at each sample point, which would increase the accuracy. Furthermore, there are most likely daily and seasonal variations in the water quality. For example, heavy rains could dilute the pollutants and wash away the invasive plants overgrowing the river. This was also mentioned during fieldwork. Therefore, the data collected should be used as a more indicative means to asses the trend of the water quality in the Manyame Catchment. Moreover, within the dams, there is a large variation in the water quality through the influence of various factors such as dam dilution, differences in water depth and residence time. Therefore, these samples were, if possible, taken near the discharge point of the dam and the outlet of the dam to obtain, as close as possible, the water quality flowing into the river.

6.3. Findings

The trend of the water quality for the Manyame Catchment will be discussed in this section. Based on the preliminary results, a more in-depth analysis was performed on a particular problem area in the Manyame Catchment (see Case Study 1). In the following subsections the most important water quality parameters will be discussed and the indication of these parameters for the water quality and subsequent water users. Furthermore, where possible, possible sources of the poor water quality are indicated. Following the analysis, conclusions are drawn on the major sources of pollution. An overview of all sample points tested is shown in Figure 24 and the corresponding descriptive names are given in Table 6.1.

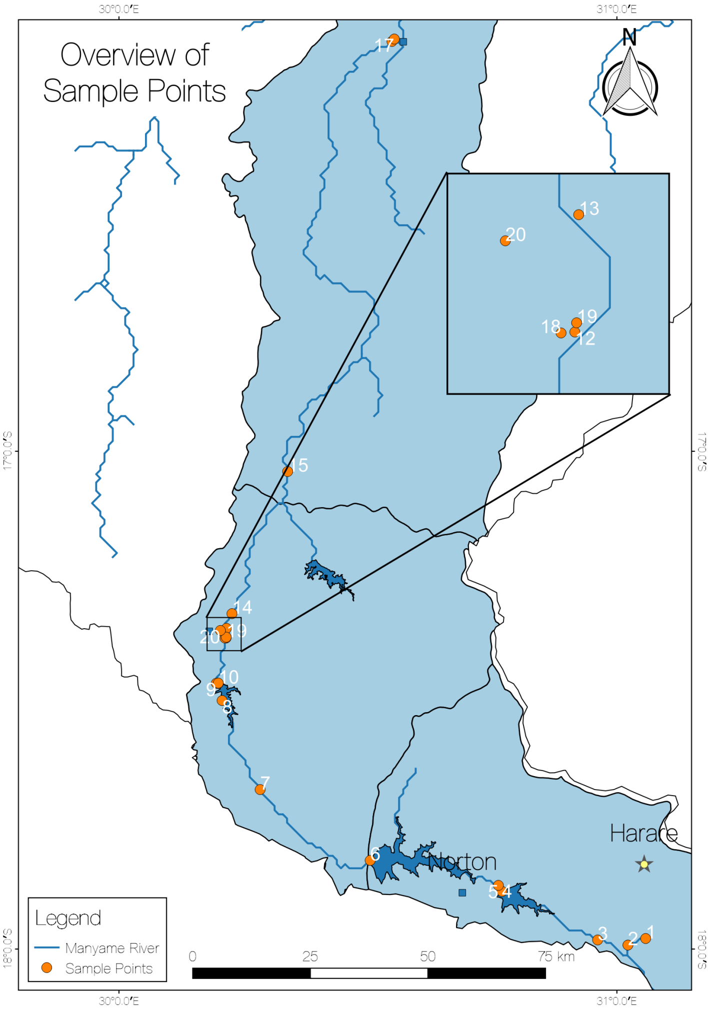


Figure 24: Overview of the sample points for water quality in the Manyame Catchment

Sample Point number	Sample point descriptive name
1	Downstream of Seke Dam
2	Chitungwiza
3	Skyline bridge, Chitungiwza
4	Lake Chivero (near drinking water inlet pipe and overflow)
5	Downstream of Lake Chivero
6	Lake Manyame (Discharge point)
7	Upstream of Biri Dam
8	Biri Dam - Farm inlet point
9	Biri Dam- beginning of Dam wall
10	Biri Dam - near dishcarge intake
11	Biri Dam - Dam outlet
12	Chinhoyi - start of water hyacinth
13	Chinhoyi - Manyame Bridge
14	Chinhoyi - Downstream of Coldstream discharge
15	Manyame Balancing Weir
16	Mushumbi pools - before confluence of Dande River
17	Mushumbi pools - after confluence of Dande River
18	Chinhoyi - Leaking WWTP pipe, Loc 1 (Discharge)
19	Chinhoyi - Leaking WWTP pipe, Loc 2 (Discharge)
20	Chinhoyi - Coldstream (Discharge)

Table 6.1: Corresponding descriptive names for the sample points tested in the Manyame Catchment

6.3.1. EC and pH

The EC, pH and DO results are shown in Figure 25 and are discussed in this section and the subsequent section.

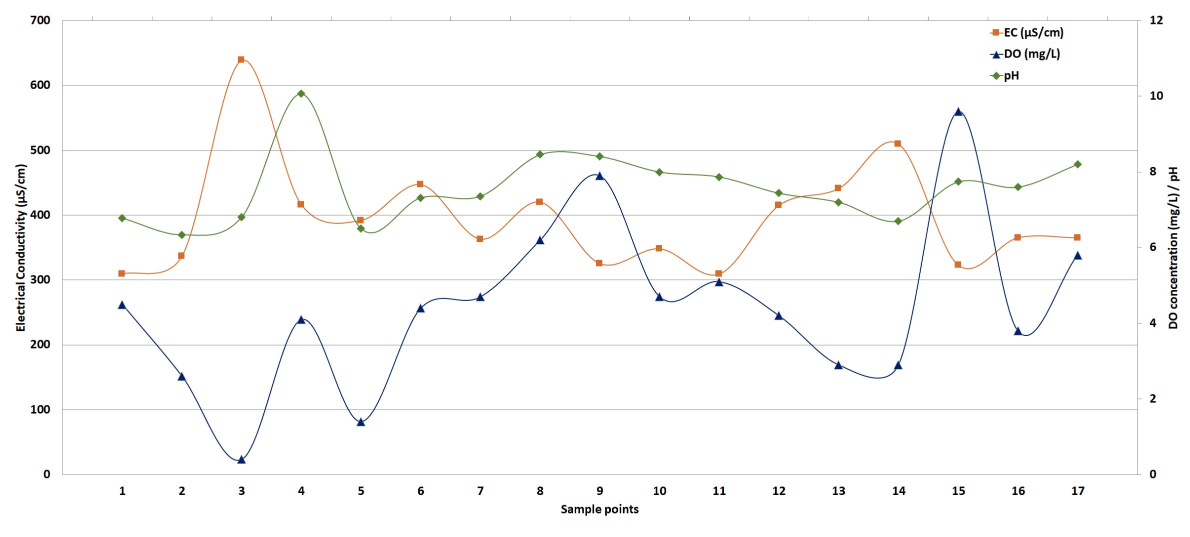


Figure 25: EC, DO concentration and pH results for samples taken throughout the Manyame Catchment

The trend of electrical conductivity is a good indicator of the water quality and to observe whether there are changes in the water quality. It is observed that the EC of the Manyame River ranges from 300μS/cm to 450μS/cm throughout the catchment except for at the Skyline bridge in Chitungwiza (3) and downstream of the discharge from Coldstream (14) (see Figure 25). The lowest EC values were found at the Biri Dam outlet (11) and downstream of Seke Dam (1). Although, the EC is in the required range for fresh water for all sample points, the two peaks in the EC measurements indicate an increase in the inorganic dissolved solids in the river, therefore there is an increase in the concentration of pollutants [22]. The second peak increases more gradually due to there being various discharge sources of pollution.

The first EC peak of 639μS/cm, at Skyline Bridge, Chitungwiza (3), corresponds with the high levels of ammonium, phosphate and chlorine as a result of the sewage effluent being discharged in the Manyame River (see Figure 26). The conductivity slowly decreases as the water quality improves due to the invasion of water hyacinths and degradation of chlorine. Furthermore, the remaining pollutants are mostly likely diluted in Lake Chivero (4). Downstream from the Biri Dam outlet (11), it is also observed that the EC increases gradually to 510μS/cm. This can be explained by the discharge of the sewage effluent (at various points) from the WWTP of Chinhoyi into the Manyame River. A more in-depth analysis of the water quality around Chinhoyi can be found in Case Study 1. Moving downstream, one can see from the EC results that the water quality overall improves as there is a decrease in the EC as can be seen in Figure 25.

The pH of the river system is fairly constant in the range of 6 to 8.5, with the exception being Lake Chivero having an abnormally high pH of 10.1. The pH also increases as one travels downstream of Lake Chivero with the peak being in Biri Dam with a pH of 8.46. Possible reasons for the high pH levels are explained in the sub-section of Lake Chivero where there is a more in-depth analysis of Lake Chivero due to it being the drinking water source for Harare. Furthermore, the slightly increase in pH for Biri Dam is possibly due to the same reason that the pH increases in Lake Chivero. The pH increase for Biri Dam is slightly less.The pH is also influenced by water hardness, in such way that hard water usually has a high pH [23]. Lake Chivero can be classified as very hard, with a hardness of 185mg/L $CaCO_3$, and therefore a high pH is not surprising. For the Manyame Catchment in general, the water hardness mainly varies between 185 and 250mg/L $CaCO_3$ with three exceptions, being Chitungwiza (2) and Chitungwiza Skyline bridge (3) with both a hardness of 120mg/L $CaCO_3$and Mushumbi Pools with a hardness of 425mg/L$CaCO_3$.

6.3.2. DO

From the DO levels, one can see that it varies significantly from the UMSC to LMSC. The DO concentration decreases from downstream of Seke Dam (1) to the Chitungwiza Skyline Bridge (3) as a result of the invasion of water hyacinth that restricts photosynthesis through shading of the water column and increased sedimentation [74]. The concentration increases in Lake Chivero due to significantly less water hyacinth covering the lake and possibly due to the bloom of Microcystis that are now able to photosynthesise [74]. At the same time, it is expected that the concentration is lower at night. An interesting observation that is mentioned in the study by Rommens [74], is that although the concentration of oxygen may be high (around 5 mg/L for example) at the surface in summer, the average concentration in the water column can be as low as 2.5mg/L in summer [43]. This is most likely due to the decay of plant matter in the lake. A decrease in DO was observed downstream of Lake Chivero, which is most likely due to the decay of the filtered sludge from the drinking water plant, Morton Jefferey, that is deposited in the Manyame River. From Lake Manyame downwards the DO increases again, most likely because discharges here are higher (more opportunities for aeration with turbulence).

It can be observed that the DO varies by about 3 mg/L in Biri Dam (8, 9, 10) itself. This is most likely as some areas have more nutrients which result in the growth of algae etc. altering the DO concentration. The discharge structure of Biri Dam is built to aerate the discharge of the dam. However, currently there is an issue with the inlet tower gates that control the level of water intake. Currently, gate 3 is operational however, with the current dam level and sedimentation height it is necessary to use gate 4 and 5 (which are higher than 3). However, due to poor maintenance, this is mechanically not possible, therefore the water that recides at lower levels of the dam is being discharged. This water contains less DO than the water more close to the surface. Thus, the aeration of the discharge appears to be poor because the DO concentration increases only slightly compared to the DO of the surface water in the dam.

The DO concentration decreases again downstream of Chinhoyi (12, 13, 14) due to sewage discharge into the Manyame River resulting in the complete invasion of the water hyacinth in the river. However, the DO improves significantly after the Manyame Balancing Weir as the weir is built for aeration with 3 cascades resulting in the aeration of the water up to saturation. Thereafter, the DO decreases again as one moves downstream. For the LMSC, the DO decreases and then increases to the last sample point (Mushumbi Pools, 16 and 17). However, as these two sample points were fairly close together it was most likely the influence of where the sample was taken that affected the DO as there is no definite explanation for the rapid increase in DO.

6.3.3. Nutrients

The overall concentration of the most important parameters tested are shown in Figure 26. The results from the sulphate tests were not included because all tests results showed sulphate concentrations below 200 mg/L and the range was not small enough for the amounts present in the catchment.

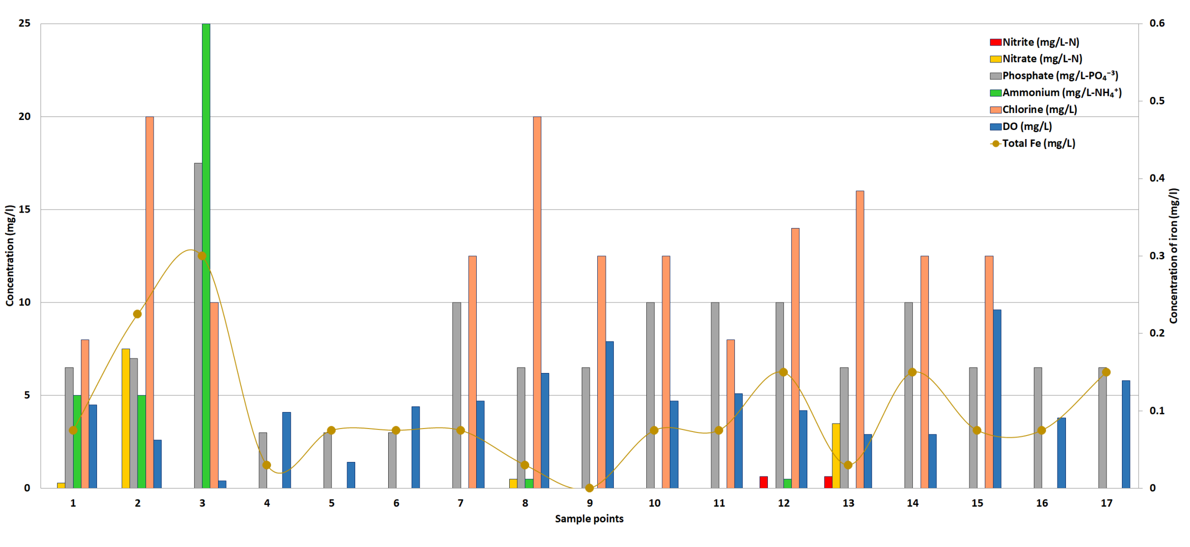


Figure 26: Overall concentration of most important parameters tested, for samples taken throughout the Manyame Catchment

In terms of nutrients (nitrogen and phosphorus), Figure 26 shows a spike in the upper part of the UMSC and two smaller spikes in the MMSC, namely at the farm pumping station (8) and near the WWTP of Chinhoyi (start of the water hyacinth) (12). There are three areas that show a significant increase in the concentration of chlorine, these are namely: Chitungwiza (2), inlet of the farm pumping station (8) and Manyame Bridge, Chinhoyi (13). Pollution in the UMSC is mainly due to the discharge of sewage effluent in the Manyame River. Around Chitungwiza, a leaking sewage pipe and overloaded WWTP are the reasons for the high levels of nutrients. It is also observed that before all three sample points (1, 2, 3), there is most likely an addition of sewage effluent, as the concentration of nitrates increases at Chitungwiza, but the concentration of ammonium does not. Furthermore, there is an increase in the concentration of phosphates from downstream of Seke Dam (1) to Chitungwiza (2). Around Chinhoyi, both the agriculture industry and the sewage effluent contribute to the poor water quality. The concentration of pollutants is most likely higher in the UMSC due to a higher population density being much higher compared to Chinhoyi and therefore more effluent is discharged into the Manyame River.

Besides a high peak in chlorine, the Skyline Bridge (3) in Chitungwiza (UMSC) also contained the highest concentrations in ammonium and phosphate. This is due to the sewage effluent, which is the main source of ammonium, being discharged upstream of this point. The spike in chlorine is as a result of the WWTP using chlorine as a treatment method in addition to more conventional treatment methods as the plant is overloaded. Another possible reason for the high usage of chlorine is to possibly reduce the outbreak of diseases such as cholera, which occur yearly. Cholera outbreaks are not only observed in the drinking water supply system from Morton Jeffrey but also groundwater has been found to be contaminated (Appendix A.2. Interview Dr. Richard Owen - GW expert).

Looking at Figure 26, it can be observed that chlorine partially degrades as one travels downstream, however it is still in excess. Unfortunately, we were unable to test for bacteria such as *E. Coli*, as it would be interesting to see if the high chlorine concentration throughout the UMSC and MMSC would significantly decrease the chance of cholera outbreaks from the water supply. The high levels of chlorine and nitrogen, which are apparent around Chinhoyi, appear to decrease when moving further downstream. At Mushumbi Pools (16, 17) there is no measurement of chlorine or nitrogen, therefore indicating that the chlorine has degraded and nitrogen has been removed. The most likely reason for the decrease in nitrogen is due the invasion of the water hyacinth or the presence of algae in the river, that absorb ammonium, nitrogen and small amounts of phosphorous.

From the water quality tests performed at Lake Chivero and Lake Manyame, the amount of nutrients such as phosphate, ammonia and nitrate are considerably less, with ammonium and nitrate not being present at all, in comparison to upstream. There is a combination of reasons that could explain this. Under the presence of oxygen, ammonia oxidises to form nitrate, with nitrite being an intermediate form of this step, thus decreasing the concentration of ammonium. From field observations, it was observed that the sections of the river with a high nutrient concentration were completely covered by the invasive water hyacinth (see Figure 27). This is because the nutrient rich water provides the ideal environment for these plants to thrive [74]. Although this invasive water plant has many negative impacts, it also has a positive effect on the water quality, as it partially 'cleans' the river by absorbing nutrients in order to grow and thus lowering the nutrient concentration in the river [74]. Therefore, the invasion of the water hyacinth and the dilution effect of the lake could be the reason for the decrease in concentration from Chitungwiza (2) to the sample point in Lake Chivero (4).

Figure 27: The Manyame River upstream of Lake Chivero covered with water hyacinths

Besides the positive effect on the removal of nutrients, water hyacinths have also been reported to have accumulated zinc, nickel and copper in their roots at a concentration factor up to 20 000 times more than in the river itself [55]. A study done by Rommens [74] on the impact of water hyacinth in Lake Chivero, Zimbabwe found that the highest removal capacity was for ammonium at 1.5% followed by total nitrates and phosphate with 0.1 and 0.025% respectively. Therefore, water hyacinth prefer the uptake of ammonium over nitrate. The low removal capacity for phosphate could explain the continuous presence of phosphates throughout the catchment. In this study, it also mentions that at the time of the study only 3.2% of the lake was covered by water hyacinth so that the overall impact on improving the water quality of the lake was low. Despite this low percentage of water hyacinth, Rommens [74] found that the water quality improved between the inflow and outflow of Lake Chivero. The Manyame River is also completely covered with water hyacinth around Chitungwiza (2) (upstream of Lake Chivero) (see Figure 27), therefore the inflow into Lake Chivero could also be partially remediated before it enters the lake. The sample point for our research was near the spillway of the lake (see Table 6.1), after the remediation would have occurred.

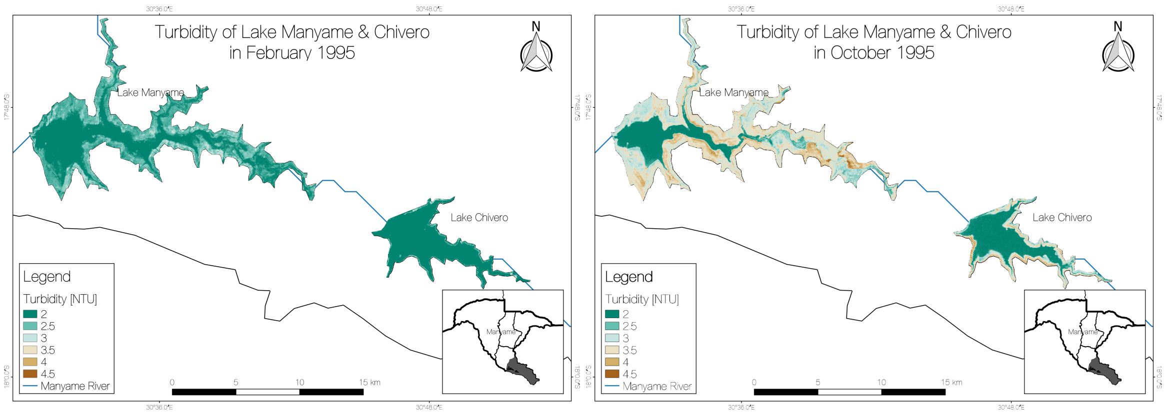
6.3.4. Iron

In terms of the iron concentration, an increase is observed where there is an increase in sewage effluent in the river. The maximum concentration tested was 0.23 mg/L around the Skyline Bridge, Chitungwiza

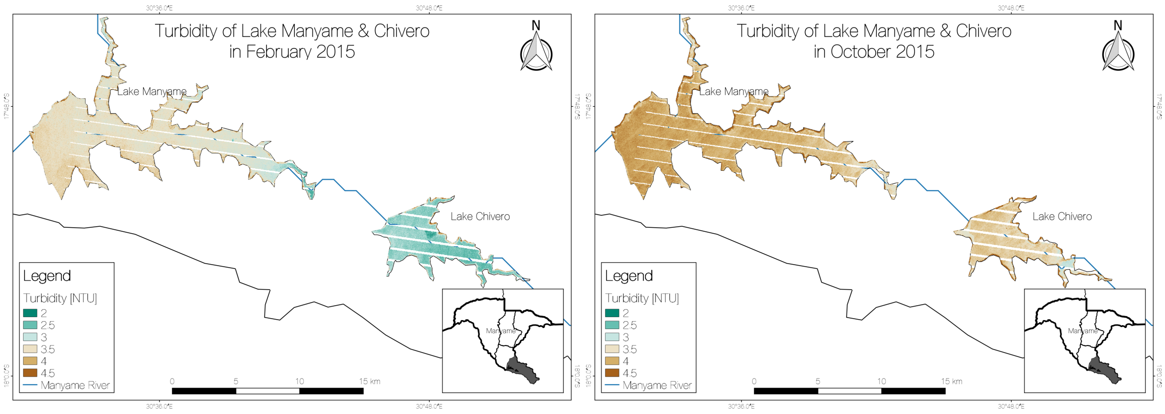
(3). The average concentration is about 0.1 mg/L throughout the Manyame Catchment. The natural source of iron in the Manyame Catchment is most likely the red clay soil that can be found throughout the catchment. Due to leaking pipes the effluent sewage flows into the Manyame River via small streams. This increases the opportunity for iron to dissolve into the surface runoff. This means that more iron dissolves from the soils into the water due to the make-shift stream that is formed and from increased surface runoff flowing into this stream. This is also evident from the water quality tests performed on the effluent wastewater in Chinhoyi and will be furthered explained in Case Study 1. In the LMSC, especially after heavy rains when surface runoff is largest, the iron content increases in the river. This is the reason for the increase in iron concentration from 0.075 to 0.15 mg/L found for two sample points 16 and 17, as it had rained the day before the second sample.

6.3.5. Turbidity

The turbidity of Lake Chivero, Lake Manyame and Biri Dam were analysed using QGIS. Turbidity can be used as an indicator of how the water quality has changed over the years. Turbidity is caused by suspended sediments, coloured organic compounds and phytoplankton. Pollutants such as pathogens (viruses, bacteria) and dissolved metals can attach to these suspended solids and some of these pollutants can have a negative impact on aquatic life [21].The turbidity of Lake Chivero and Lake Manyame from February and October 2015 was compared to the turbidity from February and October 1995 and is shown in Figure 28. The strange marks on the figures are due to poor satellite imagery.



(a) February 1995 (b) October 1995



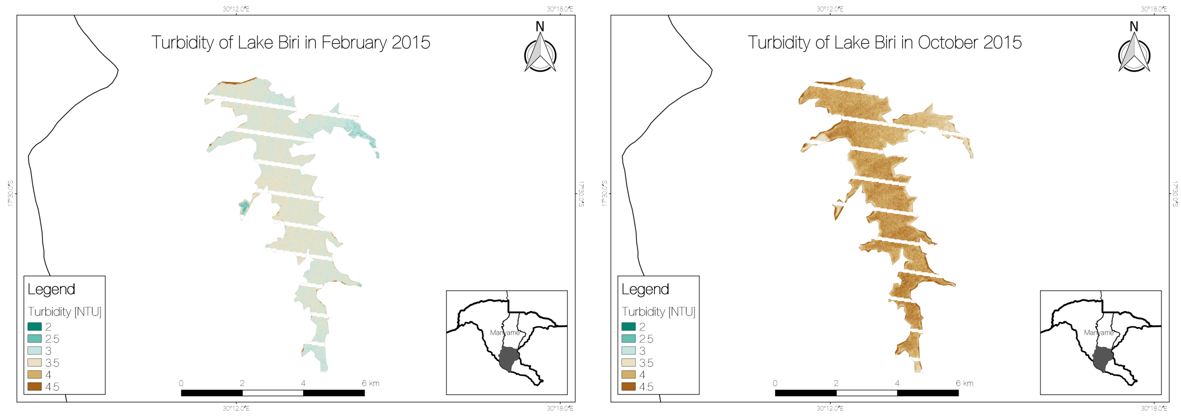
(c) February 2015 (d) October 2015

Figure 28: Turbidity of Lake Chivero and Lake Manyame for February 1995, February 2015 and October 2015

For the year 1995, one can see that both lakes are smaller than 2015 lakes and that there is no difference between the turbidity in the rainy season (February) and the dry season (October) for 1995. In contrast,the turbidity from the end of the rainy season (February 2015) was also compared to the end of the dry season (October 2015) (see Figure 28). For Lake Manyame the turbidity was around 4/4.5 NTU at the end of the dry season. For Lake Chivero, the increase was less at the end of the dry season, here the turbidity increased to about 3.5 NTU. The possible reason for this is that there is less dilution of pollutants in the river during the dry season, because of a smaller river discharge.

Comparing the years 1995 and 2015, for Lake Manyame it is observed that the turbidity has almost doubled in last 20 years. The turbidity increases more in looking at the dry season 1995 to 2015 than the rainy season. However,this is still within the range established by the World Health Organization for drinking water (less than or equal to 5 NTU) [98]. The increase for Lake Chivero was less in the dry season from 1995 to 2015. Based on the other parameters tested, the most likely source of the increase in turbidity is due to the increase of sewage effluent discharge into the Manyame River. This also increases the chance that there are bacteria, protozoa and viruses present. Furthermore, the organic suspended solids most likely also decreases the DO levels as they are decomposed.

In Figure 29, the turbidity of Biri Dam for both February and October 2015 are shown.



(a) February 2012 (b) October 2015

Figure 29: Turbidity of Biri Dam for February 2015 and October 2015

Figure 29 shows that the turbidity for Biri Dam near the end of the rainy season is on average about 3/3.5 NTU and for the dry season it increases to about 4/ 4.5 NTU for a large portion of the dam. The overall turbidity for Biri Dam is similar to Lake Manyame but higher than Lake Chivero. A similar trend, of the turbidity increasing when going from the rainy to the dry season can be seen for Biri Dam. The lower turbidity in Biri Dam in comparison to Lake Manyame and Lake Chivero could be explained by the fact that there are less sources of pollution such sewage effluent flowing into Biri Dam and the volume of agriculture runoff is less than sewage effluent.

6.3.6. Lake Chivero

Lake Chivero has a reputation of having very poor water quality and being in actual fact unsuitable for the supply of drinking water for the City of Harare and the satellite town, Chitungwiza. The majority of the residents that have access to the drinking water supply from Morton Jeffery, do not consume the water because of issues such as the water turning green after 2 days and now rely on groundwater. (Appendix A.2. Interview Dr. Richard Owen - GW expert). The pH of Lake Chivero was measured to be 10.1 near both the spillway and the drinking water inlet tower. Furthermore, the DO was measured to be 4.1 mg/L and a phosphate concentration of about 3 $mg/L\text{-}PO_4^-3$ was measured.

According to a study done by Reid [71], high pH in lakes are most likely attributed to microbial activity and that the removal of CO_2 or HCO_3^- from surface water through photosynthesis can increase the pH to as high as 10.7 in some cases. This could be the reason for the high pH in Lake Chivero. In the study it was found that a high pH was achieved after an extended period of exposure to light, in the experiments conducted by Reid [71] this was after about 4 hours. It was also found that the pH varied diurnally and the pH fell rapidly in darkness. Furthermore, it was found that the sequestering of Ca and Mg as a result of plant growth also contributed to the increase in pH. For high density plant growth, it was also found that the diffusion of CO_2 from the air was poor and therefore, was not able to compensate for the high photosynthetic demand.

The phosphate concentration throughout the catchment and in particular in the dams (Lake Chivero, Lake Manyame and Biri Dam) is above the concentration that is suitable for aquatic life. In comparing the phosphate concentration to the Canadian Water Quality Guidelines for the Protection of Aquatic Life (2004), the concentration of phosphates is in the trigger range of the lake being considered hyper-eutrophic as the concentration of phosphates is more than 0.1 mg/L P. Both Lake Manyame and Biri Dam also fall under this classification due to the high phosphate concentrations, with Biri Dam having double the concentration than that of Lake Manyame and Lake Chivero. In a study done by Magadza [40] on the re-eutrophication of Lake Chivero, it was stated that Lake Chivero was already classified as hyper-eutrophic with a total phosphorous concentration of 0.04 mg/L-P in 1967. After the initial classification in 1967, successful remediation measures were implemented to decrease the concentration. However, after the remediation measures ended in 1978, the concentration increased by more than 20,000 times to a value of 2.24 mg/L of total phosphorous in 2006 [40]. The current concentration of phosphates at our sample point was 0.98 mg/L -P, which is most likely higher if one samples various points in the lake and includes organic phosphorous.

Another parameter that affects the aquatic life in Lake Chivero is the declining oxygen level. At the sample point the DO was measured to be 4.1mg/L. In a study by Gratwicke [25], it was found that most species of fish found in the UMSC were unable to tolerate DO levels below 4 mg/L. In addition, thermohaline stratification is existent in Lake Chivero. This in combination with low DO levels at the surface and even lower DO levels lower down, a turnover can have detrimental effects on the fish in the lake [25]. Previously, there have been reports of major fish deaths due to a turnover and this has coincided with the collapsing of algal bloom build-ups at the end of the summer season. Such collapse of algal bloom releases algal toxins which also contribute to fish kills [49].

Taking into account the European environmental quality requirements for surface water to be used for the preparation of water intended for human consumption, it was found the water in Lake Chivero does not meet all the requirements for the parameters tested. The pH is too high (not in the required range of 7.0 – 9.0), the concentration of DO is too low (should be in the range of 5 mg/L O_2 or more) and the phosphate concentration should be at a maximum of 0.9 mg/L PO_4, and is therefore too high as well [95].

6.3.7. Overall

In summary, although to a certain extent there is self-remediation of the Manyame Catchment through the invasive water hyacinth, the water quality in this catchment is fairly poor. An overview of the water quality in terms of sewage and chlorine pollutants in the Manyame Catchment is summarised in Figure 30. Only ammonium, nitrates and nitrites are considered as 'sewage' pollutants because there is a high level of phosphates throughout the catchment.

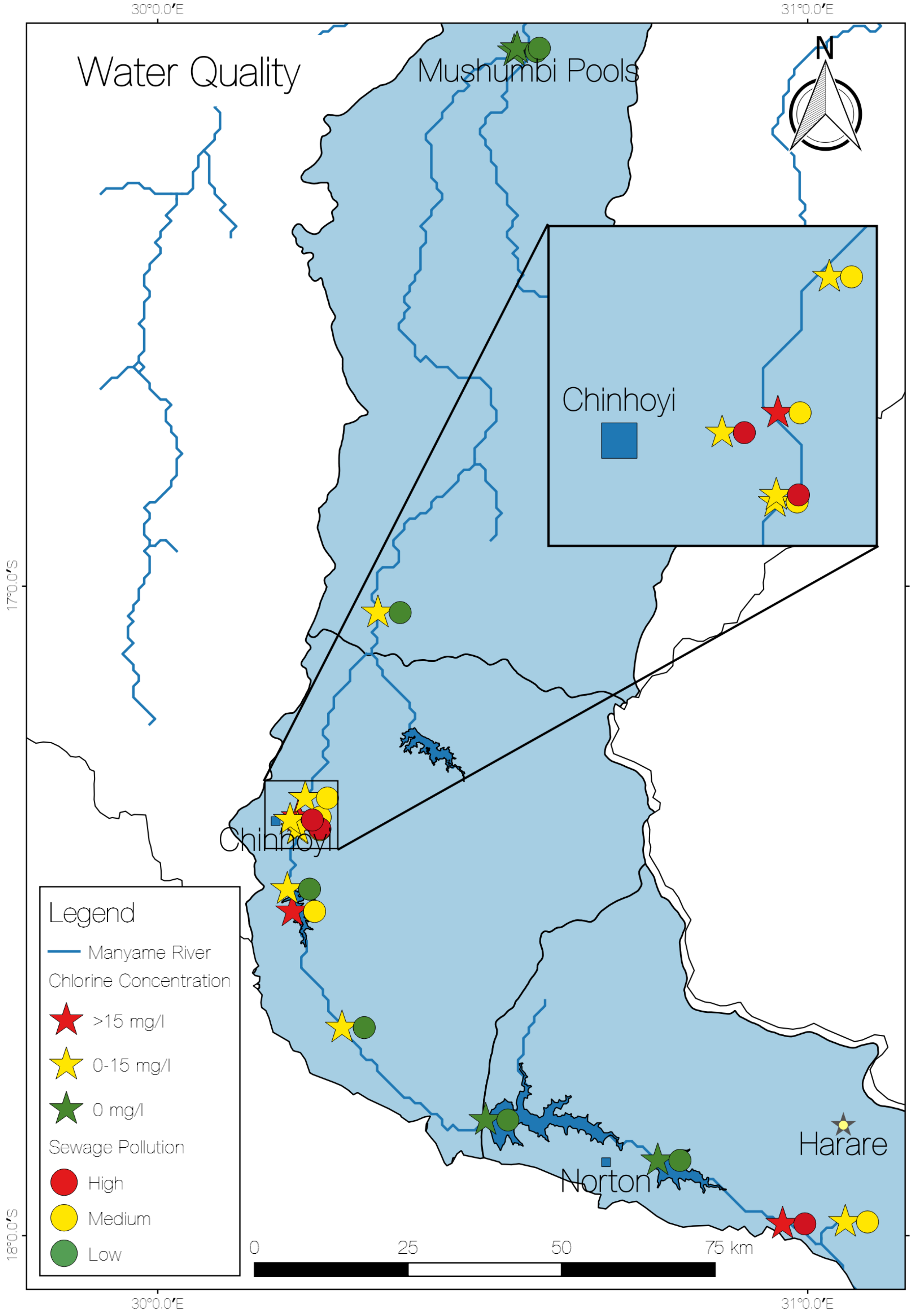


Figure 30: Overview of the water quality throughout the Manyame Catchment in terms of sewage effluent and chlorine

In terms of the standards for aquatic life, the water is only suitable for fish in the areas where the concentration of oxygen is above 4 mg/L and the abundance of fish also decreases significantly when the conductivity is higher than 400μS/cm [25]. Other than in the major dams, the water quality is not adequate for a healthy aquatic life in most parts of the Manyame River due to the invasion of water hyacinth. Furthermore, the high phosphate concentration in the river system and lakes, results in the dams and lakes being highly susceptible to hyper-eutrophication which results in algal blooms and potentially mass fish killings. The water quality of Lake Chivero also does not meet the quality required for surface water to be used as drinking water due to the high phosphate concentration and low DO. Therefore, as already mentioned, Morton Jeffery drinking water treatment plant is struggling to purify the water to an adequate potable standard.

In the MMSC, it can also be seen that sewage effluent significantly affects the water quality around the Chinhoyi area. Furthermore, there have been complaints about the poor water quality of Biri Dam, in particular due to chlorine which affects the tobacco crops (Appendix A.4. Interview Noah - Dam manager Biri Dam). In general, Biri Dam is affected by the same issues of hyper-eutrophication as Lake Chivero due to the high phosphate concentration.

In the LMSC, the main pollutant found was the high levels of phosphate, most likely due to agricultural runoff. Interestingly, there is no chlorine present below the Manyame Balancing Weir, this is because most of the settlements here use pit latrines and due to the low-density settlements, the WWTP are able to sufficiently treat the water. However, despite the water tests not showing evidence for sewage effluent in the river, cholera and other diseases are often a yearly occurrence (Appendix A.6. Interview Tafireyi Dzomba - LMCC). This, most likely, is due to a lack of chlorine present in the water and pollutants from livestock and settlements on the sub-catchment banks that have more informal sanitation.

6.4. Conclusion & Recommendations

From the overall water quality analysis, it can be concluded that the major contributors to the pollution in this catchment are sewage effluent discharge and agriculture runoff. The major issue is the poor performance of the WWTP in the UMSC and MMSC due to lack of maintenance and overloading. Lake Chivero can not be classified as an adequate source of water for the drinking water supply. In terms of water quality for irrigation, chlorine is a big issue that affects the irrigation water. A more in-depth discussion can be found in Case Study 1 explaining the possible source of this pollutant. Downstream from Biri Dam, sewage effluent affects the water quality resulting in invasive water hyacinth covering the river. This negatively affects the aquatic life, however, does improve the water quality further downstream, with the exception of phosphates. Therefore, the water quality has not improved sufficiently to surface water standard for drinking water. The sewage effluent of Chinhoyi will also be further discussed in Case Study 1.

Therefore, in order to improve the water quality in this catchment for both the population and the environmental aspect various measures need to be implemented. Especially, as the main drinking water source for Harare, Lake Chivero, is not adequate for the supply of drinking water. There need to be stricter controls on the discharges of WWTP as these contribute significantly to the poor water quality and eutrophication of the dams and lakes. Furthermore, the updating of these WWTPs is necessary to achieve the required discharge quality. Previously, in the 1970s Lake Chivero was remediated through strict discharge controls [40]. Part of the sewage effluent was used as a fertiliser on agriculture to decrease nutrient discharge. This could be implemented again.In terms of agricultural runoff, bufferzones can be implemented using grasses, wetlands etc. to filter the runoff before it enters the river or lakes [93].

7

Future water supply Harare

The city of Harare has seen a tremendous increase in population size. This coincided with an increase in water demand. Due to deteriorating water quality, especially in Lake Chivero, a poor water distribution network and declining groundwater tables, Harare is now facing two main challenges. These are a long-term water scarcity problem and the immediate water quality problems in Lake Chivero (see Chapter 6). This results in increasing pressure on drinking water availability for the City of Harare [63]. Climate change, which will cause the dry season to be longer and rainy seasons to receive less but more intense rainfall events, could even worsen this situation in the upcoming years [46]. This raises the question if the drinking water supply from both Chivero and Manyame Dam will be enough to fit the increasing water demand of Harare over the upcoming years and whether a new dam must be constructed to create a new 'clean' source for drinking water [97].

To answer this question this chapter is divided between the role of surface water and groundwater respectively.

7.1. The role of surface water

In order to supply the City of Harare from drinking water, Chivero Dam was constructed in 1952 [84]. In order to augment the Harare City water supply a second major dam was build in 1976, knowing to be the Manyame Dam [96]. From these lakes, water is treated at Morton Jeffrey water treatment plant, pumped into smaller reservoirs, and distributed to supply the piped water network in Harare. However, due to a deteriorating water quality in Lake Chivero and Lake Manyame (see Chapter 6), and the possible reduction in capacity due to siltation, the capability of both lakes supplying Harare with sufficient water in the future is under threat.

7.1.1. Methodology

To answer the question above, the variation in water volumes for both reservoirs have been analysed. For more than twenty years, ZINWA has been monitoring the dam levels and corresponding capacities of the major dams in Zimbabwe in order to keep track of water availability. However, to be able to monitor volume variations, also changes in bed levels of the reservoirs have to be taken into account as a rising bed level decreases the reservoir capacity. Traditionally, this is done by obtaining bathymetry maps from hydrologic field surveys (A.5. Interview Bilton M. Simango – MMCC) and using sonar sensors on ship transects to measure the underwater topography [11]. Another approach for dams constructed after satellite data started becoming available is to estimate the change in bed level by using Geographic Information Systems (GIS) enabling satellite data. This approach also requires either bathymetry maps or in-situ measurements. However, these kind of surveys and measurements are time consuming, costly and therefore not applicable within the time span of this research. Therefore the bed level changes of the reservoirs cannot be quantified, but in order to get an idea and to answer the question whether a new dam for drinking water is a necessity, interviews have been held with local water authorities, and water specialists.

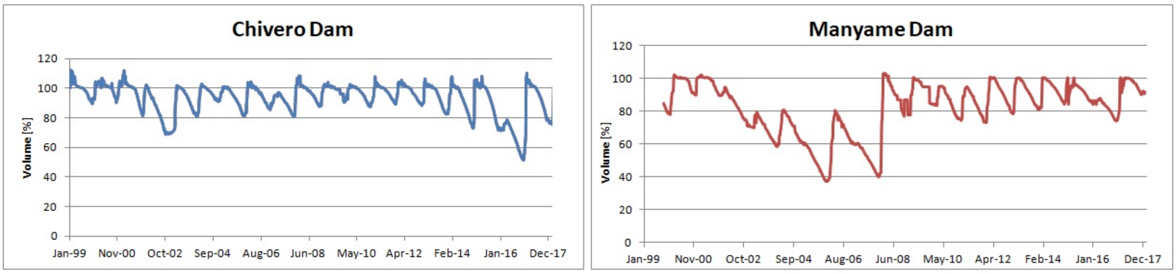
In an interview with ZINWA, Hacklin Chengeta (Appendix A.1. Interview Hacklin Chengeta - ZINWA) stated that ZINWA has performed small scale sedimentation tests in Cleveland Dam to analyse if siltation would be a problem in Lake Chivero. The tests showed positive results from which was concluded that silting up of Lake Chivero is no major issue and that there are no concerns for the dam capacity to decrease. The same conclusion can be drawn for Lake Manyame. One of the reasons for this is that Lake Manyame barely receives sedimentation from upstream as Lake Chivero is located only a few kilometers upstream and is known to have a very low sedimentation outflow.

However, according to Harare Water acting director Mabhena Moyo, the storage capacity of Lake Chivero has reduced by 10 metres, from 28m to 18m, due to siltation caused by urban agriculture [32]. However, how this is determined is not exactly clear. In addition, a Professor of environmental studies at the University of Zimbabwe Christopher Magadza says the siltation in Lake Chivero should not be treated lightly as future generations run the risk of not having a source of water [32]. He estimates that, with Harare's ever-growing population and the increase in riverbank cultivation, by 2045 Lake Chivero will be so shallow it will not be able to store water for more than six months. On top of that, the MMSC manager thinks siltation is a problem that must be taken into account (see Appendix A.5. Interview Bilton M. Simango – MMCC).

Regarding the interviews, the conclusion can be drawn that siltation in Lake Manyame is not significantly apparent. However, it is not completely clear whether the silting up of Lake Chivero is a real issue as multiple organisations have different opinions. Fact of the matter is it is a unquantified issue. As there is no unambiguous answer about siltation being a problem or not, a decrease in capacity for Chivero Dam due to siltation will not be taken into account when analysing volume variations over time. Therefore, the assumption is made that variations in water volume in both reservoirs can be estimated from only dam level-capacity relationships, and dam level time series, both obtained from ZINWA. The dam level-capacity relationship has been calculated by ZINWA before the dams were built, by enabling contour lines. Both data sets are combined to produce graphs showing the volume variations over time in percentage for both Chivero and Manyame Dam (see Figure 31).

7.1.2. Findings

In Figure 31 the change in volume in percentage is shown for both Chivero Dam and Manyame Dam for the period 1999 till 2017. Looking at these graphs, a seasonal cycle can be seen which for the last ten years (from 2008 onwards) has been reasonably stable with volumes ranging between 80% at the end of dry season and full capacity at the end of the rainy season. It can be noticed that during the rainy season, the dams are restored from 80% to 100% within one month, sometimes it only takes two weeks to restore the dams to full capacity after the dry season. However, the graphs also show periods in which the dams reach reasonably low levels, especially if we look at Manyame Dam.


Chivero Dam

Manyame Dam

Figure 31: Chivero and Manyame Dam: volume over time in percentage

The periods with low levels correspond with years of drought (see Chapter 3). From 2003 till 2005, Zimbabwe encountered a long-lasting drought (see Table 3.1) which was most severe in the summer of 2004 (see Figure 32). During this drought, Manyame Dam experienced significantly lower levels than Chivero Dam. This is probably due to the fact that Chivero Dam saved its water to supply the citizens of Harare with drinking water by not releasing any water downstream. Manyame Dam, therefore, did not receive any water from upstream. This can be seen in the graph by looking at the rainy season from November 2014 till February 2015. Instead, it had to release water for users downstream which suffered from the drought. This left Manyame Dam with a low volume percentage around 40% at the end of the dry season in 2015, as can be seen in Figure 32.

Another severe drought occurred in 2016, which especially affected Chivero Dam, as can be seen from the graphs (see Figure 33). The difference in volume behavior of the two dams with the long-lasting drought from 2003 till 2005, might be that this drought came unexpected. Where Chivero Dam saved its water just before the drought of 2004, it was releasing water in the dry season of 2015 like normal to prepare for the upcoming rainy season. However, this rainy season turned out be dry, meaning that the dam could not be restored to full capacity, resulting in low water levels.

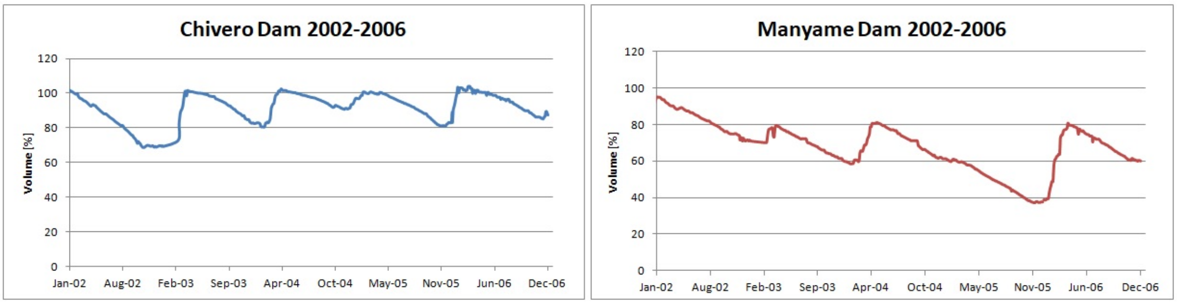


Figure 32: Chivero and Manyame Dam: volume over time in percentage during drought from 2003 - 2005

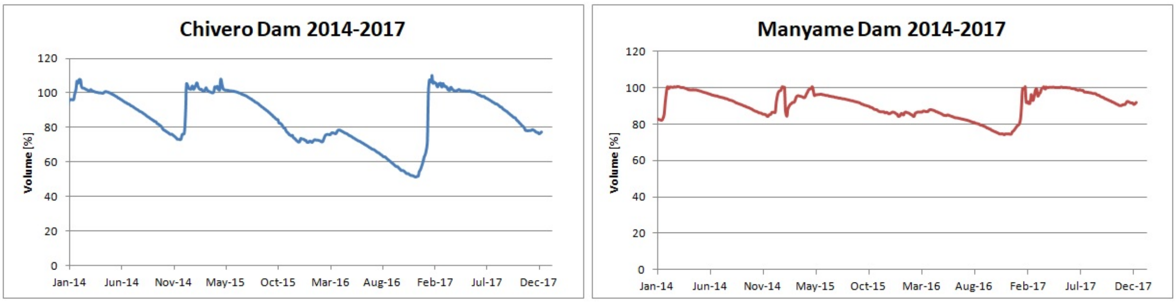


Figure 33: Chivero and Manyame Dam: volume over time in percentage during drought from 2016

Zooming in on the droughts (see Figures 32 and 33) both dams show cases of a large decline in volume, with a minimum just below 40% in 2005 for Manyame Dam. However, these were severe droughts which do not occur regularly (see Table 3.1). The figures also show that even after such intensive droughts, one rainy season can be enough to refill the dams to a capacity of up to 80%, which is also acknowledged by Hacklin Chengeta (Appendix A.1. Interview Hacklin Chengeta - ZINWA).

However, the long-term water scarcity problem of Harare is not only water quantity focused. It gets intensified by the fact that the water quality of Lake Chivero is inadequate (see Chapter 6). Especially Total Nitrogen (TN) and Total Phosphorus (TP) levels have reached critical levels considering that the lake supplies drinking water to a very large population. This is caused by continuous deterioration of the water quality in the rivers discharging into Lake Chivero, which is mainly due to the increasing water demand causing the WWTP to be overloaded. The WWTP therefore cannot treat the waste water well which leaves them with discharging the non treated water upstream of Lake Chivero. This will then flow into Lake Chivero, where Harare on its turn will use it as drinking water again. So, in practice there is a negative loop going on in which Harare is polluting its own drinking water source. The bad water quality in combination with water treatment difficulties and clogging of irrigation pipes caused by high content of algae in the lake water, augments the problem of drinking water availability [63].

7.1.3. Conclusion & Recommendations

According to our findings on both Chivero and Manyame Dam, we can conclude that there is plenty of water available for the City of Harare. According to the figures the dams reach full capacity almost every year. Thus, in terms of water quantity there seems to be no threat for drinking water supply of the City of Harare. This is acknowledged by Hacklin Chengeta (Appendix A.1. Interview Hackling Chengeta - ZINWA):

"In terms of availability, Chivero Dam and Manyame Dam are big enough to fulfill the needs. Even if Harare does not receive enough rain through the season, they might catch up in the next season without any challenges. The construction of a new dam for the supply of drinking water for the City of Harare is therefore unnecessary in terms of water quantity."

The MMCC manager (Appendix A.5. Interview Bilton M. Simango - MMCC) agrees with this, mentioning that the big dams in Zimbabwe, such as Biri, Chivero and Manyame Dam have never reached a stage whereby the dam levels were critically low. But therefore it is not exactly known at what level the dam capacities become critical.

To get an idea when critical levels are reached a comparison is made with the critical period Cape Town went through in 2018 what was called 'Day Zero'. Comparing the situation in Harare with the critical situation in Cape Town, it turns out that Chivero and Manyame Dam have not yet been down to critical levels. During its worst months, Cape Town faced dam capacities reaching below 20% [83]. This is when the situation got very critical and severe water restrictions took place. In addition, levels in the Katse and Mohale Dams in South Africa, which are key water storage systems for the South African province of Gauteng, had a combined capacity of 32% in late January 2018. This raised concerns that the water crisis would spread beyond Cape Town [83]. A comparison suggests that the minimum of 40% reached by Manyame Dam during a period of severe drought (see Figures 32 and 33) is low but not critical. The statement of the MMCC manager in which he says that the big dams in Zimbabwe have never reached a stage of critically low dam levels, can therefore be assumed to be true (Appendix A.5. Interview Bilton M. Simango - MMCC). It therefore can be concluded that in terms of water quantity a new dam to enlarge the drinking water supply for Harare does not seem to be necessary.

However, this conclusion might change when looking beyond the water quantity part, taking into account other important aspects. Dr. Richard Owen, for example, says:

"Engineers will come to the dam and they look and they say 'there is enough water in the dams, so why build another dam'. Now look at the issues. The non revenue water, huge water losses in the network and the pollution".

So, the opinion whether a new dam is necessary in order to be able to supply Harare with sufficient water depends on multiple factors and is therefore rather complex.

According to Hacklin Chengeta (Appendix A.1. Interview Hackling Chengeta - ZINWA), pollution is one of the major challenges. This is acknowledged by Dr. Richard Owen (Appendix A.2. Interview Dr. Richard Owen - GW expert). He says that when the issue of water quality is taken into account there is an argument to be made for a new dam. A new dam that is not constantly polluted by the city it is providing for would have many advantages. However, the investment needed for the dam construction and maintenance far outweighs the cost of upgrading the water treatment plants.

He also mentions that a possible reason for resorting to a new dam rather than cleaning up the current dams and improving the water treatment plants is that this dam will be partly financed by China.

"It is a form of the Chinese buying political mileage. They want to be politically well rallying with the president and the ruling party and in return they receive access to mineral resources." (Appendix A.2. Interview Dr. Richard Owen - GW expert)

The Chinese solution however, is often a very expensive solution for the Zimbabwean citizens as the example made by Dr. Richard Owen (Appendix A.2. Interview Dr. Richard Owen - GW expert) would suggest:

"It's the same as happened in Bulawayo. I mean all the studies in Bulawayo, and there have been plenty, show that this whole solution of taking water from the Zambezi or the Gwayi-Shangani dam, 255 kilometres to the north, is a very very expensive solution. It's eight times more costly than the next solution."

"Letting the residents in Bulawayo face a huge cost for energy to pump that water. Maintenance will be massive. I mean, I'm not an economist but the economists say that the price will be 8 dollars a cubic meter. The other water supplies are coming in at 1 dollar."

This reveals the decision on whether building a new dam is necessary or not is not only a matter of looking at the water quantity and water quality. Also political aspects and the influences of multiple organisations can play a big role in the decision-making process.

Another important aspect of this discussion is how serious the development of siltation is in Lake Chivero. If it turns out that Lake Chivero has indeed silted up by ten metres, as mentioned by Christopher Magadza [32], and this trend is going to continue in the upcoming years, the supply of drinking water from Lake Chivero will decrease massively. This means Harare is slowly losing a large supply of drinking water and will become more and more reliable on Lake Manyame. So if siltation is indeed apparent it plays a vital role in the question whether the drinking water supply from Chivero and Manyame Dam will be sufficient for Harare in the upcoming years. Therefore, more research into the siltation of Lake Chivero is required in order to be able to make an accurate estimation of the necessity of a new dam, thereby taking into account the water quality issues and the effect of climate change.

In addition, climate change has to be taken into account. With longer droughts and more intense rainfall it will be more difficult to store the excessive rainfall during the rainy season and to manage this water during the longer dry season. Oliver Masimba [46], states that these changes in climate affect reservoir inflows for Lake Chivero and Lake Manyame negatively by 10 – 34%. Restoring the dams to full capacity after dry season will therefore be more difficult, making both dams less resilient for droughts. In addition, the long-lasting droughts will affect the water quality negatively.

To have a better idea of the effects of climate change, a more in-depth analysis with multiple scenarios should be performed. In addition, the costs of improving the distribution network and solving the water quality issues, as well as the costs for a new dam have to be analysed.

7.2. The role of groundwater

Groundwater plays a pivotal role in providing drinking, industrial and irrigation water for many stakeholders in the world. Zimbabwe is no exception with over 68% of its population depending on groundwater (see Figure 34) [12]. The water aquifers buried deep down in the ground experience a delicate balance between recharge and discharge fluxes. The groundwater recharge is a function of the climatic factors, local geology, topography and land use [5]. Discharge fluxes in groundwater aquifers can be in the form of water transmit from areas of recharge to areas of discharge, such as rivers. As mentioned by Nhapi et al., [62] the rivers' baseflows in Zimbabwe are mainly influenced by the rainfall pattern, but in the Manyame Catchment there are a few perennial rivers whose low flows are sustained by significant contributions from groundwater.

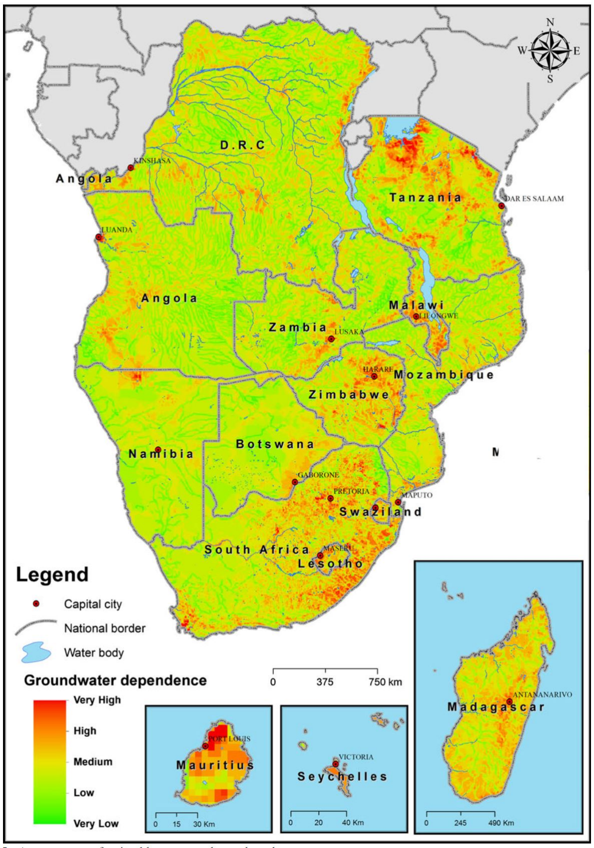


Figure 34: Groundwater dependence as developed by [91].

In the past decades however, further significant stresses generated from anthropogenic activities have affected safe usage of groundwater sources [53]. The combination of substantial expansion of the urban areas and unreliable or not available water delivery systems in the UMSC has resulted in a massive increase in private boreholes [101] (Appendix A.2. Interview Dr. Richard Owen - GW expert). Cases of salmonella and cholera has led people to further distrust the city water (Appendix A.2. Interview Dr. Richard Owen - GW expert). Many citizens have therefore converted to boreholes, leading to an increase in the official amount of boreholes in the UMSC to 15,830 in 2014 [88], with many more boreholes expected to be unregistered. As mentioned by Dr. Richard

Owen in an interview *“the Upper Manyame has I think 15,000 boreholes records. But one of their old managers estimated that there were actually 75,000 boreholes in Harare.” “People just drill. But there’s no monitoring, no policing. Just call a drilling company, drill a hole and pump water. So I mean I don’t know anyone that ever verified that figure of 75,000, but it’s probably more accurate than 15,000”*.

According to the Water Act of Zimbabwe it is a pre-requisite that no borehole or well should be sunk within a radius of 200 meters from an existing one. Groundwater borehole development in the UMSC, and especially Harare, is contrast to this legal requirement as almost every household has a groundwater source [53]. Most are found in the middle and high income suburbs as well as industrial areas where people can afford the relatively high development costs of approximately 1,500 USD. The low income earners and informal settlements however, also utilize groundwater and are mostly dependent on community boreholes [53].

Especially during dry periods, which have become longer due to changes in climate [53], but also in dry spells within the rainy season, the pressure on the groundwater reservoirs has increased over the last decades [54]. In these years of drought, also agriculture in the UMSC and MMSC have resorted to using groundwater. Since groundwater responds relatively slow to meteorological conditions compared to surface water, it can provide the natural buffer and resilience against the effects of climate change [5].

In 2008, the IPCC Technical Paper [6] on water emphasized the major uncertainty in how changes in climate may affect groundwater and what resources are currently available to help support adaptation strategies. The monitoring of quantity and quality of groundwater is therefore important in water resources management, utilization and development, but is inadequate in Zimbabwe [5]. Besides the amount and location of boreholes being badly documented, also their pumping capacities are often unknown, causing an unknown amount to groundwater withdrawal. Also, the water quality of these boreholes is highly under threat as the use of septic tanks in households, especially in Harare, is becoming very popular due to sewage systems overload. According to Sood [82], open dumps as well as controlled dumps have the potential to significantly pollute groundwater sources. Also new housing cooperatives threaten groundwater sources as most locations are not yet connected to municipal sewer systems [101]. In particular in the poorer communities quality of the borehole water is unidentified. Ineffective monitoring has contributed to unsustainable development and use of groundwater and is compromising the ability to effectively manage the quantity and quality of the resource for future generations.

Zimbabwe has a strong annual cycle of rainy and dry periods (see Figure 8). This cycle dominates the seasonal variability of the size, and also the mass which will be important for our method later on, of the groundwater aquifer. During periods of droughts, or when sanitation services experience problems, many people, farmers, industries and institutions have turned to groundwater resources. Especially the UMSC and the MMSC, make enormous use of the groundwater resources. When these resources are recharged in the rainy season, the storage stays the same, but when overexploited, the storage decreases. And just like other aquifers, at some point you will run out of groundwater. An important issue with groundwater aquifers however, is that around halfway through the aquifer water quality start to deteriorate because of dissolved solids and sediments (Appendix A.2. Interview Dr. Richard Owen - GW expert). At that point it is very cost prohibitive to use the groundwater for anything.

The big issue, not just in Zimbabwe but many other places in the world, is that it is not exactly known how much water we have underground. Using GRACE data, described below, we can address the observational gap of monitoring regional groundwater storage changes and figure out how much we are taking out. What is not known is how much is still left and how the quality of the water will change in time. If groundwater sources are being over-utilized and in a state of decline this might in the long-term have significant effects as they provide drinking and industrial water in and around Harare, most of the domestic water in rural areas and supports irrigation.

The study to groundwater changes in this research was conducted in the UMSC as it is this subcatchment that is especially characterized by significant pressure on groundwater resources. As Dr. Richard Owen suggests in his interview however, the widespread pumping of groundwater in the fractured aquifers of the MMSC is also an unsustainable activity (Appendix A.2. Interview Dr. Richard Owen - GW expert).

The GRACE Mission

The GRACE mission, consisting of two chasing satellites, looks at mass changes all over the world [61]. With water having such a contribution to the mass of the earth it gives an opportunity to understand the water cycles and water resource changes. The mission launched in 2002 and has since then been giving monthly changes in the gravity field of the earth. To calculate the temporal change in the gravity field, the gravity field of a given month is subtracted from the long term average gravity field. This is the static gravity field that is believed to not change in time. The resulting map shows the gravitational anomalies. The time series from GRACE can be interpreted to comment on how water resources and storage are changing throughout the world. Important is to see if a trend can be found over the GRACE record.

Unfortunately the spatial resolution of the GRACE satellite is relatively limited. The GRACE satellites do not measure variations in groundwater storage directly, but instead measure the Earth's gravitational field [5], resulting in no exact resolution of footprint. The satellites are dancing in orbit and feeling the pull of different masses on the ground, but they don't exactly know where this pull is coming from within a certain radius. The GRACE project uses the measured variations in the range between the two satellites, supported with other tracking data, to estimate gravitational coefficients, along with other dynamical orbit parameters. With these estimated parameters it is then possible in a least squares estimation to maximize the fit between a modelled satellite orbit and the measurements [5]. This makes the spatial resolution of the GRACE satellite around 2 degrees by 2 degrees, or roughly 200km by 200km at the equator.

7.2.1. Methodology

In the past geophysical and geoelectrical techniques have been used in groundwater exploration. These methods have been applied in various groundwater assessments across Zimbabwe [44], but the methods are expensive and time consuming. In recent developments, GIS and remote sensing techniques have become widely used tools in the assessment of groundwater resources.

Using the NASA GRACE Data Analysis Tool the NASA GRACE datasets are compared and analyzed. For computational reasons, all data has been interpolated to a 1x1 degree grid. The official GRACE Data Analysis Tool continuously releases monthly gravity solutions from two different processing centers:

- CSR (Center for Space Research at University of Texas, Austin)
- JPL (Jet Propulsion Laboratory)

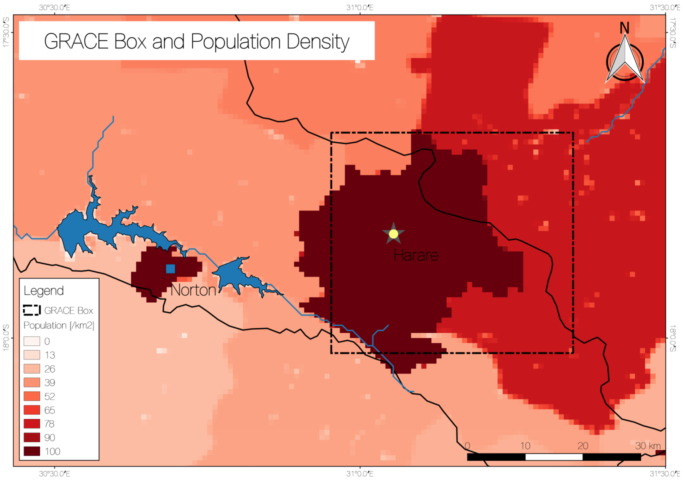


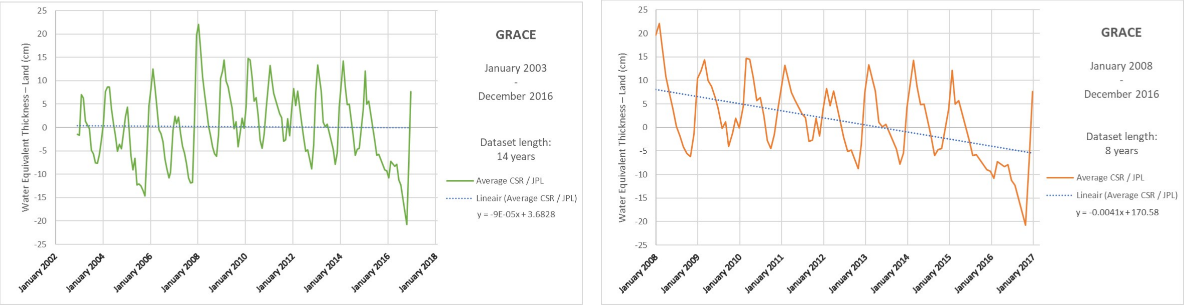
Figure 35: Population density and box of GRACE extracted data

The differences between them are certain parameter choices and solution strategies that have been explored by CSR, and JPL individually. In a paper by Sakumura et al. (2014), as well as by NASA themselves, it is suggested to use the ensemble mean, the simple arithmetic mean of JPL and CSR fields. Using the average is most effective in reducing the noise in the gravity field solutions within the available scatter of the solutions.

The monthly data, extracted from the box shown in Figure 35, is plotted for both the entire dataset of 14 years, as well as the most recent 8 years to see if a change in groundwater aquifer behaviour can be found. A trendline is retrieved from both plots to see the long-term changes (see Figure 36).

7.2.2. Findings

As can be seen in Figure 36, the changes in the gravity field, or the groundwater aquifer, show strong seasonal cycles. We find an incline of the Water Equivalent Thickness during the rainy season and a decline during the dry months in which the groundwater withdrawal of the aquifer increases. Also the years of drought, 2008 and 2015-2016, in which recharge of the aquifer was minimal, are clearly visible. Whilst there have been some good years, the general trend is undoubtedly downwards. Such declining trends have also been noted by Dr. Richard Owen (Appendix A.2. Interview Dr. Richard Owen - GW expert) who indicated that the groundwater in his observation well dropped 10m in the last two decades. This fall is significantly bigger than the average over the area computed with the GRACE data. A possible explanation is that the residence area of Dr. Richard Owen is one of the areas that has not been connected to water supply for roughly 20 years and has had to rely on pumping from boreholes and bulk water suppliers (Appendix A.2. Interview Dr. Richard Owen - GW expert), resulting in a groundwater level fall far above average.



(a) 14 years (b) 8 years

Figure 36: Water Equivalent Thickness changes over time (cm)

The results from the adopted method revealed that over the 14 year long dataset there is no long-term significant decline in groundwater levels (see Table 7.1). When looking at the most recent years however, the mean groundwater levels in the area around Harare are in a state of decline. The decline comes down to roughly 15cm per decade, which translates in a water over-utilization of 56,657 ML per year (see Table 7.1). To put this into perspective, the over-utilization could drain out Lake Chivero in 4 years (see Table 7.2).

	2002 - 2017	**2008 - 2016**
Average decline [cm/day]	0.0001	0.0041
Average decline [cm/year]	0.03	1.50
Average decline [cm/decade]	0.33	14.97
Over-utilization [m3/year]	1,243,701	56,657,490
Over-utilization [ML/year]	1,244	56,657

Table 7.1: Groundwater withdrawal in the UMSC

It must be noted that the values above represent Water Equivalent Thickness in centimeters. As mentioned by FAO [9], 70% of Zimbabwe soils are sandy and have low clay percentages. With this information the porosity is estimated to be around 0.25. Dr. Richard Owen however, suggested that calculating with porosity has high inaccuracies (Appendix A.2. Interview Dr. Richard Owen - GW expert). Specific yields would be more trustworthy. Over years of experience he would estimate and can justify a 10 percent specific yield for the weathered and fractured basement that is foudn around Harare. This means that with a Water Equivalent Thickness decline of 15cm per decade, the lowering of the groundwater level is approximately 1.5m per decade.

Capacity Lake Chivero [ML]	247,181
Capacity Lake Chivero [m3]	247,181,000
% of lake Chivero	23%

Table 7.2: Groundwater withdrawal compared to volume of Lake Chivero

7.2.3. Conclusion & Recommendations

The research has shown that the area around Harare has had a quick decline in groundwater levels over the last decade. With water supply services failing, the people have had no choice but to turn to extracting ground water from wells or boreholes within their own backyards (Appendix A.2. Interview Dr. Richard Owen - GW expert). Groundwater usage however, according to current standards is unsustainable and will result in problems towards the near future (Appendix A.2. Interview Dr. Richard Owen - GW expert). With the current and future groundwater drought risk, the combined physical risk and human vulnerability associated with diminished groundwater availability and access during drought, already being very high in Harare [91] (see Figure 37), the development and restoration of large scale water supply system and the utilization of surrounding surface water is crucial. The groundwater demand during the dry season can only be satisfied by using the extra storage from the rainy season.

As the demand for water will continue to increase due to growing population, urbanization and improving living standards, there will be further increased competition for surface and groundwater resources. This stresses the importance of determining the current extraction and the total sustainably usable quantities. This would include checking the state of the current groundwater aquifers, linking past records to present ones, anticipating changes and forecasting trends in its quantity and quality. This will provide information for improvements in the planning, policy and management of groundwater resources. Awareness raising on the important role of groundwater management however, is crucial to develop a water wise society. National debates in government, but also institutions like ZINWA, should raise awareness and educate the population about preserving the water resources and using them wisely. Although the history of Zimbabwean governance would suggest it is purely acting on crisis management, proactive planning would be preferable to the alternative; to wait for the groundwater aquifers to dry up only for people to realize the real value of water.

Figure 37: Map of groundwater drought risk in the SADC region

Case studies

In the previous chapters it has become clear that the Manyame Catchment is characterized by many problems, which can be grouped in floods, droughts and water quality issues. From hereon this research focuses on two case studies were multiple problem groups coexist. The cases have been chosen since it is these areas and populations groups that are especially vulnerable.

The following chapters discuss two local case studies in more depth and suggest solutions on how to alleviate the issues at hand.

II

Case Studies & Advise

8

Case Study 1

Based on the overall analysis, it was found that the combination of drought and water quality is a big issue for the area around Biri Dam and Chinhoyi. It is therefore chosen as Case Study 1, the area is marked in Figure 38 by the black circle.

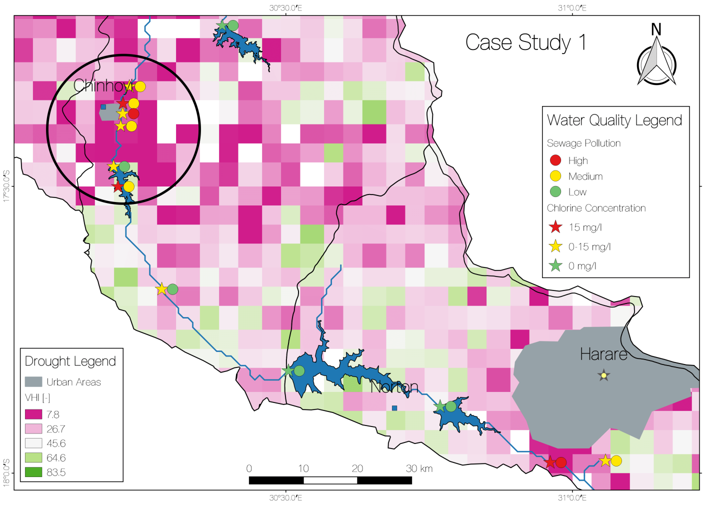


Figure 38: Location of Case Study 1

Unlike our expectations, the area has a very low Vegetation Health Index in comparison to other regions, indicating a high proneness to dry spells. This seems very contradictory, since Biri Dam is full of water (see Figure 42). In addition, the area around Biri Dam has an abundance of agricultural activities which results in droughts being an even more important hazard. Agriculture is highly affected in terms of economic losses due to drought.

Based on the general water quality analysis of the Manyame Catchment, one of the main areas of concern is Chinhoyi. Besides water pollution coming from the agriculture sector and sewage effluent in the MMSC, also the UMSC contributes to the pollution of the water quality. This in combination with the experienced droughts, has a bad influence on the crop yield and got farmers to complain about both water quality and water shortage. To get a better understanding of these current problems around Chinhoyi, a more in-depth investigation was performed to address the issues of droughts and poor water quality supply.

8.1. Droughts

We visited Priska Marauira who is farming on her urban plot near Chinhoyi, downstream of Biri Dam. The plot is about half a hectare in size and is run by the family. It supplies the family with maize, the staple food of Zimbabwe. We interviewed Priska Marauira to gain more insight on droughts experienced by urban farmers. Priska Marauira told us that they are experiencing drought this year. The crops were not as mature as they normally would have been at this time. Despite being near a waterbody, the Manyame River, if a dry spell occurs, they are unable to improve the crop growth through irrigation. They simply do not have the resources to transport water from the river to their plot.

Figure 39: Priska Marauira on her urban plot near Chinhoyi

The family relies on the maize and they suffer tremendously if the harvest fails. This would mean they would have to buy sadza (maize meal) at the shop, which they cannot afford. In a successful year, for example in 2017, there was some maize leftover from their harvest which they could sell at the market. In the years 2009 and 2016, she experienced the worst droughts.

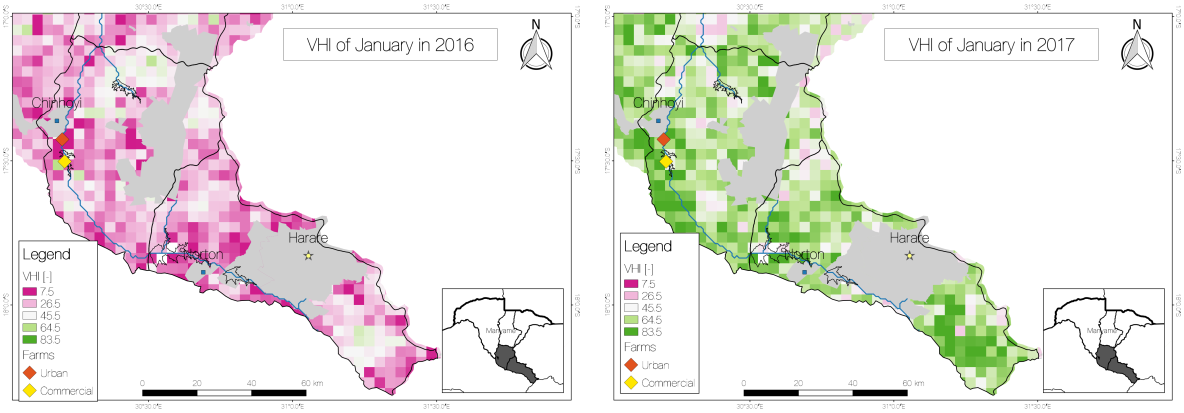
(a) Farm of Clive Zulu (Appendix A.3. Interview Clive Zulu - Farm Manager)

(b) Biri Dam

Figure 40: Biri Dam from the sky

We also interviewed the manager of a commercial tobacco farmer, Clive Zulu, at Biri Dam. They do not experience annual droughts. *"It goes by different years. Drought will not be every year. Like this year, we have a serious drought. So far we haven't received a meaningful rainfall. Normally the rain starts in November. In November we received 65mm, after which it was dry for 3 weeks. Then after 3 weeks we received 50mm. We are in January now, we just received 200mm cumulatively, while in the season we should receive 800 to a 1000mm. We are very, very much below average and the other crops, like the groundnuts that we have got under dryland, which is just 1.5 hectares, it suffered a lot. Instead of making it happen within 2 weeks, it will be on a vegetative level. It will be germinating. The germination percentage is normally on around 90%, but this time it will be far below. Like 65 - 45%. It is not feasible if you want to go for commercial farming."* (Appendix A.3. Interview Clive Zulu - Farm Manager)

The remote sensing images confirm what Priska Marauira and Clive Zulu have mentioned (Appendix A.3. Interview Clive Zulu - Farm Manager). The VHI is computed for the years both farmers experience crop failure or success. As concluded before, dry spells are considered as fatal for crop harvest and happen mostly in January. Looking at Figure 41, the image of January 2016 show poor VHI near the farmers which indicates a dry spell. In contradiction to 2016, 2017 has a very high VHI which indicates a good year with surplus harvest.



(a) 2016

(b) 2017

Figure 41: VHI in January

Listening to Priska Marauira and the commercial tobacco farmer, Clive Zulu, it becomes clear that droughts have a big impact on their livelihood. The droughts they experienced in 2009, 2016 and 2018 had negative consequences for their crop yield. However, looking at the Biri Dam, these droughts are not affecting its storage (see Figure 42). In all these years, Biri was left with at least 70% of its capacity at the end of the dry season. Therefore, you would think there is no reason for farmers close to or downstream from Biri Dam to suffer from droughts, as there is plenty of water available. However, according to Bilton Simango (see Appendix. A.6. Interview Bilton M. Simango – MMCC), Biri Dam only releases water downstream when farmers request and pay for it. In addition, farmers who are close to Biri Dam, want the dam manager to keep water in the dam rather than to release water downstream even for environmental flow, as they might be afraid of the dam reaching critical levels. However, as can be seen in Figure 42, for the last 12 years (from 2007 onwards) Biri Dam has not reached capacities below 70%. So, the dam is far from critical levels, as critical levels are only reached at percentages far lower than this, as assumed in Chapter 7.1.3. This induces that Biri Dam is highly underutilized.

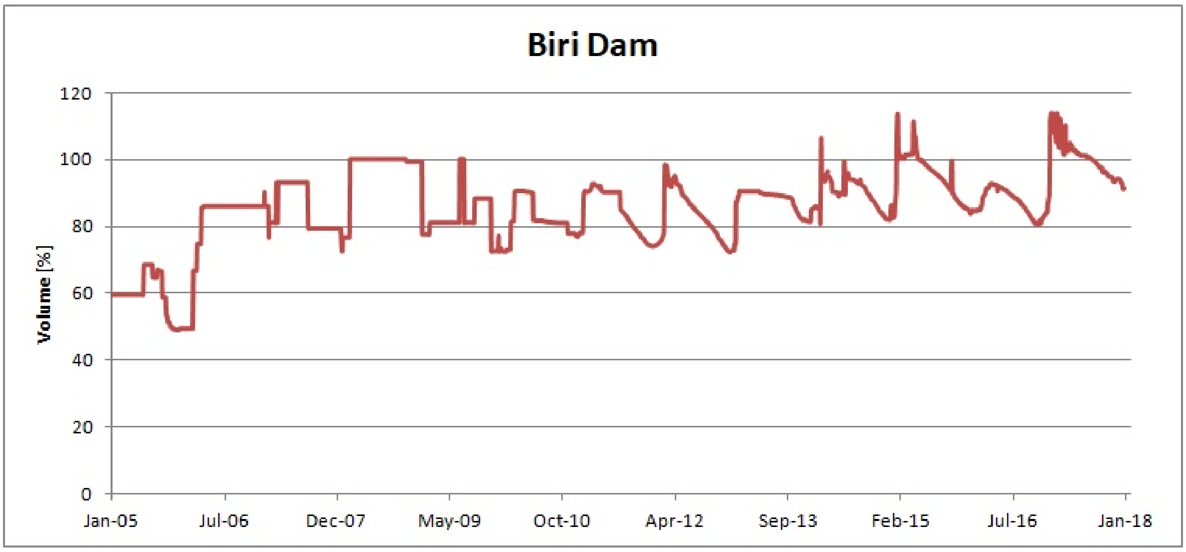


Figure 42: Biri Dam: volume over time in percentage

One of the main reasons for this underutilisation is a lack of infrastructure, making it difficult for farmers to use sufficient water, which causes them to suffer from droughts. As Clive Zulu mentioned, there are plans to increase the irrigation capacity, but due to a lack of resources he is unable to irrigate the entire farm. This is partly due to the land reform which took place in 2001 (see Chapter 2). This left farmers with damaged or stolen equipment for irrigation. Due to limited financial resources it was not possible for them to solve this problem on their own. To date, most of the problems imposed by land reform have still not been solved, and the recent economical and political developments have made it even more difficult for farmers to invest in new resources. This prevents them from extracting water from nearby water bodies, leaving Biri Dam underutilized. Even for farmers for whom it is possible to extract water, the deteriorating economic situation makes it more expensive to utilize the water from Biri Dam.

8.2. Water Quality

Another cause for the underutilization of Biri Dam is the poor water quality. Around Biri Dam and downstream there are many tobacco farms, however there have been complaints about the water quality. This is due to the fact that the water in Biri Dam contains high levels of chlorine (see Chapter 6), which affects the tobacco crops. This means that they do not want to use the water as it decreases the value of the crops. Instead, they end up growing dry-land tobacco which is not as economical (see Appendix A.6. Interview Bilton M. Simango – MMCC). Furthermore, as the MMSC is mainly focused on farming, the downstream users of the water are also affected by the poor water quality from the dam and the sewage effluent from Chinhoyi also influences the water quality (see Figure 43). Therefore, the following two sections include a more in-depth analysis on the two major concerns regarding the water quality. These are namely the source of pollution affecting Biri Dam and the influence of sewage effluent on the water quality downstream of the dam.

(a) Downstream of Biri Dam

(b) Water treatment plant and urban agriculture

Figure 43: Downstream of Biri Dam from the sky

Agricultural Irrigation

As mentioned before, one of the main water quality issues experienced in the MMSC is the high level of chlorine in the water. Since about 2016, there have been complaints by farmers that the high level of chlorine in the water (Manyame River and Biri Dam) negatively affects their tobacco crops (Appendix A.4. Interview with Noah – Dam Manager Biri Dam). Although there have been complaints about chlorine, a study by Broyer et al. (1954) found that chlorine is an essential micro-nutrient element for the growth of tobacco. Since this study, various studies have found that small amounts of chlorine are favourable for the tobacco plants and increases the tobacco yield. However, excessive chlorine negatively affects the growth and quality of the tobacco. Very high concentrations of chlorine in the early stages of growth resulted in the retardation of growth [31]. It has been found that the toxicity of chlorine in plants occurred at a chlorine content of the plants of 3.5-5.6% but this is also dependent on the form of nitrogen present. It was found that there was no toxicity when $NO_3 - N$ is applied but occurs when $NH_4^+ - N$ is present. In terms of quality, the colour and burning rate of the dried tobacco leaves are negatively influenced by too high concentrations of chlorine [31].

From our interview with an affected farmer, Clive Zulu, it was found that the issues of the chlorine resulted in the retardation of growth in the seedlings and the final harvested tobacco leaves had small 'burn' spots on them as is shown in Figure 44 (Appendix A.3. Interview Clive Zulu - Farm Manager). The 'burn' spots are most likely due to chlorine bleaching from the irrigation of the tobacco through a central pivot system.

Figure 44: 'Burn' marks on the tobacco leaves

The results from our water quality tests concerning chlorine that were taken in the Manyame River and Biri Dam are shown in Figure 45.

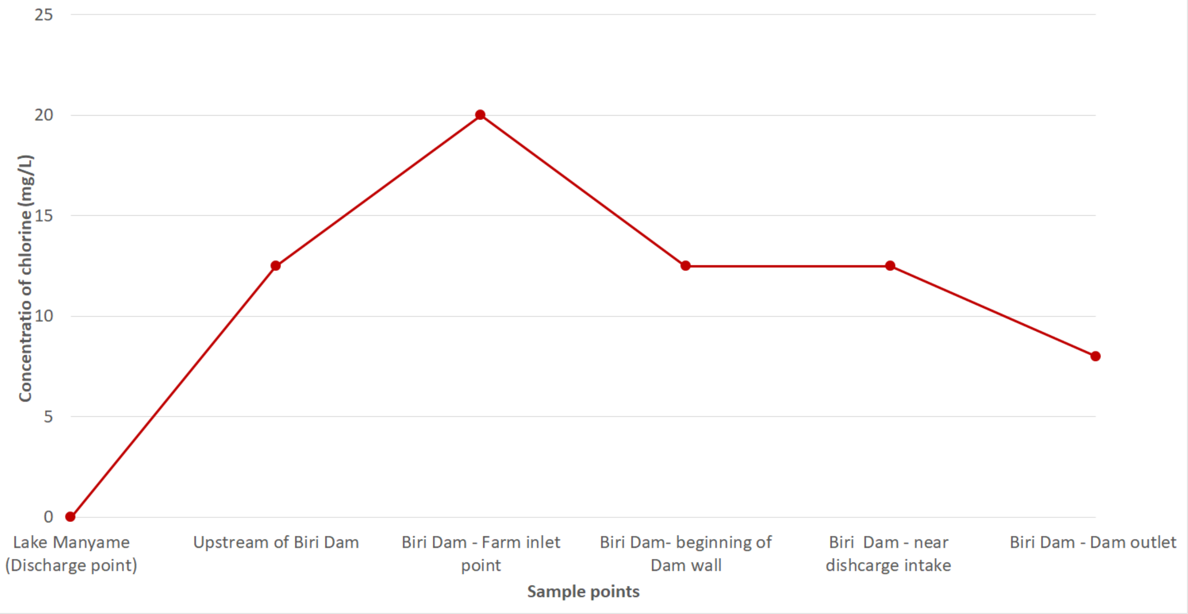


Figure 45: Concentration of chlorine found in various sample points upstream and surrounding Biri Dam

From the results, it can be observed that the discharge of Lake Manyame contains no chlorine and the concentration increases as one travels further downstream. From our discussion with Clive Zulu (affected tobacco farmer) and Noah (Biri Dam manager), it was mentioned that many of the farmers complained that the source of pollution concerning the chlorine is from the UMSC (Appendix A.3. Interview Clive Zulu - Farm Manager, Appendix A.4. Interview Noah - Dam Manager Biri Dam). However, based on our research results (see Figure 45), it was found the source of chlorine is downstream of Lake Manyame. This was also confirmed by the Biri Dam manager that previous tests done by the Environmental Management Agency (EMA) have indicated that the chlorine is not as a result of the WWTPs effluent discharges from Harare and surrounding areas in the UMSC (Appendix A.4. Interview Noah - Dam Manager Biri Dam). Unfortunately, we were unable to gain access to these test results.

From our land-use analysis and discussions with the MMCC, we found that there are no WWTP or effluent discharges downstream of Lake Manyame and that agriculture is the dominant land-use from Lake Manyame down to Chinhoyi (MMSC). The agriculture crops in this sub-catchment are predominantly tobacco, maize, soy beans and wheat. From our discussions with Clive Zulu, it was found that tobacco is the only crop that is negatively affected in terms of quality and economic value by the irrigation water (Appendix A.3. Interview Clive Zulu - Farm Manager).

The fertiliser used by the farm was found to contain chlorine (Potash fertilizers) and the company that produces the fertiliser is called Omnia Fertilisers. Based on the discussions with Clive Zulu and Bilton Simango (Appendix A.3. Interview Clive Zulu - Farm Manager, and Appendix A.5. Interview Bilton M. Simango - MMCC), and the results from the water quality tests, the most likely source of the chlorine in the river and dam is the fertiliser being washed off into the dam. On some farms the crops are planted roughly about 50m from the dam shore and in the rainy season these crops are underwater (Appendix A.3. Interview Clive Zulu - Farm Manager) and the highest concentration of chlorine was found near the farm water inlet point close to the shore. It was also mentioned that the chlorine concentration decreased further into the middle of Biri Dam (Appendix A.3. Interview Clive Zulu - Farm Manager). However, pumping water from the middle of the dam, where the concentration of chlorine is lower, is too expensive for farmers, which leaves them with using the chlorine rich water close to the shore (Appendix A.3. Interview Clive Zulu - Farm Manager). Therefore, looking at the water quality results and from the interviews, one can conclude the fertilisers are the major source of the chlorine.

Furthermore, the concentration of phosphate and nitrogen increased downstream of Lake Manyame as shown by Figure 26 (Chapter 6). This increase in concentration of phosphorous and nitrogen is most likely due to the fertilisers as there are no other major sources of pollution in this rural farming area. In particular the high concentration of phosphates supports the fact that the nutrients are from agriculture activities because most soils in Zimbabwe are known to be phosphorous poor, thus needing additional nutrients [17] .

Sewage Effluent

Downstream of Biri Dam, the water quality is not only affected by the quality of the discharge from Biri Dam but also the sewage effluent from Chinhoyi. This is because of the poor condition of the WWTP (Mpata Treatment Plant) which is discharging sewage effluent into the Manyame River. From our fieldwork, we were able to identify four sewage effluent discharge locations. Two of these discharge locations (see Figure 47) are due to leakages in the WWTP effluent pipe, the third and fourth samples points are the main sewage effluent pipe itself and a heavily sewage polluted stream, named Coldstream. Location 1 is a discharge stream, being fed by the leaking effluent pipe further upstream of our tests. At location 2, we were able to measure the water flowing straight out of main sewage effluent pipe (about 5m from the river) (see Figure 46). Figure 47 shows the location of these two sample points with respect to the WWTP and start of the water hyacinth (encircled in red). The actual location of the sewage effluent discharge is further downstream. The subsequent results of the water quality tests are given in Figures 48 and 49. The discharge streams are encircled in red and the water quality of the Manyame River before and after the discharge are shown by the non-encircled labels.

Figure 46: Leaking sewage effluent pipe in Chinhoyi (sample location 2)

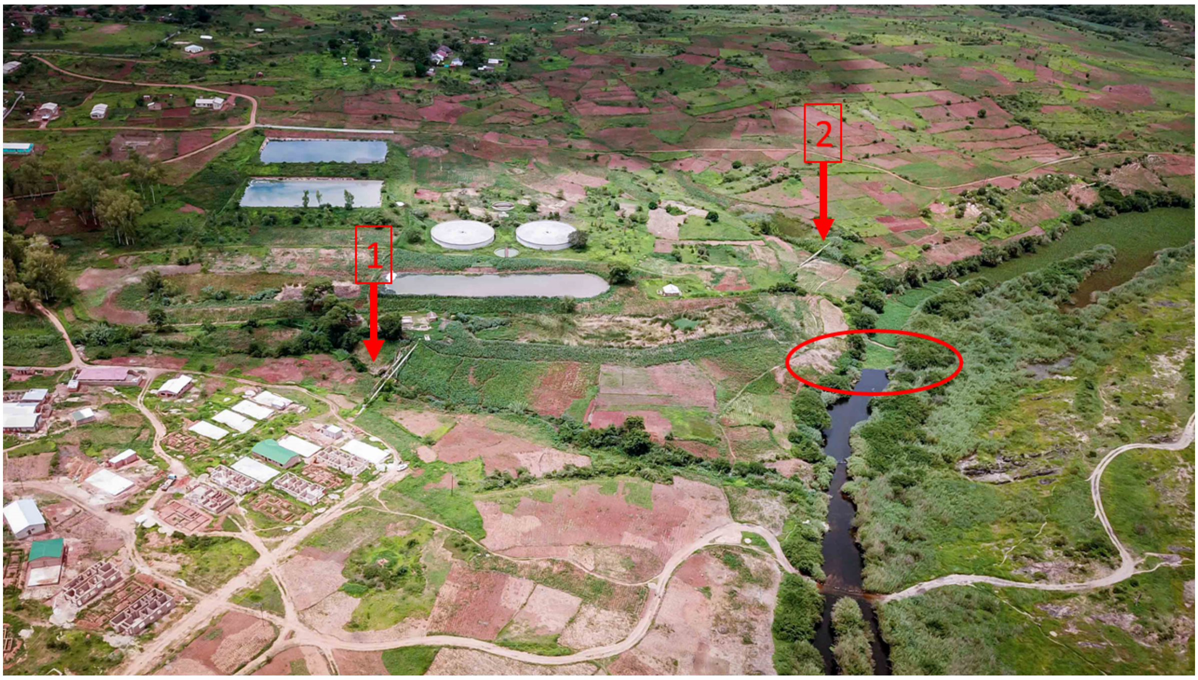


Figure 47: Location of the two sample points from the leaking sewage effluent pipe and start of the water hyacinths

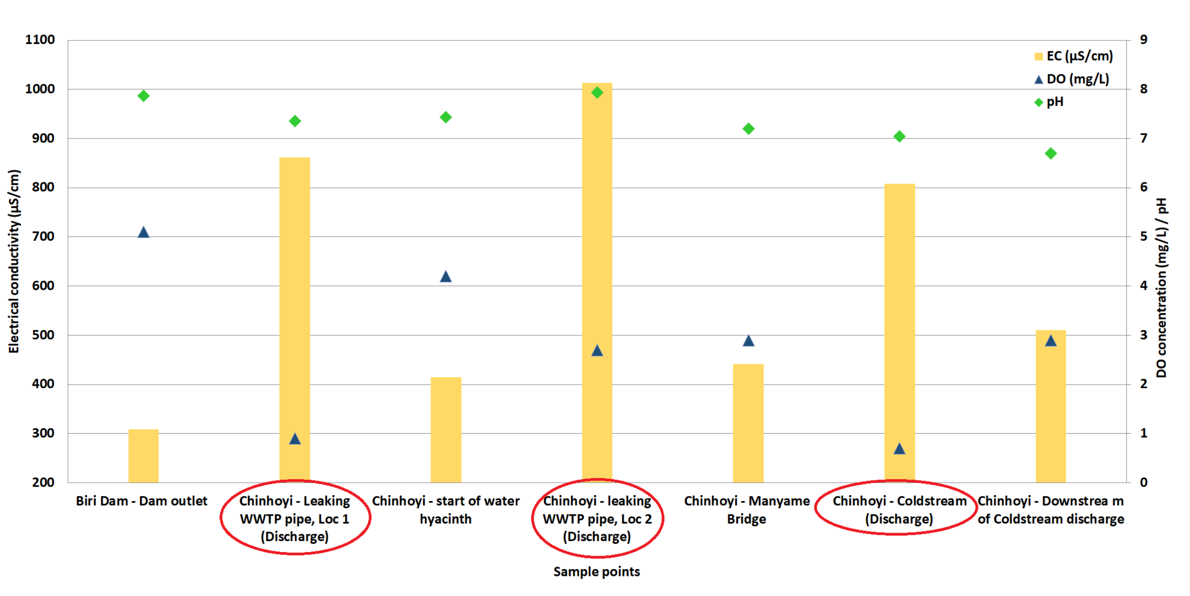


Figure 48: Electrical conductivity, dissolved oxygen concentration and pH for the sewage effluent streams and Manyame River around Chinhoyi, MMSC

Comparing the discharge streams to the Manyame River, one can see that the all 3 discharge streams have an EC that is almost double than that of the Manyame River (Figure 48). This indicates that there is a high concentration in these streams, as expected. The DO for all 3 stream is also very low.

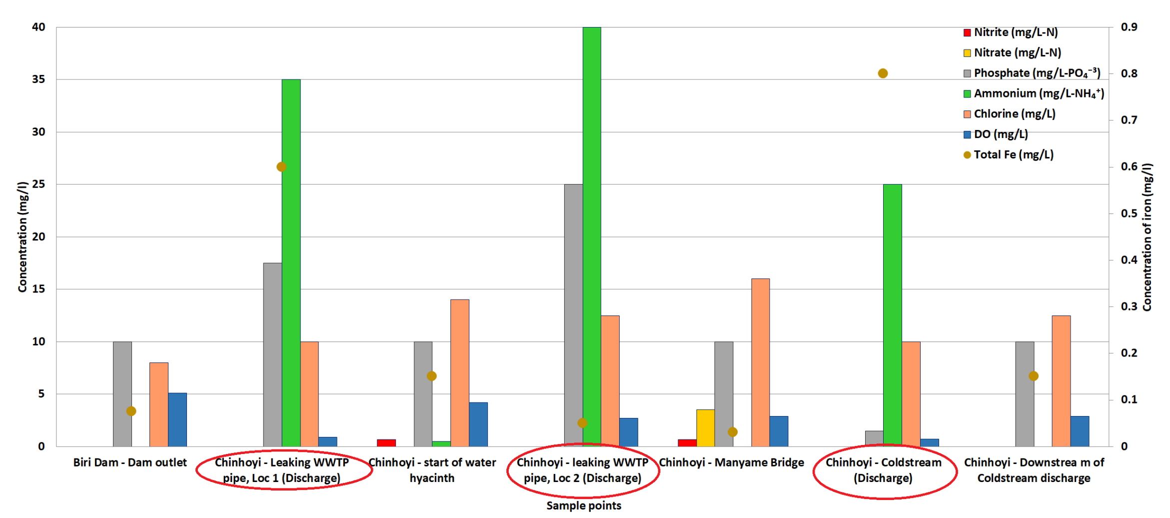


Figure 49: Overall concentration of most important parameters tested for the sewage effluent streams and Manyame River around Chinhoyi, MMSC

From the water analysis, after discharge location 1, it is observed that the Manyame River significantly dilutes this small stream (leaking pipe) and that this stream is already slightly diluted in comparison to the effluent pipeline (Sample point - location 2), as the concentration of ammonium is already less. In comparison to the pipeline effluent, the flowrate from location 1, is considerably less than the effluent pipeline and there is only small increase in the concentration of nutrients after the discharge point. In addition to this, it is observed that the oxidation of ammonium already occurs shortly after the discharge point. The increase in nutrients from the effluent discharge has led to the growth of the invasive water hyacinth. From our observations with the drone and in the field, we were able to observe that the growth begins almost immediately after the discharge point (see Figure 47). Due to lack of access, we were unable to test the water quality in the Manyame River just after discharge location 2 and the actual discharge point of the WWTP effluent pipe. However, from Figure 49, one can see that by the time the water has reached Chinhoyi Bridge, all the ammonium has oxidised to form nitrate and the intermediate compound, nitrite. The overall concentration of nitrogen has decreased due to the remediation effects of the water hyacinth. From our field observation, the two leaking pipe discharges are considerably less in volume than the main effluent pipe. Therefore, the main increase in pollutants is further downstream before Manyame Bridge, Chinhoyi.

Despite the complete invasion of the water hyacinth from the location of Chinhoyi (start of water hyacinth) to downstream of Coldstream (and further downstream as the river was still completely covered at this location), the DO is not as low as it was in other testing samples that were completely covered by water hyacinth such as Chitungwiza. Possible reasons for this are that there are areas in this section of the river that are being aerated. For example the weir bridge, located before Chinhoyi Bridge, could aid in the aeration of the river as seen in Figure 50.

Figure 50: Weir aeration between sewage effluent discharge and Manyame Bridge, Chinhoyi

For the phosphate water quality tests, it is observed that the general trend is that phosphate concentration stays the same in this section of the river. However, there is most likely a variation in the concentration, but due to the course range of the water quality test it is difficult to observe a small decrease or increase in the phosphate concentration. However, despite this insecurity, we can say that there is a considerable concentration of phosphate present in the river

The third effluent discharge tested was Coldstream. The pollution in Coldstream is supposedly as a result of the hospital and the rapidly growing housing community surrounding the river. The high levels of ammonium in this stream also indicate the presence of sewage effluent pollution. The Manyame River water quality was tested downstream of the confluence between Coldstream and Manyame River. The low flowing Coldstream and invasive water hyacinth result in no ammonium, nitrites or nitrates being present in the river. However, there is still a high concentration of phosphate and chlorine, and the concentration of phosphates actually increased. Therefore, another source of these two compounds could be from fertilisers leaching into the river from the agricultural activities occurring around the river as seen upstream around Biri Dam.

In terms of chlorine, all three sewage effluent points discharge a concentration of 10mg/L or more into the Manyame River. This affects the farmers using this water for tobacco irrigation as the concentration in the river is about 12.5 mg/L after the third discharge point. This is not as high as in Biri Dam, but still negatively affects the tobacco crops.

8.3. Conclusion & Recommendations

In conclusion, the drought experienced by farmers in the MMSC can be partially improved by addressing issues such as quality of water and infrastructure development. However, the urban farmers are particularly affected by the periods of dry spells due to the lack of finances for irrigation which makes them unable to use the available water. The cost of the irrigation water is a further burden on the farmers. Therefore, government subsidies in terms of finances for both infrastructure and irrigation water would be advised. This would help farmers to actually use the water available and increase the certainty on their harvest.

Looking at the risk for dry spells, introducing short-cycle crops or more varieties of drought-tolerant crops like sorghum and pearl millet can reduce this risk. For Priska Marauira, this would mean that she can not grow as much maize as she used to do, however, it would give her more certainty on her harvest. Clive Zulu might not be willing to grow alternative crops, since the economic gain would most likely be less. However, it might be considerable to grow crops which are more resilient to the inconsistent rainfall pattern. Growing crops with a relatively high chance of failure might not be economically worth it.

Applying mulch is another low-cost method which can be implemented to reduce food insecurity. Mulch are old crops leftovers which are placed on the bare ground in the plot. This helps in reducing erosion and it adds nutrients to the ground which makes the soil more fertile. Furthermore, it reduces evaporation resulting in more efficient water use. Next to these recommendations, making use of water conservation techniques like rainwater harvesting is advisable.

Besides the dry spells, the poor water quality is another major issue that affects the commercial farmers. As seen from the analysis, the agricultural runoff is the main contributor to the poor quality upstream from Chinhoyi and particularly Biri Dam. In order to decrease the amount of chlorine leaching into the water source, chlorine-free fertiliser can be implemented. Over time this will decrease the concentration in the water source. Furthermore, in general more efficient use of fertiliser should be used as one can see that the crops are not able to fully utilise the fertiliser and nutrients are lost.

Another solution is to have more of a bufferzone around the dam to prevent the crops from flooding during the rainy season which significantly decreases the amount of nutrients lost to the dam. Introducing a wetland area around the dam could help improve the water quality by acting as a filter for the nutrients and decrease the amount of nutrients leaching into the dam. Another bufferzone could be established by planting grasses, trees and shrubs around fields that can help absorb and filter the runoff water before it flows into the lake [93].

As the sewage effluent also contributes to the amount of chlorine in the river, upgrading of the WWTP to be able to clean the water sufficiently would decrease the amount of chlorine needed to minimise risk of water-borne diseases. This would increase the water quality in general in the river for the aquatic life.

9

Case Study 2

For case study 2 the village of Mushumbi Pools in the LMSC was chosen as the town is located in an area where droughts and floods are apparent. The LMSC can be divided into two hydrological zones, CH1 & CH2. The CH1 area is the Zambezi valley and the upper area CH2 is found above the escarpment. While both area's experience drought, the area below also faces major floods risks (Appendix A.6. Interview Tafireyi Dzomba – LMCC). Mushumbi Pools is central to this area and also hosts the confluence of two rivers. Consequences of the droughts and floods are widely apparent.

Also, due to discharge of domestic, agricultural and industrial waste from the upstream sub-catchments, the water quality of both surface water and groundwater has significantly decreased. Not only pollution form upstream however, but also locally open defecation and leaking septic tanks taking place on a large scale through the sparsely distributed settlements were identified to be a contributing source of pollution. In certain times the conditions have worsened to the extent that the water was unfit for human consumption. Tafireyi Dzomba from the LMCC reported that at the end of the dry season the water appears greenish in color (Appendix A.6. Interview Tafireyi Dzomba – LMCC). As a result of the water pollution, cases of the waterborne disease cholera have been reported (Appendix A.6. Interview Tafireyi Dzomba – LMCC). Since our water quality test results didn't show any significant pollution this time of the year this case study focusses on the floods and droughts in the Mushumbi Pools area.

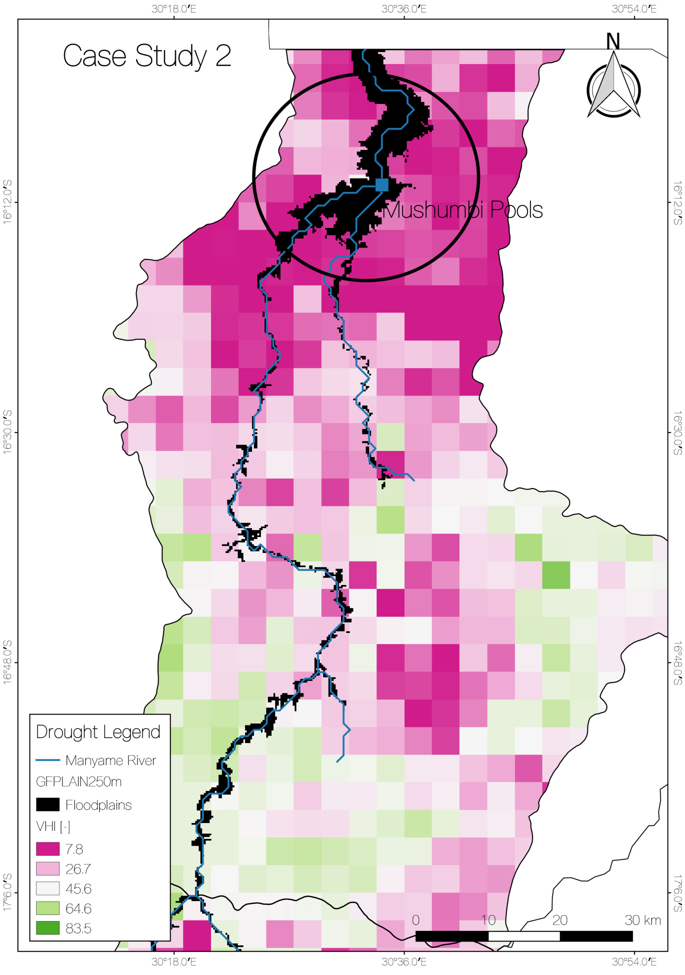


Figure 51: Location of Case Study 2

9.1. Floods

In Mushumbi Pools two main rivers, the Manyame and Panhame meet (see Figure 52), resulting in dangerous flooding when it has rained heavily and upstream dams are filled up and therefore unable to hold water. The discharge carried down by the rivers finds itself trapped in this lower part of the subcatchment as the backwater curve from the Cahora Bassa Dam obstructs its way.

The Cahora Bassa Dam is constructed in the lower middle Zambezi basin primarily for hydropower production purposes. It therefore maintains a high hydraulic head in order to maximize power production [70]. This creates positive possibilities for inland fishing, industry and tourism. However, the dam also induces negative effects for upstream areas, especially during the rainy season between December and February. In this period the Kariba and Kafue dams release water to avoid dam failure. This causes the water flow in the Zambezi to increase substantially. Therefore, the Manyame River, sandwiched between the three major dams Kariba, Kafue and Cahora Bassa experiences an increase in resistance as it tries to discharge in the Zambezi resulting in water accumulating at the confluences of the Zambezi and Manyame River, leading to flooding of previously unflooded area. On top of that, the Cahora Bassa Dam water level continues to rise as releases from the dam are exceeded by inflows due to releases from Kariba, Kafue and Zambezi tributaries. The higher water levels of the Cahora Bassa Dam leads to a backwater curve flooding the upstream areas, including part of the LMSC. This has led to loss of livestock, crops, property, infrastructure and human life, leaving the rural communities in an even poorer state. Since the soils in the LMSC are generally poor for agricultural activities as they are mostly sands with shallow depths and poor moisture retention, people seek out the fertile areas in the flood plains by practicing stream bank and flood plain cultivation (see Figure 52) [70] (Appendix A.6. Interview Tafireyi Dzomba – LMCC). This behavior however, makes them even more vulnerable to floods from the Cahora Bassa backwater curve. An extinction can be made between two types of flood:

- Seasonal flood - Most frequent type of floods is the seasonal flood occurring in January or February at peak of rainfall season.)
- The reservoir operation induced flood - This type of flood has become more frequent than before due to the high water levels in the Cahora Bassa since 2000 due to the occurrence to two major cyclone events in 2000 and 2003.

(a) Manyame River with the dry Panhame flowing into it

(b) High bank erosion around Mushumbi pools

Figure 52: Manyame River from the sky around Mushumbi pools

The floods have had adverse effects on the population in various ways. Tafireyi Dzomba from the LMCC mentioned in an interview that the frequency with which these floods occur depends heavily on the rainfall patterns but that severe floods happen roughly once every five years. *”When the flood comes their crops are scraped away and people will be left with nothing”* (Appendix A.6. Interview Tafireyi Dzomba – LMCC). LMCC and EMA have been trying to educate the people cultivating and living in the floodplains on how to take precautions, but so far they have had little influence. Officially, according to the current Water Act, it is not allowed to cultivate within 30 meters from the river, but enforcing this law has proven to be impossible. The main reason for this, according to Mr. Dzomba for the LMCC, is that *“ Most of the people they don’t have adequate irrigation facilities. They end up getting too close to the river just because it will be less costly.”* Most people ignore the rule as for them, it is a matter of survival. Not that 30 meters distance from the river around Mushumbi Pools would be enough. According to Mr. Dzomba and Figure 51 the river will broaden significantly more than 30 meters. For smaller flood events however, increasing the distance to 30 meters from the river will most certainly help.

Besides, people cultivating at the edge of these rivers will loosen up the soil and when the rains come they will easily be carried away. This erosion process results in heavily silted lower areas, which in turn raises the river bed, decreases the rivers discharges capacity and increases flood risk.

Another issue is that large dams upstream, like Biri and Mazvikadei Dam, fill up relatively early in the rainy season (see Figure 53), after which any access rainfall is released, increasing the flood risk for flood prone areas downstream. By clear communication between the MMSC and LMSC, such circumstances could be avoided. However, according to Mr. Dzomba communication between the dams upstream and the flood prone area downstream is relatively minimal and was only established a year ago by means of a WhatsApp group. The communication however, is merely reporting of dam levels, rather than adaptive management behavior.

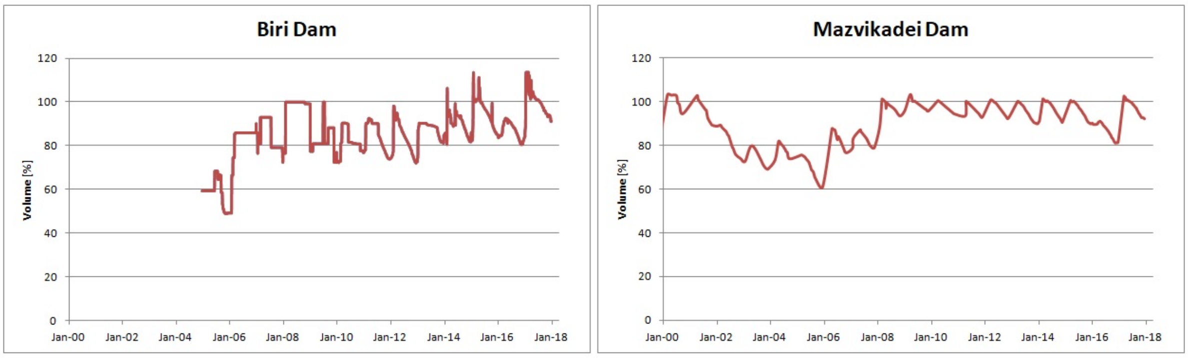


Figure 53: Biri and Mazvikadei Dam: volume over time in percentage

9.2. Droughts

Food insecurity is highly prevalent in the Zambezi Valley of LMSC [100]. One of the major causes of this situation is drought since the main challenge to food security for many communal and small-scale commercial farmers in the country is water for crop production [66]. The high variability of seasonal rainfall makes the area even more susceptible to drought.

Tafireyi Dzomba of the LMCC stated that people in Mushumbi Pools are left with no other option than to get to the river. *”When there is this drought nothing can grow outside away from the river. The drought gives pressure to the river. Everyone would want to go there, but there is not enough space for everyone to cultivate. Soils are not fertile and boreholes are not strong enough. LMCC has received a lot reports that boreholes have silted or collapsed. People have realised that the soil is not good for agriculture, so instead they have resorted to holding cattle and goats”* (Appendix A.6. Interview Tafireyi Dzomba – LMCC).

Mavhura et al. (2015) has investigated the impact of drought on food security and the strategies used by smallholder farmers in the Zambezi Valley to cope with drought. The study focused on three themes during their conducted interviews. The impact of drought on food security, strategies to cope with food shortages and drought adaptations.

In terms of impact, the interviews revealed that high food security was the major concern among smallholder farmers. Only 5 out of 60 households had harvested sufficient cereals for home consumption at the end of the 2011/12 season [48]. Consequently, they are forced to cut down on the number of meals per day or the amount per meal. Some also altered their diet. For the ones without sufficient harvest things were made even more difficult, because of an increased maize price of 300% that same year. The economical and political situation of Zimbabwe is far from helping them.

There are numerous strategies that communities apply in case of food insecurity. The most common strategy, persued 60% of the questioned people, is to rely on food-aid by Non-Governmental Organisations (NGO's) if available. The second common adaption strategy is to buy food on the local market (15%). Some households where forced to sell their livestock at relatively low prices, whilst buying food at high prices. Forced to change revenue streams, people earlier cultivating cash crops(cotton and tobacco) and small-scale horticultural activities, as their main sources of income, were now more reliant on livestock sales, informal trading, sale of household goods, savings and formal employment [48].

Lastly, in adaptation to droughts, the measures taken by the smallholder farmers before a drought occurrence were aimed at avoiding the drought risks. These included traditional Shona rituals, use of indigenous drought warning and forecasting signs, and monitoring the number of grazing animals. During the drought, the survey revealed that smallholder farmers used water conservation techniques such as rainwater harvesting, run-off water harvesting and flood diversion in order to improve their crop harvest [48].

Unfortunately, all these strategies are not robust enough to cope with this uncertainty as food insecurity remains high. There is need to invest in and adopt some sort of irrigation farming throughout the whole year to ensure food security in the valley [48].

9.3. Conclusion & Recommendations

Reservoirs play an important role in water management. They store water that in case of shortcomings can be used downstream. The water storage is an important means of meeting the needs of various stakeholders when the natural supply is less than the demand. If managed well, the reservoirs can provide substantial benefits to human societies and their economic activities.

Dams however, have another important role. They can reduce flood risks by attenuating the flood peaks and intensity of flooding in areas downstream of the dam. In the case of the area around Mushumbi Pools however, the man-made dams upstream have not necessarily always provided this positive buffer advantage. Although the area of Mushumbi Pools suffers from the consequences of the backwater curve from Cahora Bassa, the situation has not been helped by extensive water releases by the Chivero, Manyame, Biri and Mazvikadei Dam upstream during rainy season. Almost every year, at the start of the rain season, these dams quickly fill up and any additional rainfall will be released to the flood prone areas downstream. The dam data (see Chapter 7 and Figure 53) shows us that if there is no significant drought, dam levels can be replenished by roughly 40% in one rainy season. Why then are the dam levels at the end of the dry season still at 80% of their full capacity? The conscious decision to keep as much water as possible upstream (Appendix A.1. Interview Hacklin Chengeta - ZINWA, Appendix A.2. Interview Dr. Richard Owen - GW expert, Appendix A.5. Interview Bilton – MMCC), even just before the rainy season is about to replenish, is putting the people around Mushumbi Pools under serious threat. Improved communication and consequent adaptive behavior between the LMSC and the dams upstream would help decrease the risk of flooding extensively.

The drought and flooding in the area spark contradictory pushing people to or away from the river. The official buffer zones, the distance from the river however, assigned by the Water Act should be reconsidered and re-established. These buffer zones must afterwards be regulated, monitored and enforced where possible.

In the dry areas further away from the river, there are various actions that can be taken to improve livelihoods and increase food security in the Zambezi Valley. Strategies like run-off water harvesting and flood diversion are occasionally already implemented. Unfortunately, this is not sufficient to significantly decrease the risk for droughts. There are additional measures which can be implemented to reduce the risk even further. One of the measures is introducing short-cycle crop varieties or drought-tolerant crops like sorghum and pearl millet that have minimum crop water requirement of 300 mm or less. This means however that they have to change their staple food, maize meal, to an alternative diet. The application of mulch, as explained in Case Study 1, is another method which can be implemented to reduce food insecurity. Next to these recommendations, expanding the water conservation techniques which are already implemented is advisable.

10

Conclusion & Discussion

As the demand for water will continue to increase due to growing population, urbanization and improving living standards, there will be further increased competition for surface and groundwater resources. Manyame Catchment, in essence, has enough water, but the main issue is the spatial distribution of water resources and the quality hereof. In some areas there are dams, but no farmers to utilize the water. In other areas there are farmers that are desperate for water, but don't receive any. This is not an issue of wrong dam locations, but a result of the land reform that started in 2000.

Dams surrounded by commercial farmers saw demand collapsing when new A1 and A2 farmers took over without the capacity to irrigate. The dams therefore have stayed relatively full and water authorities so far have opted for a strategy in which as much water as possible is kept upstream (Appendix A.1. Interview Hacklin Chengeta - ZINWA, Appendix A.2. Interview Dr. Richard Owen - GW expert, Appendix A.5. Interview Bilton M. Simango – MMCC). In the rainy season this has resulted in an inability of the dams to buffer and store the rains, causing water to be discharged downstream, contributing to the problematic flooding downstream. Since downstream areas in LMSC also suffer from long dry spells and drought, people have been forced to live and cultivate close to the river beds, making them even more vulnerable to the potential flooding. In general, limited actions are taken to improve the robustness of communities against drought and thus food security. In order to improve the food insecurity across the country, organisations or ministries could implement risk management strategies for drought to help communities prepare, mitigate and respond.

Drinking water provision to the city of Harare is seriously under threat with problems closing in from all sides. Groundwater aquifers are drying up, surface reservoirs are possibly silting up, water quality has degraded to hardly treatable levels, drinking and waste water treatment plants have lacking capacity and water sanitation infrastructure is in urgent need of replacement. A national debate however, is hardly existing. This stresses that awareness raising on the important role of water management is crucial to start developing a water wise society. National debates in government, but also campaigns by water authorities like ZINWA and the catchment councils, should raise awareness and educate the population about preserving the water resources and using them wisely.

Other issues are facilitated by shortcomings in regulations. Take the issue of siltation, apparent on many locations in the Manyame Catchment. Dams are silting up because of upstream farmers cultivate too close to the water. The official buffer zone according to the current Water Act is an homogeneous 30 meters, independent of the soil types, gradients and land cover. The type of water body is also not taken into account. Whether a major river, stream or dam, the Water Act subscribes 30 meters. It is crucial to relook and re-establish the buffer zones as assigned by the Water Act. These buffer zones must afterwards be regulated, monitored and enforced where possible. This will tremendously decrease the problems of siltation of dams and flooding of the silted up Zambezi Valley.

All in all, the situation stresses for better awareness, monitoring and guarding of the water resources. This will provide information for improvements in the planning, policy and management. Although the history of Zimbabwean governance would suggest it is purely acting on crisis management, proactive planning would be preferable to alternative; to wait for the aquifers to dry up only for people to realize the real value of water.

Bibliography

[1] APEC Water (2019). What is methylmercury and why is it such a concern in aquatic environments? `https://www.freedrinkingwater.com/water_quality/quality1/30-08-methylmercury.htm`.

[2] Battjes, J. A. and Labeur, R. J. (2017). *Unsteady flow in open channels*. Cambridge University Press.

[3] Broyer, T., Carlton, A., Johnson, C., and Stout, P. (1954). Chlorine—a micronutrient element for higher plants. *Plant physiology*, 29(6):526.

[4] Chawira, M., Dube, T., and Gumindoga, W. (2013). Remote sensing based water quality monitoring in chivero and manyame lakes of zimbabwe. *Physics and Chemistry of the Earth, Parts A/B/C*, 66:38–44.

[5] Chikodzi, D. (2013). Groundwater resources of zimbabwe: An assessment of fluctuations. *International Journal of Scientific Reports*, 2:629.

[6] Climate Change (2008). Water. technical paper of the intergovernmental panel on climate change. *IPCC Secretariat, Geneva*, page 210.

[7] Climate Zone (2019). Climate of zimbabwe. `https://www.climate-zone.com/climate/zimbabwe/`.

[8] Cuneo, C. N., Sollom, R., and Beyrer, C. (2017). The cholera epidemic in zimbabwe, 2008–2009: A review and critique of the evidence. *Health and human rights*, 19(2):249.

[9] Dhliwayo, D. K. C., Nyapwere, N., Mhaka, L., Chkwari, E., Manygana, A., and Nyamangara, J. (2018). Status of soil resources in zimbabwe the needs and priorities for sustainable management.

[10] Diersing, N. (2009). Water quality: Frequently asked questions.

[11] Duan, Z. and Bastiaanssen, W. (2013). Estimating water volume variations in lakes and reservoirs from four operational satellite altimetry databases and satellite imagery data. *Remote Sensing of Environment*, 134:403–416.

[12] Dzwairo, B., Hoko, Z., Love, D., and Guzha, E. (2006). Assessment of the impacts of pit latrines on groundwater quality in rural areas: a case study from marondera district, zimbabwe. *Physics and Chemistry of the Earth, Parts A/B/C*, 31(15-16):779–788.

[13] Emam, A. R., Kappas, M., Nguyen, L. H. K., and Renchin, T. (2016). Hydrological modeling in an ungauged basin of central vietnam using swat model. *Manuscript under review for journal Hydrol. Earth Syst. Sci. Published*, 18.

[14] Enderlein, U. S., Enderlein, R. E., and Williams, W. P. (1997). *Chapter 2 Water Quality Requirements*, page 9–29. E&FN Spon, first edition.

[15] Enfors, E. I. and Gordon, L. J. (2008). Dealing with drought: The challenge of using water system technologies to break dryland poverty traps. *Global Environmental Change*, 18(4):607–616.

[16] ESA CCI (2015). Land cover map 2015.

[17] FAO (2006). *Fertilizer use by crop in Zimbabwe*. Food and Agriculture Organization of the United Nations, first edition.

[18] FAO (2015a). Agriculture stress index system (ASIS). `https://http://www.fao.org/resilience/news-events/detail/en/c/296089/`.

[19] FAO (2015b). Country-level asis: an agriculture drought monitoring system. `http://www.fao.org/3/CA0986EN/ca0986en.pdf`.

[20] Fashola, M., Ngole-Jeme, V., and Babalola, O. (2016). Heavy metal pollution from gold mines: environmental effects and bacterial strategies for resistance. *International journal of environmental research and public health*, 13(11):1047.

[21] Fondriest Environmental, Inc. (2014). Turbidity, total suspended solids water clarity. `https://www.fondriest.com/environmental-measurements/parameters/water-quality/turbidity-total-suspended-solids-water-clarity/`.

[22] Fondriest Environmental, Inc. (2018). Conductivity, salinity and total dissolved solids. `https://www.fondriest.com/environmental-measurements/parameters/water-quality/conductivity-salinity-tds/`.

[23] Foster, S. (2019). Water chemistry basics: ph, temperature, water hardness, waste breakdown, minerals, and chemicals. `https://www.petcoach.co/article/water-chemistry-basics-ph-temperature-water-hardness-waste/`.

[24] Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., et al. (2015). The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. *Scientific data*, 2:150066.

[25] Gratwicke, B., Marshall, B., and Nhiwatiwa, T. (2003). The distribution and relative abundance of stream fishes in the upper manyame river, zimbabwe, in relation to land use, pollution and exotic predators. *African Journal of Aquatic Science*, 28(1):25–34.

[26] Guha-Sapir, D. (2019). The emergency events database. `https://www.emdat.be`.

[27] Gumindoga, W., Makurira, H., Phiri, M., and Nhapi, I. (2016). Estimating runoff from ungauged catchments for reservoir water balance in the lower middle zambezi basin. *Water SA*, 42(4):641–649.

[28] Gumindoga, W., Rwasoka, D. T., Nhapi, I., and Dube, T. (2017). Ungauged runoff simulation in upper manyame catchment, zimbabwe: Application of the hec-hms model. *Physics and Chemistry of the Earth, Parts A/B/C*, 100:371–382.

[29] Hove, T., Derman, B., and Manzungu, E. (2016). Land, farming and iwrm: A case study of the middle manyame sub-catchment, zimbabwe. *Water Alternatives*, 9(3):531.

[30] Hrachowitz, M., Savenije, H., Blöschl, G., McDonnell, J., Sivapalan, M., Pomeroy, J., Arheimer, B., Blume, T., Clark, M., Ehret, U., et al. (2013). A decade of predictions in ungauged basins (pub)—a review. *Hydrological sciences journal*, 58(6):1198–1255.

[31] Ishizaki, H. and Akiya, T. (1978). Effects of chlorine on growth and quality of tobacco. *Jarq*, 12(1).

[32] Kadirire, H. (2019). Harare may run out of water. `https://www.dailynews.co.zw/articles/2019/01/13/harare-may-run-out-of-water`.

[33] Kamusoko, R. and Mufandaedza, J. (2012). Heavy metal analysis of fresh water supplies and wastewaters: A case of chinhoyi and harare, zimbabwe. *International Researcher*, 1:13–19.

[34] Kashangura, C. (2014). Policy issues for possible temporal and spatial rainfall distribution changes due to climate change.

[35] Kauffeldt, A., Wetterhall, F., Pappenberger, F., Salamon, P., and Thielen, J. (2016). Technical review of large-scale hydrological models for implementation in operational flood forecasting schemes on continental level. *Environmental Modelling & Software*, 75:68–76.

[36] Kentucky Department for Environmental Protection (1996). Sulfate and water quality. `http://www.state.ky.us/nrepc/water/ramp/rmso4.htm`.

[37] Khatir, Y. (2014). *Early Warning using Flood Routing in the Gash River, Kassala State, Sudan*. PhD thesis, University of Gezira.

[38] Kogan, F. N. (1995). Application of vegetation index and brightness temperature for drought detection. *Advances in space research*, 15(11):91–100.

[39] Magadza, C. (2003). Lake chivero: a management case study. *Lakes & Reservoirs: Research & Management*, 8(2):69–81.

[40] Magadza, C. (2008). Re-eutrophication and pathenogenic contamination of lake chivero.

[41] Manatsa, D. (2009). *Disaster Risk Management: A Resource Book For Educational Institutions in Zimbabwe*.

[42] Manning, T., Wilson, S., and Chapman, J. (1996). Toxicity of chlorine and other chlorinated compounds to some australian aquatic organisms. *Bulletin of environmental contamination and toxicology*, 56(6):971–976.

[43] Marshal, B. (1997). Lake chivero after forty years: The impact of eutrophication. *Lake Chivero a Polluted Lake. University of Zimbabwe Publications*, pages 1–12.

[44] Martinelli, E. (1984). National masterplan for rural water supply and sanitation. *Report of Ministry of Energy and Water Resources, Government of Zimbabwe*.

[45] Masere, T. P., Munodawafa, A., and Chitata, T. (2012). Assessment of human impact on water quality along manyame river. *International Journal of development and sustainability*, 1(3):754–765.

[46] Masimba, O. (2016). An assessment of the impacts of climate change on the hydrology of upper manyame sub-catchment, zimbabwe.

[47] Matope, Matingo, Chaguala, Muzenda, and Chimbaza (2016). Integrated water resources management plan for the biri dam in middle manyame sub-catchment of zimbabwe. page 86.

[48] Mavhura, E., Manatsa, D., and Mushore, T. (2015). Adaptation to drought in arid and semi-arid environments: Case of the zambezi valley, zimbabwe. *Jàmbá: Journal of Disaster Risk Studies*, 7(1):1–7.

[49] Mhlanga, L., Day, J., Chimbari, M., Siziba, N., and Cronberg, G. (2006). Observations on limnological conditions associated with a fish kill of oreochromis niloticus in lake chivero following collapse of an algal bloom. *African Journal of Ecology*, 44(2):199–208.

[50] Minnesota Pollution Control Agency (2007). Phosphorus: Sources, forms, impact on water quality - a general overview.

[51] Minnesota Pollution Control Agency (2008). Nutrients: Phosphorus, nitrogen sources, impact on water quality - a general overview.

[52] Minnesota Stormwater (2019). Minnesota stormwater manual: Design infiltration rates. `https://stormwater.pca.state.mn.us/index.php?title=Design_infiltration_rates`.

[53] Misi, A., Gumindoga, W., and Hoko, Z. (2018). An assessment of groundwater potential and vulnerability in the upper manyame sub-catchment of zimbabwe. *Physics and Chemistry of the Earth, Parts A/B/C*.

[54] Morgen, P. (2016). A study of rainfall and ground-water levels in a suburb of harare, zimbabwe.

[55] Moyo, P., Chapungu, L., and Mudzengi, B. (2013). Effectiveness of water hyacinth (eichhornia crassipes) in remediating polluted water: The case of shagashe river in masvingo, zimbabwe. *Advances in Applied Science Research*, 4(4):55–62.

[56] Mupedziswa, F. (2016). *Impacts of Land Use and Land Cover Changes on the Water Quality of Surface Water Bodies: Muzvezve Sub-Catchment, Zimbabwe*. PhD thesis, University of Zimbabwe.

[57] Murwira, A., Masocha, M., Magadza, C. H., Owen, R., Nhiwatiwa, T., Barson, M., and Makurira, H. (2014). Zimbabwe-strategy for managing water quality and protecting water sources.

[58] Nangombe, S. (2015). Drought conditions and management strategies in zimbabwe. In *Proceedings of the Regional Workshops on Capacity Development to Support National Drought Management Policies for Eastern and Southern Africa and the Near East and North Africa Regions*, pages 84–89.

[59] Nardi, F., Annis, A., Di Baldassarre, G., Vivoni, E., and Grimaldi, S. (2018). Gfplain250m global floodplain dataset. `https://doi.org/10.6084/m9.figshare.6665165.v1`.

[60] Nardi, F., Annis, A., Di Baldassarre, G., Vivoni, E., and Grimaldi, S. (2019). Gfplain250m, a global high-resolution dataset of earth's floodplains. *Scientific data*, 6:180309.

[61] NASA (2019). Gravity recovery and climate experiment (grace).

[62] Nhapi, Makurira, and Gumindoga (2014). Integrated water resources management river system outline plan for the upper manyame sub-catchment of zimbabwe. page 118.

[63] Nhapi, I. (2009). The water situation in harare, zimbabwe: a policy and management problem. *Water Policy*, 11(2):221–235.

[64] Norah, M., Shumirai, Z., Zelma, M. L., and Upenyu, M. (2015). Impacts of untreated sewage discharge on water quality of middle manyame river: A case of chinhoyi town, zimbabwe. *International Journal of Environmental Monitoring and Analysis*, 3(3):133–138.

[65] Northeast Georgia Regional Development Center (2001). *Appendix B - Description of commonly considered water quality constituents*, pages B–1–B–11. Brown and Caldwell.

[66] Nyakudya, I. and Stroosnijder, L. (2011). Water management options based on rainfall analysis for rainfed maize (zea mays l.) production in rushinga district, zimbabwe. *Agricultural Water Management*, 98(10):1649–1659.

[67] Oram, B. (2014a). Ammonia in groundwater, runoff, surface water, lakes and streams. `https://www.water-research.net/index.php/ammonia-in-groundwater-runoff-and-streamsr`.

[68] Oram, B. (2014b). Phosphate in surface water streams lakes. `https://www.water-research.net/index.php/phosphate-in-water`.

[69] Orem, W. H. (2011). Sulfate as a contaminant in freshwater ecosystems sources impacts and mitigation. `https://conference.ifas.ufl.edu/ncer2011/Presentations/Wednesday/WaterviewC-D/am/0850_Orem.pdf`.

[70] Phiri, M. (2012). An analysis of the cahora bassa dam water balance and reservoir operations and their flooding impact on upstream settlements.

[71] Reid, R. and Mosley, L. (2015). Causes of high ph in south east wetlands.

[72] Ritter, A. and Muñoz-Carpena, R. (2013). Performance evaluation of hydrological models: Statistical significance for reducing subjectivity in goodness-of-fit assessments. *Journal of Hydrology*, 480:33–45.

[73] Rojas, O., Vrieling, A., and Rembold, F. (2011). Assessing drought probability for agricultural areas in africa with coarse resolution remote sensing imagery. *Remote sensing of Environment*, 115(2):343–352.

[74] Rommens, W., Maes, J., Dekeza, N., Inghelbrecht, P., Nhiwatiwa, T., Holsters, E., Ollevier, F., Marshall, B., and Brendonck, L. (2003). The impact of water hyacinth (eichhornia crassipes) in a eutrophic subtropical impoundment (lake chivero, zimbabwe). i. water quality. *Archiv für Hydrobiologie*, 158(3):373–388.

[75] Ross, C. W., Prihodko, L., Anchang, J., Kumar, S., Ji, W., and Hanan, N. P. (2018). Hysogs250m, global gridded hydrologic soil groups for curve-number-based runoff modeling. *Scientific data*, 5:180091.

[76] Running, S., Mu, Q., and Zhao, M. (2017). Mod16a2 modis/terra net evapotranspiration 8-day l4 global 500m sin grid v006 [data set].

[77] Sakumura, C., Bettadpur, S., and Bruinsma, S. (2014). Ensemble prediction and intercomparison analysis of grace time-variable gravity field models. *Geophysical Research Letters*, 41(5):1389–1397.

[78] Salmon and Conservation, T. (2017). The impact of chlorine and chlorinated compounds in freshwater systems.

[79] Scharffenberg, B., Bartles, M., Brauer, T., Fleming, M., and Karlovits, G. (2018). Hydrologic modeling system hechms user's manual.

[80] Seelig, B. and Nowatzki, J. (2001). Water quality and nitrogen.

[81] Snyder, F. F. (1938). Synthetic unit-graphs. *Eos, Transactions American Geophysical Union*, 19(1):447–454.

[82] Sood, D. (2004). Solid waste management study for freetown, sierra leone. *Component Design for the World Bank, Draft Report Project*, (P078389).

[83] Stoddard, E. (2018). Cape town 'day zero' pushed back to 2019 as dams fill up in south africa. `https://www.reuters.com/article/us-safrica-drought/cape-town-day-zero-pushed-back-to-2019-as-dams-fill-up-in-south-africa-idUSKCN1HA1LN`

[84] Tendaupenyu, P. (2012). Nutrient limitation of phytoplankton in five impoundments on the manyame river, zimbabwe. *Water SA*, 38(1):97–104.

[85] Timmer, Bakker, and Ketelaars (2009). Drinkwatervoorziening van harare lijdt onder politieke wanorde.

[86] Trambauer, P., Dutra, E., Maskey, S., Werner, M., Pappenberger, F., Van Beek, L., and Uhlenbrook, S. (2014). Comparison of different evaporation estimates over the african continent. *Hydrology and Earth System Sciences*, 18(1):193–212.

[87] Tsiko, R. G. and Togarepi, S. (2012). A situational analysis of waste management in harare, zimbabwe. *Journal of American Science*, 8(4):692–706.

[88] Upper Manyame Sub-catchment Council (2014). Upper manyame sub-catchment council annual report. *Unpublished Report. Harare, Zimbabwe.*

[89] U.S. Bureau of Reclamation (1973). California culverts practice.

[90] Valentine, K. (2019). Unveiling earth's floodplain. `https://asunow.asu.edu/20190115-unveiling-earth%E2%80%99s-floodplains`.

[91] Villholth, K. G., Tøttrup, C., Stendel, M., and Maherry, A. (2013). Integrated mapping of groundwater drought risk in the southern african development community (sadc) region. *Hydrogeology Journal*, 21(4):863–885.

[92] Volterra, L., Boualam, M., Menesguen, A., Duguet, J., Duchemin, J., and Bonnefoy, X. (2002). Eutrophication and health. *World Health Organization*.

[93] Waikato Regional Council (2019). Runoff and leaching. `https://www.waikatoregion.govt.nz/environment/natural-resources/water/rivers/waikato-river/runoff-and-leaching/`.

[94] Washburn, B., Yancey, K., and Mendoza, J. (2010). User's guide for the california impervious surface coefficients. *California Environmental Protection Agency Google Scholar*.

[95] Wettenbank (2009). Besluit kwaliteitseisen en monitoring water 2009. `https://wetten.overheid.nl/BWBR0027061/2017-01-01/0/BijlageIII/afdrukkeninformatie`.

[96] World Bank (2013). World bank group technical assistance to zinwa for dam safety assessment: summary of dam safety assessments. 1(103576).

[97] World Bank (2014). Zimbabwe - greater harare water and sanitation strategic plan : investment plan report : Main report. 1(103574).

[98] World Health Organization (2010). Hardness in drinking-water: Background document for development of who guidelines for drinking-water quality. Technical report, Geneva: World Health Organization.

[99] Zimbabwe Meteorological Services Department (2006). Climate issues and facts: Zimbabwe.

[100] Zimbabwe Vulnerability Assessment (2013). Rural livelihoods assessment.

[101] ZINWA (2009). Manyame river system outline plan (RSOP).

[102] ZINWA (2018). Manyame catchment.

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Appendix

Appendix available on request.