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Evaluation of Long-term Impact of Coal Mining in Zambezi River Basin in Mozambique

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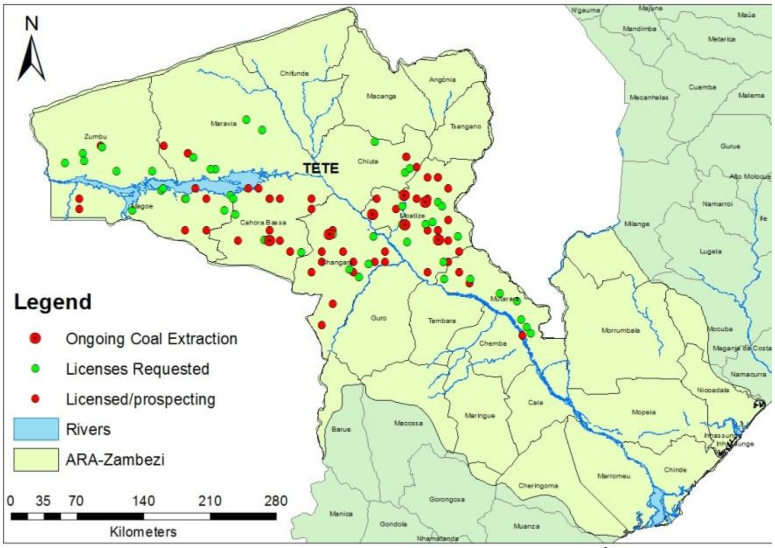

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Evaluation of Long-term Impact of Coal Mining in Zambezi River Basin in Mozambique

Assessment to Establish Monitoring Program of Water Quality Changes Due to Acid Mine Drainage from Coal Mining

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Keywords: Zambezi, coal, river, mine, acid, drainage, water, wastewater, alkalinity, monitoring, Mozambique and Tete.

Master Thesis Degree Project Presented on 30th of May 2013

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Abstract

Zambezi River Basin is an international river basin which sustains life of about 30 million people in its riparian countries: Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia and Zimbabwe. The main stream of the river enters to Mozambique with average flow of about 2330 m^3/s and reaches the outfall in the Indian Ocean with about 4134 m^3/s. This makes both the activities in the upstream countries and inside Mozambique interfering greatly in the water quality of the river. Nowadays coal mining is developing faster in the upstream area of Zambezi River Basin in Mozambique and it may influence greatly the water quality of the river basin in future.

This makes relevant to evaluate the long-term impact of acid mine drainage from coal mining in Zambezi River Basin in Mozambique, establish a prediction system and sustainable monitoring program of water quality.

There are three coal basins identified in Tete province and almost 30 companies holding licenses to prospect and extract coal in these basins. The Chicôa-Mecúcoè basin located more to the west of Cahora-bassa dam and do not have any coal mine in operation until now. The other two basins, Sanângoè-Mefídezi and Moatize-Minjova, are located more to the east of the Cahora-bassa dam and there are already seven mines in operation in these coal basins. All coal basins are located near the main stream of Zambezi River and this has to be considered when planning water quality monitoring.

The main problem of coal mining is acid mine drainage generation. When the acid mine drainage reaches the natural sources of water it contaminates by lowering the pH and increasing the content of sulphate, iron, aluminium, manganese and heavy metals. From the estimations done it was concluded that no significant impact is expected in the main stream of Zambezi River but particular attention has to be given to the tributaries of the area affected by coal mining. These tributaries and some groundwater aquifers passing near the coal mines may be greatly affected by the acid mine drainage, threatening the environment, biodiversity and human health.

Acronyms and Abbreviations

AMD – Acid Mine Drainage.
ARA – Zambeze – Regional Administration of Water in Zambezi River Basin in Mozambique (Administração Regional de Águas do Zambeze).
DNG – National Geology Directorate (Direcção Nacional de Geologia).
DNM – National Mining Directorate (Direcção Nacional de Minas).
GW – Groundwater.
IIP-Songo - National Institute for Fishing Investigation of Songo (Instituto Nacional de Investigação Pesqueira).
MICOA – Ministry for Coordenation of Environmental Action (Ministério Para a Coordenação da Acção Ambiental).
MIREM – Ministry of Mineral Resources (Ministérios dos Recursos Minerais).
SADC – Southern African Development Community.
WW – Wastewater.
WWTP – Waterwater Treatment plant.
ZAMCOM – Zambezi Watercourse Commission.
ZR – Zambezi River.
ZRB – Zambezi River Basin.

Contents

1. Introduction

Mozambique is a developing country and its economy was based on agriculture and tourism until the past few years. In the last 10 to 15 years many geological surveys showed that Mozambique is rich of mineral resources like coal, gas and heavy mineral sands. In the last years there was a lot of investment going to mining industry and it is becoming the main source of economic development.

The major reserves of coal are located in Moatize District in Tete Province. There are at least 40 companies holding coal mining licences in Mozambique and 95% of them are based in Tete (Hatton & Fardell, 2011).

On the other hand, the biggest river of Southern Africa, Zambezi River, passes through the coal mining area in Tete Province and it may result in several environmental and ecological impacts in the River Basin.

Coal mining can contaminate both surface and groundwater by so called acid mine drainage (AMD). AMD is causing significant and costly environmental impacts worldwide (Inter-Ministerial Committee, 2010). AMD affects surface and groundwater for a long time after the operations of mining has ceased (Inter-Ministerial Committee, 2010).

The companies working in coal mining have an obligation to make detailed environmental studies and environmental management plans before starting the coal extraction activities, but each company presents its own environmental study and environmental management plan. As there are several companies involved in the activity even if the effect of single company does not seem significant, probably the effect of all the companies together can damage the environment. For that reason it is important to assess the overall and long-term effect of coal mining and establish a prediction system and sustainable monitoring program of water quality changes in Zambezi River Basin. The general monitoring program should be done by an independent institution, not by the coal mines.

The Regional Administration of Water for Zambezi River Basin (ARA-Zambeze) is the institution which is responsible for the general monitoring of water quality within Zambezi River Basin. However it has problem of lack of resources. The other institution which can be directly involved in the general monitoring programme is the National Institute for Fishing Investigation of Songo (IIP-Songo) by monitoring the amount of species sensitive to pollution, but this institution has also problem of lack of resources.

To guarantee the establishment of a sustainable water quality monitoring program a detailed study about the sources of pollution, pathways used by the pollutants to reach the river have to be considered in order to minimize the sampling and get more representative information about water quality in the river basin. The implementation of prediction system of water quality changes can reduce the usage of resources for the monitoring by minimizing the sampling and analysis. Associated to this is important to create a legislation which makes all companies involved in the coal mining to participate in a general water quality parameters monitoring in Zambezi River Basin.

This study conducted as Master Thesis Degree project will come up with a list and description of necessary studies to establish a prediction system and a sustainable monitoring programme of water quality in Zambezi River Basin in Mozambique and propose the way to make all the stakeholders participate in general water quality monitoring programme.

1.1 Objective

The overall objective of this study is to evaluate the long-term impact of acid mine drainage from coal mining in Zambezi River Basin in Mozambique as pre-assessment to establish a prediction system and sustainable monitoring programme of water quality.

Specific objectives

In order to achieve the goal of the main objective is necessary to:

- Identify, map, describe and predict the development of the main sources of acid mine drainage from coal mining;

- Make a rough prediction of water quality changes in the main stream and tributaries of the area affected by coal mining in Zambezi River in Mozambique based on the pH, alkalinity and the amount of water generated in the coal mines;
- To make a rough estimation of contaminated water generated from coal mines considering groundwater seepage and precipitation;
- Suggest a sustainable water quality monitoring procedure for Zambezi River Basin in Mozambique;
- To develop a research plan to establish a prediction system and sustainable monitoring program of water quality in Zambezi River Basin in Mozambique.

1.2 Methodology

The study was conducted based on literature review; investigation of documentation available in different institutions working in water management of Zambezi River Basin and coal mines; and field study visit to Tete Province.

Description of the problems caused by coal mining in water resources was done based on literature review of scientific articles and papers related to water pollution due to coal mining.

A study visit and consultation to documentation available in the following institutions: Mining National Directorate (DNM) and Geology National Directorate (DNG) under Ministry of Mineral Resources (MIREM); Ministry for Coordination of Environmental Action (MICOA); Regional Administration of Water in Zambezi River Basin (ARA-Zambeze); National Institute for Fishing Investigation of Songo (IIP-Songo) were conducted to fulfil the first and second specific objectives. Some literature review and ArcGIS were used to complement the information found in the field investigation and consultation.

Based on the results of first and second specific objectives a desk study was conducted to predict the overall and long-term impact of coal mining in water quality of Zambezi River Basin in Mozambique. The overall and long-term assessment gave the necessary information to identify and describe the studies to establish a prediction system and sustainable monitoring program of water quality in Zambezi River Basin considering the development of coal mining in Tete Province in Mozambique.

2. Coal mining in the world

The coal mining was being developed in a small scale many years ago and coal was used to produce energy for domestic activities. The large scale coal production was developed during the industrial revolution in the 18th century and it became the main source of energy for industry. Nowadays coal mining is well developed and it is still the cheapest and most abundant source of energy (Wikepedia, 2013).

Many countries have a well developed coal mining industry. The example of these countries is: China, USA, India, Australia, South Africa, Russia, Indonesia, Kazakhstan, Poland, Colombia, Brazil (Wikepedia, 2013). Mozambique is a country with its part of emerging economy due to coal mining.

Associated to coal mining there are several environmental Impacts. One of the main problems is the generation of acid mine drainage (AMD) discussed in this report.

There are many rivers and groundwater aquifers affected by acid mine drainage in South Africa, USA, Australia and Brazil. Many reclamation projects are implemented in mines in USA for example, but these projects are very expensive and the environment is already affected.

The streams affected by AMD have low pH, high content of metals and the bottom is usually covered by precipitates of iron which makes them brown, **Figure 1.** This scenario can be found in many streams in the countries with mining.

Figure 1 Stream affected by acid mine drainage (Ely Minnesota, 2009)

2.1 Wastewater in coal mines

In general the wastewater from coal mining can be classified as mine water, process water, domestic wastewater and surface run-off. The biological pollutants in the coal mining can be found in the wastewater from domestic and sanitation facilities within the amenity buildings. The mine and process water usually have significant changes in physical and chemical parameters. The run-off can be a potential problem when it comes into contact with mine or process water.

The most likely sources of AMD are the mine water and the runoff in the mining area and/or where the tailings of mining process were stored. The process water sometimes can have a low pH depending on the contact time with the minerals during the process. The most convenient configuration is that the mine water, process water and run-off from the mine area should have special treatment; and the domestic wastewater (WW) and runoff from the amenity area should be sent to the sewage system or treated in a domestic wastewater treatment plant (WWTP) see **Figure 2**.

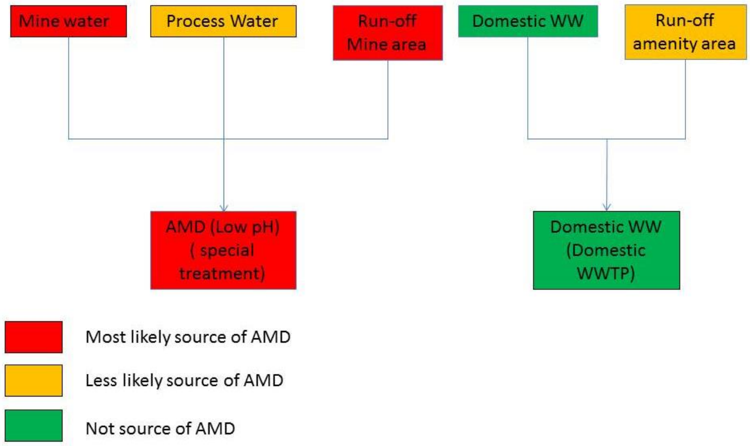

Figure 2 Sources of wastewater in a coal mine

Normally wastewater from coal process may have high content of total dissolved solids (TDS), hardness, conductivity and apparent colour; moderate concentration of other minerals (Na^{+}, Mg^{2+}, Ca^{2+}, CO_3^{2+}, Cl^{-}, SO_4^{2-} and trace elements like Al and Fe); low suspended solids, BOD and COD; the pH ranges between 7-9.5 (Hagare, et al., n.d.). The main characteristics of coal processing wastewater are given in **Table 1**.

Table 1 General characteristics of coal processing wastewater (Hagare, et al., n.d.)

Parameter	**Range of concentration**	**Units**
Total Dissolved Solids	500-2000	mg/l
Hardness	500-2000	mg/l
Suspended Solids	10-100	mg/l
BOD	<5	mg/l
COD	10-100	mg/l
pH	7-9.5	Standard units
Conductivity	600-10000	µs/cm
Apparent Colour	30-600	Units

The major water problem from mining is caused by AMD formed when water comes into contact with tailings of mining activity in the presence of oxygen. This water can be from rain, runoff, and groundwater. The problem of AMD occurs during the operation of the mine and even when mining activities have ceased it is difficult to control. The main parameters affected are the pH, concentration of heavy metals and sulphate.

3. Description of the study area

The study area is all Zambezi River Basin (ZRB) in Mozambique. As the ZRB is international this area can be affected by activities in upstream counties in Mozambique. The coal mining area is located in Tete province in the west part (the upstream part) of the river basin in Mozambique.

3.1 Zambezi River Basin

Zambezi River Basin (ZRB) is one of the most valuable and diversified natural resources in Africa. It is the major river basin in Southern Africa with a surface area of about 1.370.000 Km^2 and the average discharge at the outfall is about 4134 m^3/s (World Bank, 2009). The water of Zambezi River sustains the economy and it is used to develop projects to reduce the poverty of the region (World Bank, 2009). Beyond sustaining life of about 30 million people and keeping the natural environment rich and diversified the river is essential for the economy of its riparian countries: Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia and Zimbabwe, see **Figure 3** (World Bank, 2009). The river is also essential for food security and hydroelectric energy production (World Bank, 2009).

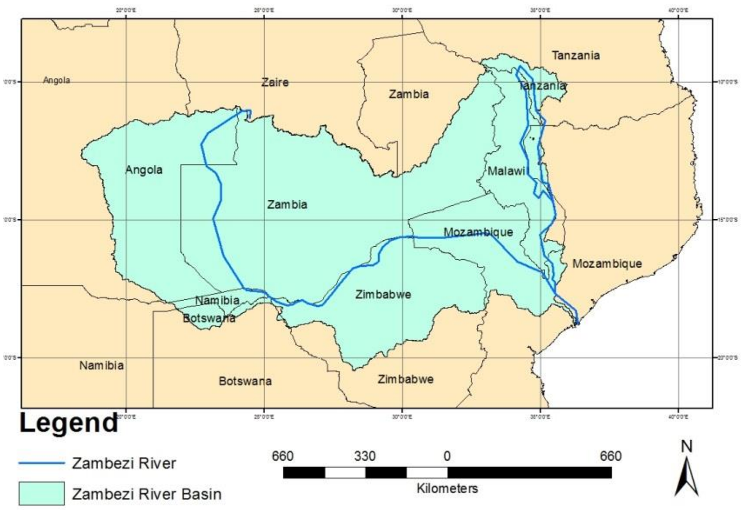

Figure 3 Zambezi River Basin

Due to the distribution of rainfall the north area of the basin contributes with larger volumes of water than the south, see **Figure 4**. The tributaries in north area of the sub-basin contributes with water as follow: Higher Zambezi 25% , Kafue River with 9%, Luangwa with 13%, and Shire with 12%. The minimum average precipitation is registered more to the south with about 500 mm/year and the maximum is registered more to the north east with about 2400 mm/year. The overall average precipitation in ZRB is about 950 mm/year.

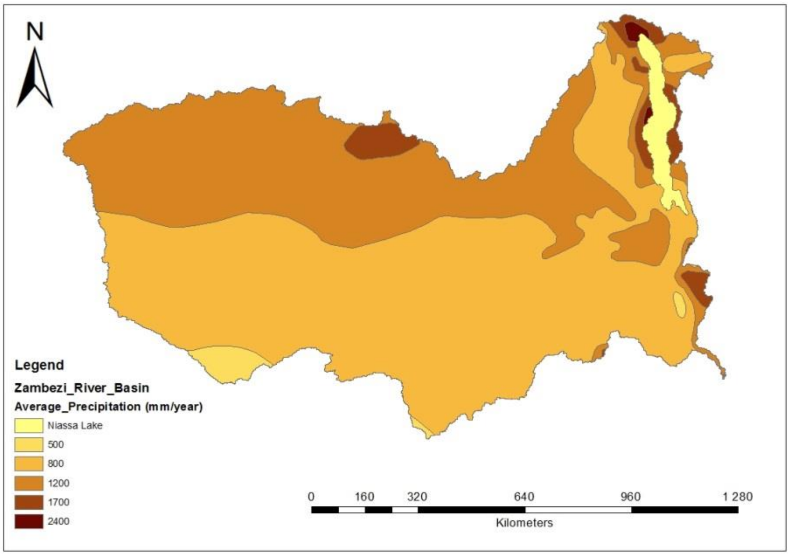

Figure 4 Precipitation in Zambezi River Basin (USGS , 2012)

Water Use in Zambezi River Basin

The water of ZRB is used to develop several economic activities such as energy production, agriculture, fishing, tourism, drinking water supply, etc. (World Bank, 2009). All these activities and others which are not directly related to water usage like mining and industrial activity result in several impacts to the natural environment. In general all activities taking place downstream the river can be affected by activities taking place upstream.

Several dams were constructed along the river for water storage and/or for energy production. These dams disturb the water flow changing the biodiversity in the river and in the riparian areas. Actually there were almost 12 dams and 53 new projects of dams being analysed until 2008 (World Bank, 2009). The total installed capacity for energy production in Zambezi River is about 5000 MW and the major hydroelectric power plant (Cahora-Bassa dam) is located in Mozambique, in Tete province which is producing 2075 MW (World Bank, 2009). The Cahora-bassa dam influences significantly the study area.

With regard to agriculture, there are large irrigated areas along ZRB. Until 2008 the larger irrigated area was located in Zimbabwe, which had about 108.717 ha/year followed by Zambia (74.661 ha/year), Malawi (37.820 ha/year), Tanzania (23.140 ha/year), Mozambique (8436 ha/year), Angola (6125 ha/year), Namibia (140 ha/year) and Botswana (0 ha/year) (World Bank, 2009). The prediction of development of agriculture shows that Mozambique will became the second with larger irrigated areas with about 137.410 ha/year following Zimbabwe with 183.431 ha/year. If the analysis includes long term projects and large scale irrigation, Mozambique has the higher potential for irrigation than all other countries with about 600000 ha/year (World Bank, 2009).

The agriculture taking place in upstream countries affects the water quality in Mozambique and this has to be considered when planning water quality monitoring program. The leaching of nutrients (phosphorous and nitrogen) can lead to eutrophication of the stream and changing the quality of life of aquatic species, influencing the flow of the stream, increasing the probability of flooding.

Agricultural lands in Mozambique are located more to the east of the coal mining area, downstream to the river. The AMD coming from coal mining area can negatively impact the agriculture area compromising the expected development of agriculture. This is more one reason to guarantee that the coal mining is not only polluting the water of the river but also affecting one of the most sensible sectors of any society which is food production and food security.

There is not enough data to have good estimations about the amount of water for other uses like domestic, industrial and livestock (SADC-WD/Zambezi River Authority, 2007). A rough estimation done using the number of population showed that approximately 175 Mm^3/day is used for domestic supply in urban areas and 24 Mm^3/day is used for domestic supply rural area

(SADC-WD/Zambezi River Authority, 2007). Considering the conditions of the region it was assumed that 90% of urban water and 15% of rural water supply is from surface water and the remaining is from groundwater sources (SADC-WD/Zambezi River Authority, 2007).

All figures discussed above show that the two most important sectors of water usage upstream the mining area which can interfere in the water quality of the river are dams constructed for water storage or/and energy production and agriculture. The urban and industrial uses of water cannot be evaluated because of lack of data but these two sectors of water usage cannot be ignored because they can interfere significantly with the water quality.

The difficulty to evaluate clearly the water usage upstream of the mining area cannot inhibit the implementation of water quality monitoring in the mining area. This difficult can be overcome by analysing water immediately upstream of the mining area by looking at the changes in the water quality in this area it is possible to predict the source of pollution. The first potential sources to look at are dams and agriculture, followed by urban and industrial wastewaters, and livestock. It has to be considered that probably there are other sources of pollution not identified at this stage which can influence the water quality of the river before the mining area.

3.1.1 Zambezi River Basin in Mozambique

The ZRB in Mozambique covers over Tete and a small area of the Niassa province (ARA-Zambeze, n.d.). Approximately 11.5% of the total area of ZRB is in Mozambican territory which is about 157.000 Km^2. The hydrologic system of Zambezi River in Mozambique is shown in **Figure 5**. There are 7 major tributaries and there are 7 villages or cities along the river basin (ARA-Zambeze, n.d.). The main stream of Zambezi River makes the border between Zambia in the north and Zimbabwe in south and it connects with one of the main tributaries the Luangwa River which makes border between Zambia in west and Mozambique in east. The main stream of Zambezi river crosses the Mozambican border where it connects to Luangwa River. The average flow of the river when it crosses the Mozambican border is about 2330 m^3/s. When the river passes through Mozambique until its outfall in Indian Ocean the river receives more 1804 m^3/s of water raising its flow up to 4134 m^3/s. The main stream of Zambezi River receives from rainfall and its tributaries 1193 m^3/s of water from the area of Tete affected by coal mining, approximately 70% of the total flow received in Mozambique. It can influence significantly the quality of water downstream of the river.

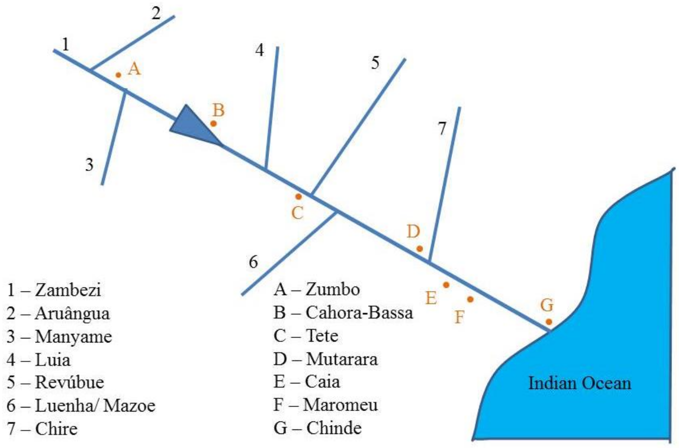

Figure 5 Hydrologic System of Zambezi River Basin in Mozambique (1-7 are tributaries and A-G are villages) (ARA-Zambeze, n.d.)

The average precipitation in Mozambican area of ZRB is approximately 1000 mm/year. In general the north area presents higher precipitation than the south and it means that the tributaries in the north of the river contribute with more water than the ones from south. The maximum average precipitation is registered in the north east of the basin which is about 1700 mm/year and the minimum value of average precipitation is registered in south west which is about 800 mm/year, see **Figure 6**. A small area in south east has average precipitation of about 500 mm/year, but this area is very small.

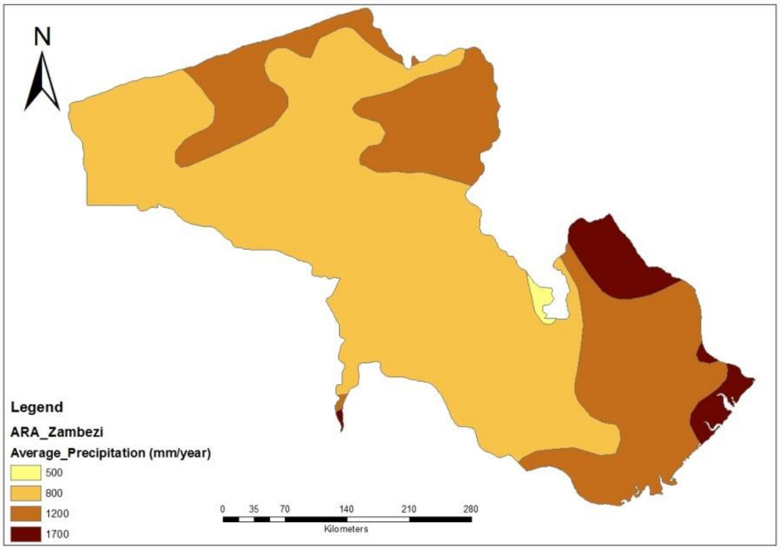

Figure 6. Average Precipitation in Zambezi River Basin in Mozambique (USGS , 2012)

The evapotranspiration in Mozambique was estimated using the map in the Hydrology and Hydric Resources" Hidrologia e Recursos Hídricos", see **Figure 7**. A grid of squares was created on the original map of evapotranspiration. The number of squares is proportional to the area of the river basin. The average evapotranspiration was estimated by summing up the product of evapotranspiration of the area for the number of squares with same evapotranspiration and then dividing by the total number of squares in the river basin in Mozambique. The average evapotranspiration in ZRB in Mozambique was estimated to be about 740 mm/year.

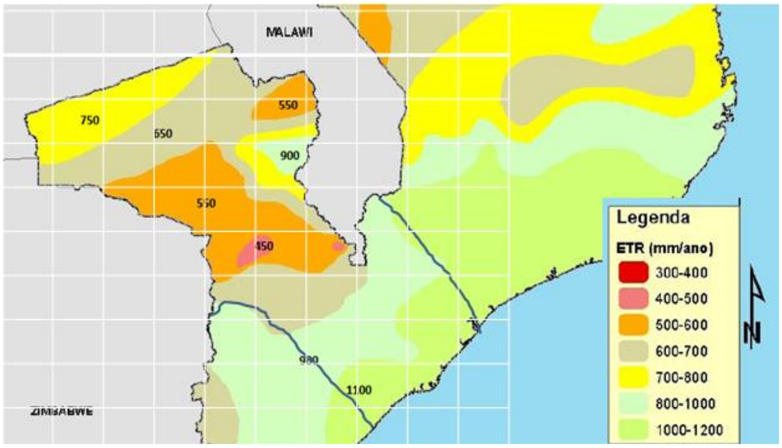

Figure 7 Estimation of actual evapotranspiration of Zambezi River Basin in Mozambique, adapted from (Hipólito & Vaz, 2011)

There are several activities taking place in these areas as, energy production, irrigation, livestock, fishing, withdrawal of surface and ground water for domestic use, etc.

The major dam in the river is located in Tete province, the Cahora-bassa dam, which produces about 2075 MW of energy. Cahora-Bassa separates the west and east regions in the geology of Tete. In both regions there is coal but the east area is the most exploited. This dam influences the water quality and life in the river before the main mining area. There is a project of other dam downstream, 70 km after Tete city the called Mphanda – Nkwuwa Project. It is expected that after implementation of this project the capacity of hydroelectric energy production in Mozambique doubles but this dam will increase the environmental impacts caused by Cahora-bassa dam.

The agriculture in Mozambique is not well developed but it was estimated that if ZRB in Mozambique is well exploited is possible to produce food for about 280 million people (Moçambique para todos, 2011). This capacity can be reduced if there is AMD from the coal mining region upstream the agriculture land.

The other important sector which can be affected by AMD is the fishing. The population of fish may reduce significantly if the pH of the water reduces or the concentration of heavy metal increases. Out of these important sectors of economy the human health can be also threaten by reducing pH and increasing concentration of heavy metals in natural sources of water. The population which uses either surface or groundwater contaminated without any treatment, especial rural population can be directly affected and the cost of water treatment can also increase in drinking water treatment plants.

3.2 Water Management in Zambezi River Basin

3.2.1 **International perspective**

The management of trans-boundary Rivers is still a serious challenge in Southern Africa particularly in ZRB. This difficult to manage international river basins rises because countries have multiple and competing interests; inadequate river basin level institutional structure; institutional, legal, economic and human resources constrains; poor data collection; poor communication and inadequate training (Kirchhoff & Bulkley, 2008).

With the increasing of damming of the stream associated with poor communication between the countries the floods become more unpredictable and these phenomena also increases the potential conflicts due to water management between the countries. The need of adequate integrated water resources management within ZRB becomes much more important issue.

Knowing the importance of the river and different threats to a sustainable water management in the river, more than 20 decades ago the riparian countries under Southern African Development Community (SADC) came with a formulation of Zambezi River Action Plan Project in 1991 (Mott MacDonald , 2012). The project aimed at integrated development and management of the water resources in the SADC region to support sustainable economic and social development, regional integration and eradication of poverty (Mott MacDonald , 2012).

The action plan was implemented in two phases. Phase 1 from 1991 to 2000, was concerned with the development of database for water resources to support the establishment of effective planning and management of the water resources of the region. The phase 2 was from 2001 to 2008 and had two main objectives: establishment of an institutional framework for management of shared water resources in ZRB; and formulation

of an integrated water resources strategy for the river basin (Mott MacDonald , 2012). The negotiation between the eight riparian countries led to an agreement signed by seven countries in 2005 which created a river basin organization, the Zambezi Watershed Commission (ZAMCOM) (Mott MacDonald , 2012).
The objective of ZAMCOM is "to promote the equitable and reasonable utilization of the water resources of the Zambezi watershed as well as efficient management sustainable thereof" (ZAMCOM, 2005).
This organization was created but the lack of resources and data availability limits greatly the implementation of sustainable integrated water resources management in ZRB.

3.2.2 National perspective

The management of water resources in Mozambique is based in river basin called Regional Administration of Water "Administração Regional de Águas" (ARA). There are five regional administrations of water in Mozambique: ARA – Sul, ARA – Centro, ARA – Zambeze, ARA – Centro Norte and ARA – Norte. The regional administrations of water have financial autonomy but they have to report the accountability to National Directorate of Water under the Ministry of Public Buildings and Habitations (Kit de Sensibilização Sobre o Rio Limpopo, 2010).
The water issue is considered as a transversal issue which involves several ministries: Ministry of Public Buildings and Habitations, Ministry of Agriculture and Fishing, Ministry of foreigners affairs and Cooperation, Ministry of Industry and Trade, Ministry of Mineral resources and Energy, Ministry of Estate Administration, Ministry of Health and Ministry for Coordination of Environmental Action which are forming the National Council of Water (Kit de Sensibilização Sobre o Rio Limpopo, 2010). The ZRB is managed by ARA – Zambeze it is based in Tete city, capital of Tete Province and is responsible for the area shown in **Figure 8**.

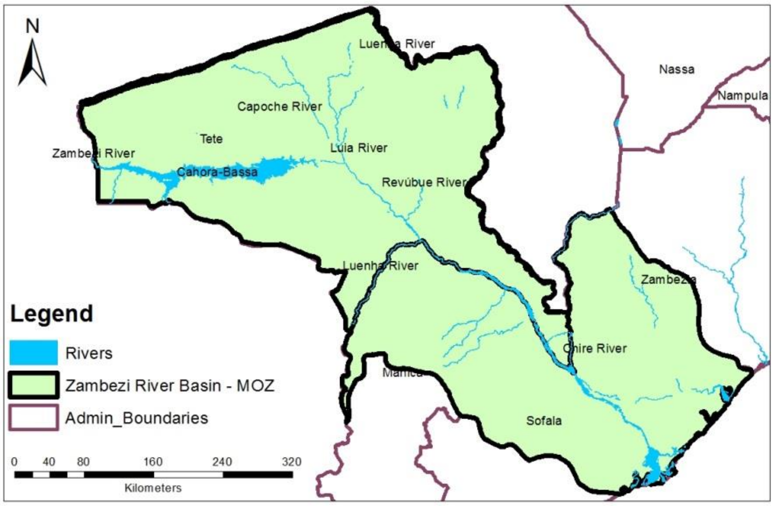

Figure 8 Zambezi River Basin in Mozambique

ARA-Zambeze is responsible to ensure the rational usage of water resources; safeguarding surface water sources; controlling the flow to the ocean by promoting the building of dams to store water; reducing the wastage of water with cooperation with other institutions which have more direct responsibilities, raising awareness in the population about water being exhaustible resource and becoming serious issue in the XXI century; collecting fees by the usage of raw water which are used to maintain the hydrometric activity, other activities to protect the water resources and in future the fees will include the recovery of investments in hydraulic infrastructures; and protecting the surface and groundwater resources against to pollution and inadequate uses which may result in high costs to make the water potable again (ARA-Zambeze, n.d.).

As one of the responsibilities of ARA-Zambezi is to protect surface and groundwater resources against to pollution and inadequate uses, this institution is now doing a monitoring of water quality along ZRB. The lack of resources limits the water quality monitoring and the institution cannot collect enough data for complete and exhaustive monitoring. To find financial resources to develop more sustainable monitoring program is challenge to the institution.

The National Institute for Fishing Investigation of Songo (IIP-Songo) plays important role in water quality monitoring in ZRB in Mozambique, by monitoring the population of fish in the river.

But the actually records of fish monitoring are more related to Cahora-Bassa dam and do not include the area affected by coal mining. It is important to expand the fish monitoring to all areas of the river which are affected by coal mining but this means more resources and a need of development of more sustainable fish monitoring program.
The participation of stakeholders in water monitoring programs has to be improved. The companies working in coal mining are doing individual environmental monitoring programs but they should participate more actively in general monitoring program. The users of water downstream the coal mining area should also participate, by supplying records of water quality to ARA-Zambezi.

3.3 Characterization of Tete

To perform a water quality monitoring in a river, it is important to identify the main sources of pollution or the target source of pollution. In this case the target source of pollution is coal mining. Coal mining can affect different parameters of water like transported of sediments, alkalinity, pH, total dissolved solids and leaching metals (Farrell-Poe, 2000). The monitoring discussed in this report is focused on AMD which affects directly the pH. The AMD influences also the content of heavy metals in the stream because lower pH enhances the leaching of metals into the water. The kind of metals leaching to the river is dependent to the geology and chemistry of the region.

3.3.1 Geology of Tete Province

The geologic formation of Tete province is diversified and characterized by Karoo Supergroup. "Karoo is typically geology of Sothern Africa and is defined as strata unconformable overlaying Precambrian base-rock followed by bimodal igneous formation of Lower Jurassic age and/or unconformable overlayin by middle or younger strata" (Vasconselhos, 2009). Zambezi valley in Mozambique is divided into west and east by horst of Precambrian rock in Cahora Bassa. Each of these areas is subdivided into small structurally controlled sub-basins

(Vasconselhos, 2009). The Karoo Supergroup in Tete is divided into three main basins Chicôa-Mecúcoè, Sanângoè-Mefídezi and Moatize-Minjova, see **Figure 9** (Vasconselhos, 2009).

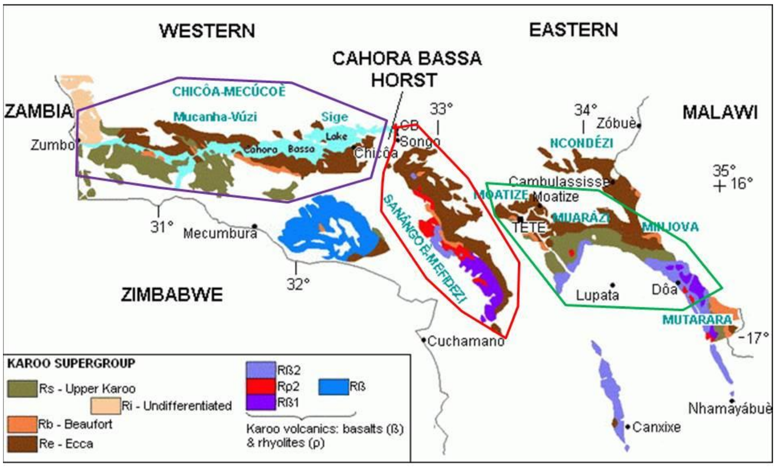

Figure 9. Geology of Tete Adapted from (Vasconselhos, 2009)

The geology of Tete is characterized by layers of coal intercalated by different formations as sandstone, grey shale, argillite and tillite. The **Figure 10** shows the general configuration of geological layers and the respective thickness in the three coal sub-basins in Tete. In Moatize the Chipanga layer is the thickest and is the only one which was exploited until now (José & Sampaio, 2011). The Chipanga layer is located at about 200 meters below the ground surface which means that all upper layers have to be removed to extract the coal and this will influence significantly the natural environment.

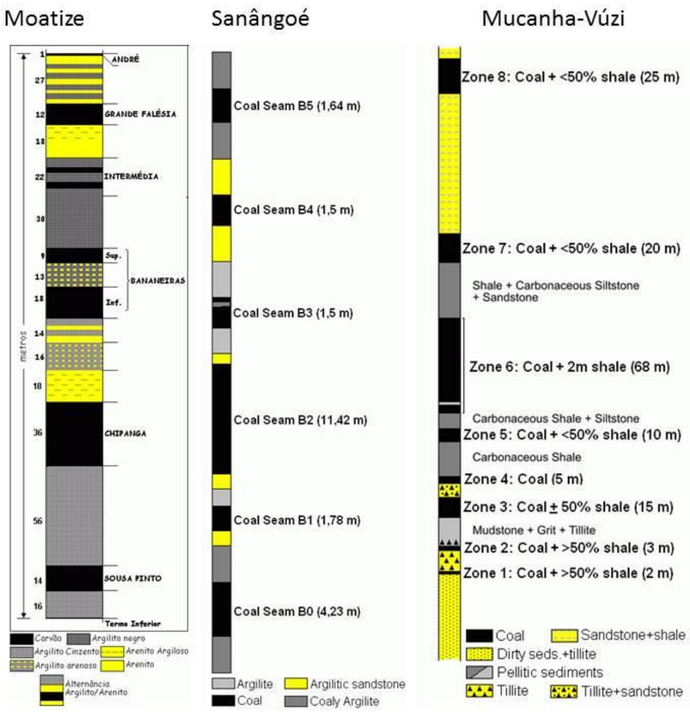

Figure 10 Layers of coal in three coal basins in Tete adapted from (Vasconselhos, 2009) & (José & Sampaio, 2011)

3.3.2 Chemistry of coal of Tete

There are few studies about the chemistry of Tete coal available. Most studies are about coal reserves in Moatize. Studies about trace-elements in the ashes of coal of Mozambique done using coal from Moatize basin revealed that elements like Ba, Cr, Cu, Ni, and Zn deserve particular attention in regard to human health (Vasconselhos, et al., 2009). In addition to this list lead (Pb) should be considered because of its harmful characteristics. The **Table 2** shows the minerals detected and the concentration in ppm in the ash of coal from Moatize basin and the information about effects on human health. More detailed information about the effects of metals to human health and to the environment can be found in (Lenntech, 1993).

Table 2 Elements detected from the ash of Moatize coal, the compositions data from: (Vasconselhos, et al., 2009)

Element	Name	Composition(ppm)			Effect to human health
		Min.	Average	Max.	
Ba	Barium	101	476	1300	Large amounts causes paralyses even death but the amount present in water is usually small (Lenntech, 1993).
Co	Cobalt	3.8	9.9	26	It causes health problems mainly by breathing (Lenntech, 1993).
Cr	Chromium	9.3	23	56	Cr(IV) is dangerous causing several health problems but usually it is in low concentrations (Lenntech, 1993)
Cu	Copper	14.4	32.7	68	No information
Mn	Manganese	9.5	37.4	109	Necessary to human body but high concentrations may be serious harmful (Lenntech, 1993).

Table 2 (Cont.)

Element	Name	Composition(ppm)			Effect to human health
		Min.	Average	Max.	
Ni	Nickel	4.9	20.8	153	Necessary to human body but high concentrations may be serious harmful (Lenntech, 1993).
Pb	Lead	3.9	18.8	74	Is one of the four elements which have more harmful effect to human health (Lenntech, 1993).
Sr	Strontium	8.9	151.9	379	No information
Ti	Titanium	183	1511	4584	No information
V	Vanadium	21	46.2	128	No information
Zn	Zinc	17.6	47	94	Essential for human health but large amounts may cause problems (Lenntech, 1993)
Zr	Zirconium	8.3	27.4	109	No information

Elements like barium (Ba), Copper (Co), Chromium (Cr), Manganese (Mn), nickel (Ni), lead (Pb), titanium (Ti), vanadium (V), zinc (Zn) and Zirconium (Zr) are present in the geology of Tete and they can be expected to be present in natural streams. Their content may be increased by the effect of AMD. The concentrations of these metals in water cannot be easily predicted because they depend mainly on the pH, temperature and the content of each metal in the geology of Tete. The best way to know the concentrations of the metals is by analysing samples of water. The metals detected by this study can be a good starting point to select metals to be monitored in water affected by AMD from coal mines in Tete. However it may happen that other metals were not detected because the analysis was done on the ash of coal and did not involve all layers in the geology of Tete.

3.4 Coal Mining in Tete

The coal mining in Mozambique started in colonial period in 1920 by Portuguese companies (Alexandre, 2012). The activity of Moatize Company started in 1948 and in 1978 it was stabilised the government coal company CARBOMOC E. E (Alexandre, 2012). The highest production of coal in that period was in 1981 with about 575000 tons. But in 1983 the activities of carbonic were stopped due to political problems (Alexandre, 2012).

In 2004 the Mozambican government opened the international contest to the development of Moatize Coal Basin and Companhia do Vale do Rio Doçe (CVRD) won (Alexandre, 2012). In 2011 two projects of extraction of coal were started by two companies, the Moatize project by Vale Moçambique Lda and Benga Project by Rivesdale Moçambique, Lda. The Benga project is actually owned by Rio Tinto (Alexandre, 2012).

There are more than 60 licenses and 40 requests for licenses for coal mining owned by around 30 companies. There were three companies extracting coal until the end of 2011 and all were located in Moatize, which are Vale Moçambique, Rio tinto, and Minas de Moatize (RM, 2012). In 2012 four more companies started with coal extraction, which are Jindal in Changara district, ENRC in Cahora-Bassa district, Ncondedzi Coal Company and Minas Revúbue in Moatize (RM, 2012).

The **Figure 11** shows the distribution of coal mining licences, requests of licenses and operating mines in Tete Province. Note that the location of the licences, requests of licences and mining sites shown in the map are not true, as the licenses of coal mining should be shown by surfaces not points. But the analysis using point layer helps to know in which regions the coal mining companies are more interested in and predict future development of coal extraction. The **Figures 1A, 2A** and **3A in Appendix A,** shows the licenced areas.

Comparing the **Figures 9** and **11** is possible to see that the licences, request of licences and the mining sites are located in the three main basins: Chicôa-Mecúcoè, Sanângoè-Mefídezi and Moatize-Minjova. These three basins are located near the main stream of Zambezi River or in its tributaries, and if coal is exploited in all the licenced areas it can be expected significant impact to the water of the river and its tributaries.

The **Figure 11** shows that all 7 operated mining until now are located downstream the Cahora-Bassa Dam and the monitoring of water quality in the river considering the impact of mining activity now should consider the region downstream the Cahora-Bassa Dam. Particular attention also has to be given to the Moatize district, to Revúbue and Moatize Rivers because five mines which are already operating are located near to these two rivers, see **Figure 8** and **11**.

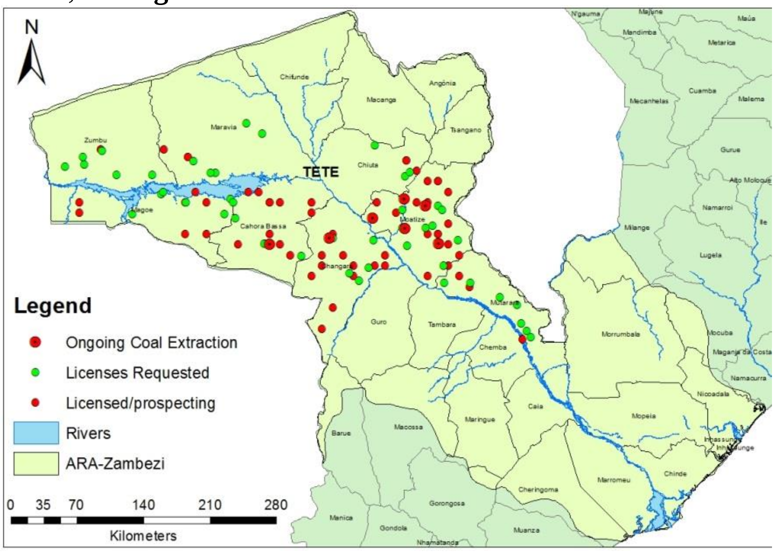

Figure 11 Coal Mining in Tete province (data collected in MIREM)

3.4.1 Projections of coal production in Tete

The Ministry of Mineral Resources (MIREM) has produced projections of coal production in Mozambique and it shows that the coal production will grow from 2.9 millions of tons in 2011

to 39.0 millions of tons in 2019. After this peak the production will reduce to 6.7 millions of tons until 2028, see **Figure 12**. The journal Macauhub reported that the production of coal grew from 500 thousand tons in 2011 to 4 million tons the first nine months of 2012 which is relatively low compared to the projections of MIREM (Macauhub, 2013).
The projection of coal production presented in **Figure 12** was done considering 6 main coal mining companies and the production of other companies is extremely low.

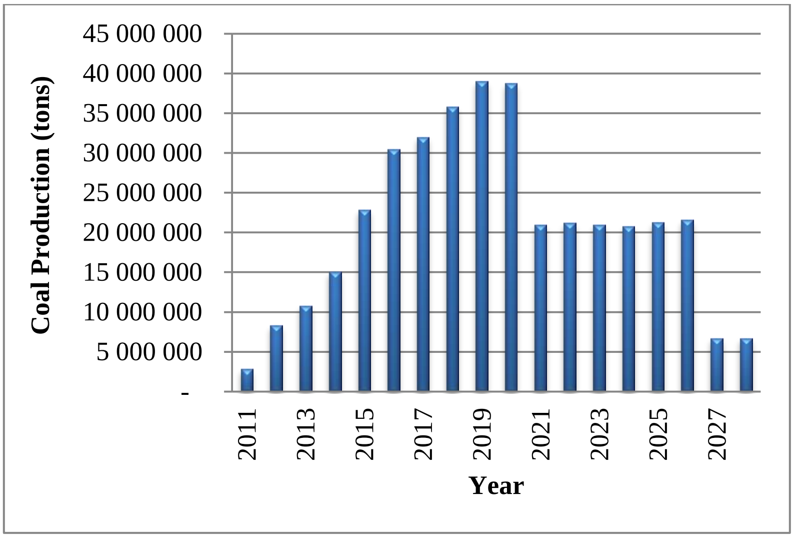

Figure 12 Projections of Coal Production in Mozambique (data collected in: MIREM)

Using the predicted values of coal production is possible to estimate the wastewater generation from coal mining and predict the possible impacts in Zambezi River Basin and its tributaries.

3.5 Water quality in Zambezi River Basin in Mozambique

The institution responsible for water quality monitoring in Zambezi River Basin (ZRB) in Mozambique is ARA-Zambeze as described before, but there are other institution playing important roles in water quality monitoring in the river basin such as National Institute for Fishing Investigation of Songo (IIP-Songo) and the coal mining companies.

ARA-Zambeze is not doing a complete monitoring of all relevant water quality parameters in whole river basin due to lack of resources. ARA-Zambeze is only able to do the monitoring of few physical parameters such as pH, conductivity, turbidity, dissolved oxygen, total dissolved solids and temperature. The chemical and biochemical parameters are not monitored. In the case of coal mining it is also important to monitor the alkalinity, content of sulphate and leaching metals because they are directly related to the lowering of pH which can be caused by AMD.

Some records of water quality monitoring done by ARA-Zambeze in the proximities of Tete city, Leunha and Revúbue rivers and Cahora-Bassa dam show that the pH is in the range of 7 to 10.

A more detailed characterization water quality of ZRB can be found in the environmental study report of Vale Moçambique, the company operating the major coal mine in Moatize. But its monitoring is limited to its area of influence. The result of pre-assessment of water quality done by Vale Moçambique shown that the main stream of Zambezi River had pH between 7.3 to 7.90 and the alkalinity between 60 to 64 mg/l of $CaCO_3$ in 2005 and it did not change too much until 2009. The concentrations of cations of calcium, magnesium, sodium, potassium and anions of bicarbonate and carbonate are low compatible with the level of hardness which is about 50 mg/l (Vale Moçambique Lda, n.d.).

The pH, hardness and total alkalinity in some tributaries of Zambezi River in Moatize district are also reported in the Environmental Study report of Vale Moçambique Lda and are given in **Table 3**.

The information presented in this chapter is based in a few measurements. The minimum and maximum values obtained in the measurement are reported in the description above and in the **Table 3**.

Table 3 pH, hardness and alkalinity of some Tributaries of Zambezi River in Moatize (Vale Moçambique Lda, 2010)

River	Parameter	Minimum	Maximum
Revúbue	pH	7.36	8.38
	Hardness (mg/l $CaCO_3$)	59	91
	Alkalinity (mg/l $CaCO_3$)	72	109
Murarazi	pH	7.22	7.79
	Hardness (mg/l $CaCO_3$)	64	342
	Alkalinity (mg/l $CaCO_3$)	88	342
Nharenga	pH	7.32	7.67
	Hardness (mg/l $CaCO_3$)	53	235
	Alkalinity (mg/l $CaCO_3$)	60	240
Nhacomba	pH (only one record)	7.7	
	Hardness [mg/l $CaCO_3$] (only one record)	50	
	Alkalinity [mg/l $CaCO_3$] (only one record)	60	

In order to evaluate the impact of changing of water quality parameters in the life in the river it is important to monitor the population of fish in the river. This is currently done by IIP-Songo, but the lack of resources limits the fish monitoring to Cahora-Bassa and the monitoring is mainly focused on the changing in fish population due to the impacts produced by Cahora-Bassa Dam. A few researches have been done downstream the river but no continuous monitoring is being done.

It is very important that ARA-Zambeze, IIP-Songo, the coal mining companies and other stakeholders like drinking water supply and agriculture companies in the river basin cooperate for water quality monitoring in the river basin. ARA-Zambeze should act as coordinator, do final assessment and plan mitigation measures to the negative impacts.

No data about groundwater investigations was found in ARA-Zambeze. Vale Moçambique, Lda did pre-assessment of groundwater quality in Moatize district. Samples were taken from different sections of the concession area at different depths to be analysed. From the analyses it was concluded that groundwater has almost neutral pH and most of other parameters are inside the standards.

It was important to discuss the trends of surface and groundwater parameters with time in this chapter but due to lack of data is not possible. Discussion of trends can help to predict the changes in water quality without coal mining activity and avoid confusing the changing in water quality due to other effects with the changings due to coal mining.

4. Theoretical background

Coal mining can be classified as surface or underground. Both surface and underground coal mining can result in acid mine drainage (AMD). In surface coal mining the rock overlaying the coal layer is broken into small fragments in order to be removed and they are replaced into the pit after the removal of coal. This exposes the acid forming material to the water and air, increasing the probability of forming AMD. In underground coal mining the AMD can be formed in cavern-like passages created during the mining activity (Office of Water - Engineering and Analysis Division, 2000).

AMD is formed when air and water come into contact with certain minerals associated with mining such as pyrite or other coal associated rocks containing sulphide. Sulphide reacts with oxygen from air and water to form acid and yields dissolved metals such as aluminium, iron and manganese (Office of Water - Engineering and Analysis Division, 2000). AMD is characterized by high concentration of salts, heavy metals and radionuclides (Inter-Ministerial Committee, 2010). Commonly value of pH of AMD is in between 2-3 standards units (Hagare, et al., n.d.).

When the AMD reaches the surface or groundwater, the pH can be lowered to values lower than 6.0 standards units; and the concentration of sulphate and dissolved metals may increase (Office of Water - Engineering and Analysis Division, 2000). Even if the pH of surface water further is neutralized, the content of metals may remain high or precipitate and coat the streambed making it unsuitable to support the life in the water (Office of Water - Engineering and Analysis Division, 2000). In the case of groundwater the persistent intrusion of AMD can destroy the buffer capacity of the aquifer and make it sensitive for small changes of pH in future.

In general coal mining can cause several impacts such as depletion of cover forest; pollution of water, soil and air; scarcity of water; and degradation of agricultural lands forcing the farmers to abandon the area (Swer & Singh, 2006). Associated to this it can increase the risk of waterborne diseases due to high concentration of heavy metals in water affected by AMD.

4.1 Pathways of acid mine drainage

AMD may affect simultaneously surface and ground water because they are interconnected. Consider the example of interrelation between river and groundwater of an adjacent aquifer. If the water table is toward the stream, meaning that the hydraulic gradient of the stream is toward the stream, the groundwater will flow into the river, the stream is called *gaining stream* (Fetter, 2001). When the opposite situation is happening and the water from the river is leaking into the aquifer the stream is considered *losing stream* (Fetter, 2001).

If an aquifer is recharged through a mining site where AMD is taking place the groundwater will be contaminated. The groundwater with low pH will dissolve several minerals depending on the geology of area. If the groundwater from this aquifer comes into contact with river it can lower the pH and add significant amount of pollutants like heavy metals. Once the river is contaminated, if it becomes losing stream downstream it can contaminate several groundwater aquifers, see **Figure 13**.

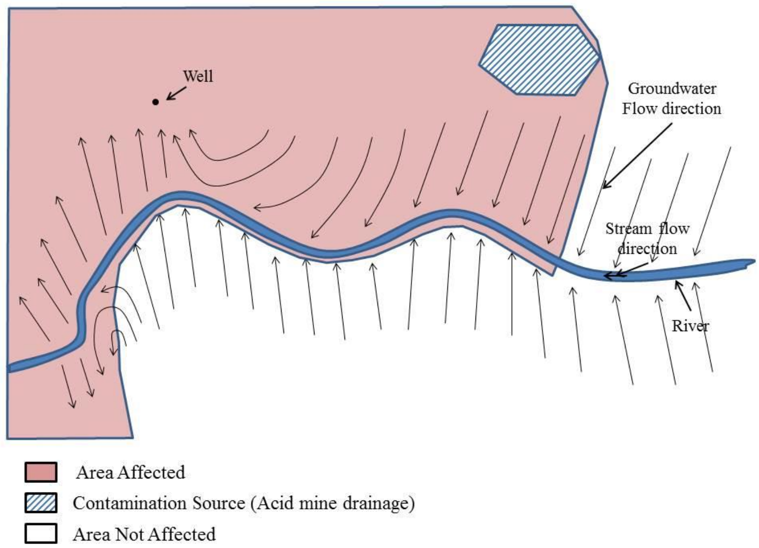

Figure 13 Schematic representation of transport of AMD (possible scenario)

It is possible that also the river receives AMD through runoff. If the mining site is located near to the river, during the rain seasons the polluted water can reach the stream directly through surface runoff.
Floods can also influence the transport of pollutants of AMD to the river streams so that is important to investigate the probability of the mining site being flooded and how severe the situation would be if it happens.

4.2 Basic chemistry of acid mine drainage

The chemistry of AMD apparently seems to be straightforward but it becomes complicate as geochemical and physical characteristics of the aquifers and streambeds affected may vary a lot (Capello, 2003). The following description is not detailed; it describes the most common chemistry of AMD in coal and hard-rock sites (Capello, 2003).
Pyrite (FeS_2) is responsible to start the AMD and metals dissolution in coal and hard-rock sites (Capello, 2003). When pyrite is exposed to oxygen and water it is oxidized resulting in hydrogen ion release (acid), sulphate anions and iron, **equation 4.1**. This process occurs in nature in the hard-rock in undisturbed environment but at slow rate and the water can buffer the acid generated (Capello, 2003). The mining activity increases the rate of decomposition of pyrite bound in coal and hard-rock by increasing the exposed surface area. In this case the acid is generated in a rate that exceeds the buffer capacity of water (Capello, 2003).

$$2FeS_{2(s)} + 7O_{2(aq)} + 2H_2O \rightarrow 2Fe^{2+} + 4SO_4^{2-} + 4H^+ \quad (4.1)$$

Further the Fe^{2+} (ferrous ion) is oxidized to Fe^{3+} (ferric ion), this reaction occurs when the dissolved oxygen in water containing iron is enough, **equation 4.2** (Capello, 2003).

$$2Fe^{2+} + 1/2\,O_2 + 2H^+ \rightarrow 2Fe^{3+} + H_2O \qquad (4.2)$$

This reaction seems to reduce the acidity but the presence of Fe^{3+} in water leads to precipitation of $Fe(OH)_{3,}$ base with low solubility increasing the acidity again as shown by **equation 4.3**.

$$2Fe^{3+} + 6H_2O \Leftrightarrow 2Fe(OH)_3 \downarrow + 6H^+ \quad (4.3)$$

The ferric ion can either react with pyrite increasing the acidity as the **equation 4.4** shows.

$$14Fe^{3+} + FeS_{2(s)} + 8H_2O \Leftrightarrow 2SO_4^{2-} + 15Fe^{2+} + 16H^+ \quad (4.4)$$

If ferrous ion is produced as a result of **equation 4.4** and if there is enough oxygen the cycle of **equations 4.2** and **4.3** will perpetuate (Capello, 2003). If there is no oxygen, the reaction presented by **equation 4.4** will continue to generate ferrous iron and the result is that the water will have high content of ferrous iron (Capello, 2003).

When the water is acidic the acidophilic, bacteria which grows in low pH can establish themselves. These bacteria play significant role by accelerating the reactions which take place in AMD (Capello, 2003). *Thiobacillus Ferroxidans* are bacteria which normally occur in this case which catalyse the oxidation of ferrous iron (Capello, 2003).

Nevertheless the fact that they are not very important, the precipitation reactions of some metals may contribute significantly to the lowering of pH (Capello, 2003). The most common precipitation reactions in water are shown by **equations 4.5**, **4.6**, **4.7** and **4.8**.

$$Al^{3+} + 3H_2O \Leftrightarrow Al(OH)_3 \downarrow + 3H^+ \quad (4.5)$$

$$Fe^{3+} + 3H_2O \Leftrightarrow Fe(OH)_3 \downarrow + 3H^+ \quad (4.6)$$

$$Fe^{2+} + 1/4\,O_2 + 5/2\,H_2O \Leftrightarrow Fe(OH)_3 \downarrow + 2H^+ \quad (4.7)$$

$$Mn^{2+} + 1/4\,O_{2(aq)} + 5/2\,H_2O \Leftrightarrow Mn(OH)_3 \downarrow + 2H^+ \quad (4.8)$$

There are other reactions which can increase the content of metals in water but do not generate acid. These reactions are due to the presence of other minerals similar to pyrites such as *sphalerite* (ZnS), *galena* (PbS), *millerite* (NiS), *greenockite* (CdS), *covellite* (CuS) and *chalcopyrite* ($CuFeS_2$) which are oxidized when exposed to oxygen in aqueous environment (Capello, 2003). The example of these reactions is given by **equations 4.9**, **4.10**, **4.11**, **4.12**, **4.13** and **4.14**.

$$ZnS + 2O_{2(aq)} \rightarrow Zn^{2+} + SO_4^{2-} \quad (4.9)$$

$$PbS + 2O_{2(aq)} \rightarrow Pb^{2+} + SO_4^{2-} \quad (4.10)$$

$$NiS + 2O_{2(aq)} \rightarrow Ni^{2+} + SO_4^{2-} \quad (4.11)$$

$$CdS + 2O_{2(aq)} \rightarrow Cd^{2+} + SO_4^{2-} \quad (4.12)$$

$$CuS + 2O_{2(aq)} \rightarrow Cu^{2+} + SO_4^{2-} \quad (4.13)$$

$$CuFeS_2 + 4O_{2(aq)} \rightarrow Cu^{2+} + Fe^{2+} + SO_4^{2-} \quad (4.14)$$

The other source of minerals in water is weathering which is direct dissolution of minerals from rocks (Capello, 2003). This is a natural phenomenon and it occurs slowly in natural environment, but it can be speed up by lowering the pH of the water, the plausible scenario when there is AMD (Capello, 2003).

4.3 Basic chemistry of water

The most important chemical parameter of water affected by AMD is the pH. This sub-chapter describes the most common reasons of pH variations in water and its ability to resist for these variations the so called buffer effect characterised by buffer reactions. The equations developed in this chapter are used after in the report chapter 5 for developing a model to predict the pH of a stream resulting from a mixing of two streams with different pH and alkalinity.
There are several elements affecting the pH in natural water and the most important ones are listed in **Table 4**.

Table 4 Elements affecting the pH of water in the natural environment

Element	Description
Concentration of CO_2 in the atmosphere	When the concentration of CO_2 in the atmosphere increases, the equilibrium $CO_{2(air)} \Leftrightarrow CO_{2(aq)}$ is moved to the right, dissolution of CO_2 in water, this moves the equilibrium $H_2CO_3 \Leftrightarrow CO_{2(aq)}+H_2O$ to the left increasing the $[H^+]$ in the water which means reducing the pH and vice versa.
Temperature	The increasing of temperature reduces the dissolution of CO_2 in water moving the equilibrium $H_2CO_3 \Leftrightarrow CO_{2(aq)}+H_2O$ to the right reducing the $[H^+]$ in the water which means increasing the pH and vice versa.
Photosynthesis and respiration	The photosynthesis absorbs CO_2 from the water moving the equilibrium $H_2CO_3 \Leftrightarrow CO_{2(aq)}+H_2O$ to the right reducing the $[H^+]$ in the water which means increasing the pH. Respiration add CO_2 to the water moving the equilibrium $H_2CO_3 \Leftrightarrow CO_{2(aq)}+H_2O$ to the left increasing the $[H^+]$ in the water which means reducing the pH
Addition of acid or base from nature (e.g. dissolution of minerals) or wastes from human activity (e.g. acid mine drainage, acid rain)	This results in direct addition of H^+ ions and if there is no buffer it results in direct change on pH.

Table 4 (cont.)

Element	Description
Neutralization and hydrolysis	It may happen that when certain acid or base is added from external source of water or the temperature changes result in one acid and base reacts to form insoluble salt and water [HA(acid)+BOH (base) ⇔ AB(salt)+H_2O] *Neutralization*. The opposite reaction may occur if insoluble acid or base is formed *hydrolysis*. This may result in increasing or decreasing the pH depending on the reaction.

4.3.1 Buffer reactions in water

The buffer reactions occur either in surface or groundwater and they are important to keep the pH of the water constant when small amounts of acid or base are added. The buffer reaction can be classified as acid or alkaline.

Acidic buffer

Acid buffer is characterized by pH below 7. This kind of buffer occurs when the water contains a weak acid and its conjugated base. The general reaction of acid buffer is given by the **equation 4.15**.

$$HA \Leftrightarrow A^- + H^+ \qquad (4.15)$$

The acid constant is calculated by **equation 4.16**.

$$k_a = \frac{[A^-]\cdot[H^+]}{[HA]} \qquad (4.16)$$

The pH of water with this acid can be calculated by **equation 4.17**.

$$P^H = P^{k_a} + \log\left(\frac{[A^-]}{[HA]}\right) \qquad (4.17)$$

When the concentration of A^- is equal to the concentration of HA the pH is equal to pKa. If small amount of strong acid is added to the water the equilibrium shown by **equation 4.15** will move to the left and the new pH can be calculated by **equation 4.18**.

$$P^H = P^{k_a} + \log\left(\frac{[A^-] - \Delta[H^+]}{[HA] + \Delta[H^+]}\right) \tag{4.18}$$

If small amount of base is added to the water the equilibrium shown by **equation 4.15** will be move to the right and the new pH of the water can be calculated by **equation 4.19**.

$$P^H = P^{k_a} + \log\left(\frac{[A^-] + \Delta[OH^-]}{[HA] - \Delta[OH^-]}\right) \tag{4.19}$$

Alkaline buffer

The alkaline buffer is characterized by pH greater than 7. This kind of buffer occurs when the water contains a weak base and its conjugated acid. The general reaction of alkaline buffer is given by the **equation 4.20**.

$$BOH \Leftrightarrow B^+ + OH^- \tag{4.20}$$

The base constant is calculated by **equation 4.21**.

$$k_b = \frac{[B^+]\cdot[OH^-]}{[BOH]} \tag{4.21}$$

The pOH of water with this base can be calculated by **equation 4.22**.

$$P^{OH} = P^{k_b} + \log\left(\frac{[B^+]}{[BOH]}\right) \tag{4.22}$$

Thus the pH can be calculated by **equation 4.23**.

$$P^{H} = P^{kw} - P^{OH} \tag{4.23}$$

In the **equation 4.23,** *kw* is constant of water and depends on temperature.

When the concentration of B^+ is equal to the concentration of BOH the pOH is equal to pKb. When small amount of strong base is added to the water the equilibrium shown by **equation 4.20** will move to the left and the new pOH can be calculated by the **equation 4.24.**

$$P^{OH} = P^{k_b} + \log\left(\frac{[B^+] - \Delta[OH^-]}{[BOH] + \Delta[OH^-]}\right) \tag{4.24}$$

When small amount of acid is added to the water the equilibrium shown by **equation 4.20** will be move to the right and the new pOH of the water can be calculated by **equation 4.25**.

$$P^{OH} = P^{k_b} + \log\left(\frac{[B^+] + \Delta[H^+]}{[BOH] - \Delta[H^+]}\right) \tag{4.25}$$

The most common and important examples of buffer reaction in natural water are the carbonate system reactions but other reactions involving other weak acids and bases also may act as buffer. Normally the buffer reactions in natural environment are associated with releasing of gas or formation of precipitate.

4.3.2 Carbonate species, pH, H^+, OH^-, total alkalinity and TIC in natural water

When pH and total alkalinity (TAL) of water are known the $[H^+]$, $[OH^-]$, $[H_2CO_3]$, $[HCO_3^-]$, $[CO_3^{2-}]$ and total inorganic carbon (TIC) can be calculated. The concentrations of H^+ and OH^- can be calculated directly from pH by **equations 4.26** and **4.27** respectively.

$$[H^+] = 10^{-pH} \tag{4.26}$$

$$[OH^-] = \frac{kw}{[H^+]} \tag{4.27}$$

Where kw is constant of dissociation of water, at 25ºC kw = 10^{-14}.

All equations are developed to consider initial units of TAL in mg/L of $CaCO_3$. The alkalinity can be into converted to meq/L by **equation 4.29**. The equivalent mass of $CaCO_3$ is given by **equation 4.28**.

$$M_{eq\ CaCO_3} = 50\frac{mg}{meq} \tag{4.28}$$

$$TALn = \frac{TAL}{M_{eq\ CaCO_3}}\left[\frac{meq}{L}\right] \tag{4.29}$$

In the equations above TALn is total alkalinity in equivalent units. The total alkalinity defined as the ability of water to neutralize acids is calculated by **equation 4.30**.

$$TALn = 2[CO_3^{2-}] + [HCO_3^-] + [OH^-] - [H^+] \tag{4.30}$$

$[CO_3^-]$, $[HCO_3^-]$, $[OH^-]$ and $[H^+]$ are molar concentrations of carbonate, bicarbonate, hydroxide and hydrogen ions respectively. When the concentrations are expressed in equivalent, as the equivalent of CO_3^{2-} is two and of the other ions is one the total alkalinity can be calculated by **equation 4.31**.

$$TALn = [CO_3^{2-}]_n + [HCO_3^-]_n + [OH^-]_n - [H^+]_n \tag{4.31}$$

The equilibrium equations of carbonic acid have particular importance in chemistry of water and are shown by **equations 4.32** and **4.34**. The equilibrium constants of carbonic acid are calculated by **equations 4.33** and **4.35** respectively.

$$H_2CO_3 \Leftrightarrow H^+ + HCO_3^- \quad (4.32)$$

$$k_{a1} = \frac{[H^+] \cdot [HCO_3^-]}{[H_2CO_3]} \quad (4.33)$$

$$HCO_3^- \Leftrightarrow H^+ + CO_3^{2-} \quad (4.34)$$

$$k_{a2} = \frac{[H^+] \cdot [CO_3^{2-}]}{[HCO_3^-]} \quad (4.35)$$

The equilibrium constants k_{a1} and k_{a2} at 25 ºC are equal to $4.45x10^{-7}$ and $4.68x10^{-11}$ respectively. Considering the concentrations in equivalent units the equilibrium constants can be calculated by **equations 4.36** and **4.37**. The equivalent of H_2CO_3 and CO_3^{2-} is two and the equivalent of HCO_3^- and H^+ is one.

$$k_{a1} = \frac{[H^+]_n \cdot [HCO_3^-]_n}{[H_2CO_3]_n} \quad (4.36)$$

$$k_{a2} = \frac{1}{2}\frac{[H^+]_n \cdot [CO_3^{2-}]_n}{[HCO_3^-]_n} \quad (4.37)$$

The **equation 4.37** can be rearranged into **equation 4.38**. The **equation 4.38** calculates the concentration of HCO_3^- in water.

$$[HCO_3^-]_n = \frac{[H^+]_n \cdot [CO_3^{2-}]_n}{2 \cdot k_{a2}} \quad (4.38)$$

The **equation 4.39** is obtaining replacing the **equation 4.38** in the **equation 4.31**.

$$TALn = [CO_3^{2-}]_n + \frac{[H^+]_n \cdot [CO_3^{2-}]_n}{2 \cdot k_{a2}} + [OH^-]_n - [H^+]_n \quad (4.39)$$

The **equation 4.40** is obtained by solving the **equation 4.39** to $[CO_3^{2-}]_n$. The **equation 4.40** calculates the concentration of CO_3^{2-} in water in meq/L.

$$[CO_3^{2-}]_n = \frac{TALn - [OH^-]_n + [H^+]_n}{\left(1 + \frac{[H^+]_n}{2 \cdot k_{a2}}\right)} \tag{4.40}$$

The concentration of carbonic acid (H_2CO_3) in meq/L is calculated by **equation 4.41**. The **equation 4.41** is obtained by solving the **equation 4.36** to $[H_2CO_3]_n$.

$$[H_2CO_3]_n = \frac{[H^+]_n \cdot [HCO_3^-]_n}{k_{a1}} \tag{4.41}$$

All concentrations can be converted to molarities by dividing the concentrations in meq/L by the equivalent of each ion as shown by **equations 4.42 to 4.46**.

$$[H^+] = \frac{[H^+]_n}{Eq_{H^+}} \left[\frac{mol}{L}\right] \qquad Eq_{H^+} = 1 \tag{4.42}$$

$$[OH^-] = \frac{[OH^-]_n}{Eq_{OH^-}} \left[\frac{mol}{L}\right]; \qquad Eq_{OH^-} = 1 \tag{4.43}$$

$$[H_2CO_3] = \frac{[H_2CO_3]_n}{Eq_{H_2CO_3}} \left[\frac{mol}{L}\right] \qquad Eq_{H_2CO_3} = 2 \tag{4.44}$$

$$[HCO_3^-] = \frac{[HCO_3^-]_n}{Eq_{HCO_3^-}} \left[\frac{mol}{L}\right] \qquad Eq_{HCO_3^-} = 1 \tag{4.45}$$

$$[CO_3^{2-}] = \frac{[CO_3^{2-}]_n}{Eq_{CO_3^{2-}}} \left[\frac{mol}{L}\right]; \qquad Eq_{CO_3^{2-}} = 2 \qquad (4.46)$$

The total inorganic content is calculated by **equation 4.47**.

$$TIC = [H_2CO_3] + [HCO_3^-] + [CO_3^{2-}] \qquad (4.47)$$

Using the equations developed above it is possible to calculate the molar concentrations of H^+, OH^-, H_2CO_3, HCO_3^-, CO_3^{2-}, and TIC of water known the pH and total alkalinity.

4.3.3 Carbonate species and pH in natural water

When the pH of water changes, the concentrations of the carbonate species also change. The concentration of each ion can be calculated as a function of the concentration of H^+ ions. The change in concentration is dependent on equilibrium reactions shown by **equations 4.32** and **4.34**. The equations to calculate the concentration of H_2CO_3, HCO_3^- , and CO_3^- when TIC, concentration of H^+, the constants of acid k_{a1} and k_{a2} are known are developed as follow.
The equations **4.48**, **4.49** and **4.50** define the dissociation coefficients of carbonate ions in equilibrium in water.

$$\alpha_{H_2CO_3} = \frac{[H_2CO_3]}{[H_2CO_3] + [HCO_3^-] + [CO_3^{2-}]} \qquad (4.48)$$

$$\alpha_{HCO_3^-} = \frac{[HCO_3^-]}{[H_2CO_3] + [HCO_3^-] + [CO_3^{2-}]} \qquad (4.49)$$

$$\alpha_{CO_3^{2-}} = \frac{[CO_3^{2-}]}{[H_2CO_3] + [HCO_3^-] + [CO_3^{2-}]} \qquad (4.50)$$

From **equations 4.33** and **4.35** the equations **4.51** and **4.52** are derived.

$$[HCO_3^-] = k_{a1} \frac{[H_2CO_3]}{[H^+]} \quad (4.51)$$

$$[CO_3^{2-}] = k_{a2} \frac{[HCO_3^-]}{[H^+]} \quad (4.52)$$

Replacing the **equation 4.51** in **equation 4.52** is obtained the **equation 4.53**.

$$[CO_3^{2-}] = k_{a2} \cdot k_{a2} \frac{[H_2CO_3]}{[H^+]^2} \quad (4.53)$$

The **equations 4.51** and **4.42** calculate the concentrations of HCO_3^- and CO_3^{2-}, known the concentration of H_2CO_3 and H^+. When $[HCO_3^-]$ and $[CO_3^{2-}]$ are replaced using **equations 4.51** and **4.52** in the **equations 4.48**, **4.49** and **4.50**; $[H_2CO_3]$ can be simplified and the equations rearranged to **equations 4.54**, **4.55** and **4.56**.

$$\alpha_{H_2CO_3} = \frac{[H^+]^2}{[H^+]^2 + k_{a1} \cdot [H^+] + k_{a1} \cdot k_{a2}} \quad (4.54)$$

$$\alpha_{HCO_3^-} = \frac{k_{a1} \cdot [H^+]}{[H^+]^2 + k_{a1} \cdot [H^+] + k_{a1} \cdot k_{a2}} \quad (4.55)$$

$$\alpha_{CO_3^{2-}} = \frac{k_{a1} \cdot k_{a2}}{[H^+]^2 + k_{a1} \cdot [H^+] + k_{a1} \cdot k_{a2}} \quad (4.56)$$

The TIC given by **equation 4.47** in the water is constant even when the concentration of H^+ changes. The denominators of **equations 4.48**, **4.49** and **4.50** are TIC. Replacing **equation 4.47** in **equations 4.48**, **4.49** and **4.50** are obtained the equations **4.57**, **4.58** and **4.59** which calculate the concentration of H_2CO_3, HCO_3^- and CO_3^{2-} in water.

$$[H_2CO_3] = \alpha_{H_2CO_3} \cdot TIC \qquad (4.57)$$

$$[HCO_3^-] = \alpha_{HCO_3^-} \cdot TIC \qquad (4.58)$$

$$[CO_3^{2-}] = \alpha_{CO_3^{2-}} \cdot TIC \qquad (4.59)$$

For known value of TIC, k_{a1} (4.45×10^{-7}, at 25ºC) and k_{a2} (4.68×10^{-11}, at 25ºC), the curves of concentration of carbonate ions in water can be plotted assuming different values of pH and are shown in **Figure 14**.

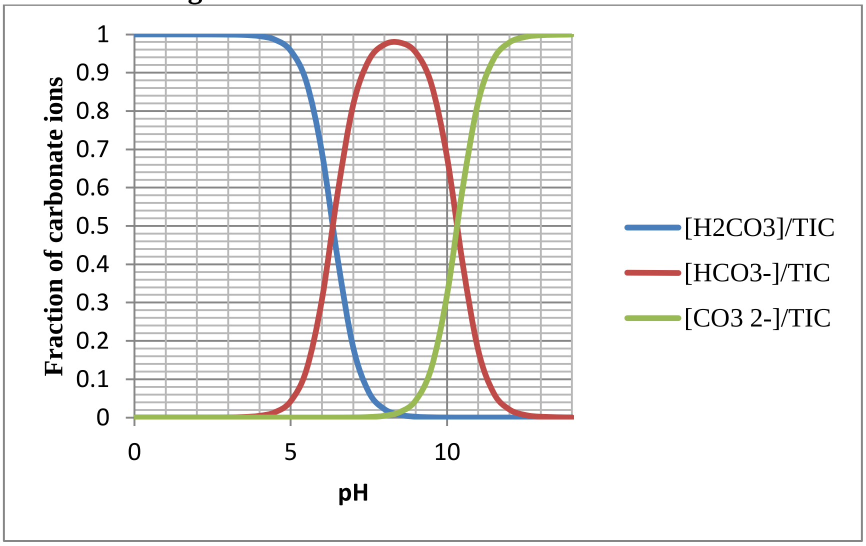

Figure 14 Concentration of carbonate species at different values of pH at 25°C.

The other important equations to understand the change of concentration of carbonate ions in water can be obtained by applying mathematical transformations to **equations 4.33** and **4.35**. The results of these transformations are the **equations 4.60** and **4.61**.

$$pH = pk_{a1} + \log \frac{[H_2CO_3]}{[HCO_3^-]} \qquad (4.60)$$

$$pH = pk_{a2} + \log \frac{[HCO_3^-]}{[CO_3^{2-}]} \quad (4.61)$$

Total alkalinity is calculated by summing up the concentrations of CO_3^{2-}, HCO_3^-, OH^- and subtracting H^- in equivalent concentrations as the **equation 4.30** shows. The **Figure 14** shows that when the pH is 14 the concentration of HCO_3^- is almost zero meaning that the total alkalinity is only characterized by OH^- and CO_3^{2-}. According to **Figure 14**, when the pH is lowered until values round 12 no CO_3^{2-} will be consumed. It means that the pH will be lowered due to consumption of OH^- ions. When the pH decreases for values below 12 the CO_3^{2-} will slowly be converted to HCO_3^-, thus reducing the alkalinity due to consumption of CO_3^{2-}. When the concentrations of CO_3^{2-} and HCO_3^- are equal the pH is 10.3 according to **equation 4.61**. Following the reduction of pH, when the pH is about 8.3 all CO_3^{2-} will be consumed. The HCO_3^- formed will started to be converted into H_2CO_3. At this stage the reason of reduction of alkalinity will be characterized by the consumption of HCO_3^-. When the concentrations of HCO_3^- and H_2CO_3 are equal the pH is 6.3 according to **equation 4.60**. According to **Figure 14,** when the pH reaches values around 4.5 all HCO_3^- will be converted to H_2CO_3. At this stage all alkalinity is consumed any addition of acid will result in reduction of pH due to direct addition of H^+ ions.

4.4 Negative impacts of acid mine drainage in natural waters

The changing of pH due to AMD influences directly the life in the natural waters and the leaching of heavy metals. The receiving waters affected by AMD can have the level of pH as low as 2 to 4.5 (Jennings, et al., 2008).

Some studies report no effect and successful reproduction of fish at pH around 6.5 and most of species are not affected when pH is between 5.5 and 10.5. When the pH drops from 5.5 to 4.5 the fish can be severely impacted (Jennings, et al., 2008).

One study revealed 68 species living in water with pH greater than 6.4; when the pH was between 5.6 and 6.4 only 38 species

were found living; and only 10 species shown tolerance to pH of 5.5 and below (Jennings, et al., 2008). Healthy unpolluted streams usually support several species and moderate abundance of individuals, while polluted streams are dominated by fewer species and low abundance of individuals (Jennings, et al., 2008).
The fish is killed in water affected by AMD by direct exposition to heavy metals and H^+ ions through their grills, impairing respiration resulting in a chronic and acute toxicity (Jennings, et al., 2008). Fish are also exposed indirectly to the heavy metals by ingestion of contaminated sediments and food (Jennings, et al., 2008).
The other negative impact caused by AMD to the streams is the precipitation of the common weathering product of sulphide oxidation which is iron hydroxide (Jennings, et al., 2008). The precipitation of iron hydroxide and oxyhydroxides may coat the streambed sediments destroying the habitat and diminishing the clean gravel for spawning (Jennings, et al., 2008).
Another study revealed abundance of insects and algae in water with pH above 4.5 compared to water with pH between 2.8 and 3.8 (Jennings, et al., 2008).

5. Evaluation of impact of coal mining in water quality in Zambezi River Basin in Mozambique

The following chapter presents a rough prediction of changes in water quality in Zambezi River Basin (ZRB) in Mozambique based on coal production, precipitation, evapotranspiration, streams flows and present water quality in ZRB in Mozambique. Different scenarios were considered and to simplify the analysis the indicative parameter of water quality changes was considered to be pH which is greatly affected by acid mine drainage (AMD). The content of dissolved metals, the other problem of water affected by AMD is greatly dependent on pH and guaranteeing that the pH is not out of the recommended interval is also controlling the content of metals in water. However the content of metals does not depend only on pH but also on other factors such as geology.

The analysis of surface and ground water quality were considered separately. But it is important to keep in mind that there is communication between groundwater and surface water as it is shown in **Figure 15**. The main stream of Zambezi River (ZR) can be affected by the contaminated water from tributaries, runoff and by the groundwater seepage from the bottom of the stream. The tributaries can receive pollutants either from runoff or from groundwater.

The groundwater can receive pollutants directly through infiltration in the mine area and contaminated surface water.

To simplify the analysis and prediction of surface water quality changes it was considered that the amount of water which the main stream receives from groundwater is smaller compared to the water which it receives from the tributaries and the mining sites are in such a distance that the pH of groundwater is buffered before the water reaches the main stream of the river. Considering this, the effect of groundwater to the main stream can be neglected.

In order to estimate the overall impact to the main stream of ZR it was considered that the coal mines in Tete can be viewed as one huge mine and the tributaries like one stream connected to the main stream with average characteristics. The pH and alkalinity were considered to be the same in all tributaries.

The analysis of groundwater was not done with details because its complex due to significant variations in hydrogeological characteristics of Tete. A very rough estimation of contaminated groundwater generated in case of operating and closed mines was considered **Figure 15 a)** and **b)** respectively.

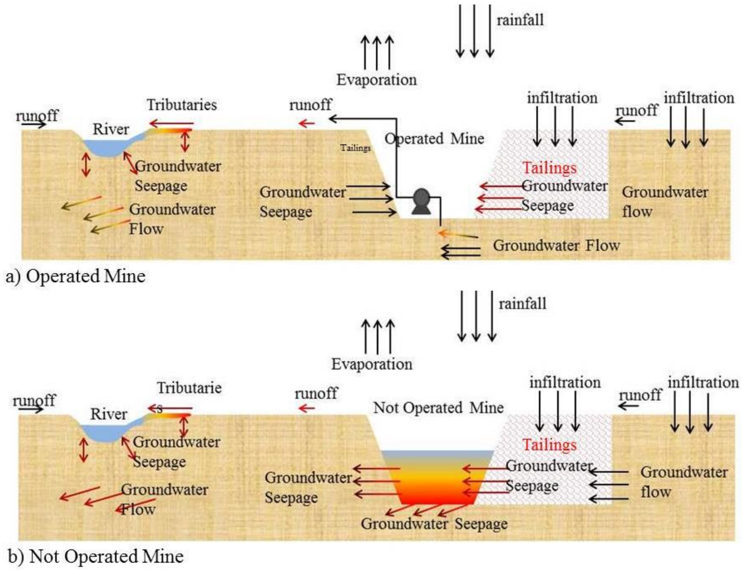

Figure 15 General view of water flow in mining area (possible scenario)

A simplified water balance; investigation of change of pH of water in the main stream of ZRB and its tributaries; and generation of contaminated groundwater in the mines was considered as follows.

5.1 Simplified water Balance in Zambezi River Basin in Mozambique

The water balance in ZRB in Mozambique was done using the data collected and presented mainly in **chapter 3.1**. Each area, affected and not affected by coal mining was estimated using ArcGIS. The area affected was considered to include all districts from Zumbo and Magoe in East up to Mutarara, Tambara and Guro in West. The other area more to west was considered not directly affected by coal mining. The area not affected is not expected to receive directly any AMD from the coal mines but the surface and ground water can be contaminated by the water coming from upstream. The **Figure 16** shows a simplified water balance in ZRB in Mozambique. There are unknowns in the water balance which are important to predict the effect of coal mining on surface and groundwater such as the infiltration rate and the flows of groundwater.

The water balance is mainly related to surface water. The surface water flowing from the tributaries from outside of Mozambique to the area affected and not affected by coal mining were estimated considering that all water resulting from the difference between precipitation and evapotranspiration joins to the tributaries. This is not true because most of water infiltrated to the groundwater. But considering this, the water calculated as coming from outside the country represents the minimum possible. In the reality there is much more water crossing the borders of Mozambique with the tributaries of ZR.

In **Figure 16** the values in parenthesis represents the percentage of flow related to the flow of the main stream of ZR at the outfall to Indian Ocean.

The water balance shows that almost 29% of the water in the outfall to the Indian Ocean passes through the affected area this can cause significant impact to the water quality of the main stream of the river. At least 69% of the water of the main stream of ZR comes from the neighbourhood countries. This shows that the water coming from outside have great impact to water quality of the river in Mozambique. Both international and national influences have to be considered in the water quality monitoring in Zambezi River Basin in Mozambique.

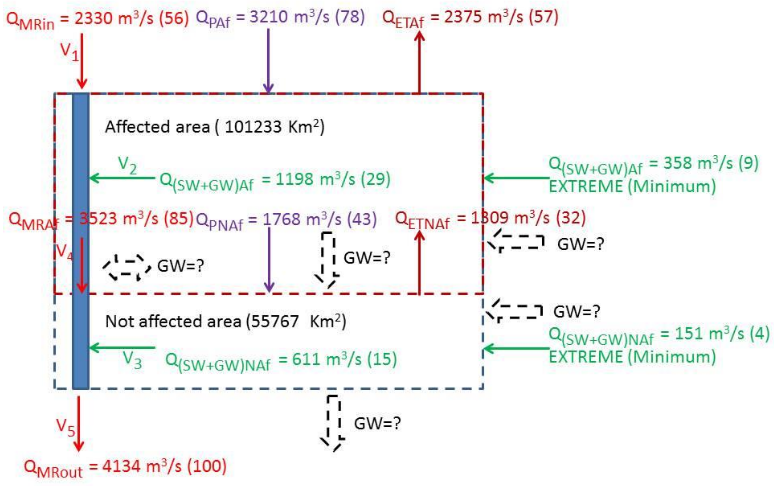

Figure 16 Water balance in Zambezi River Basin in Mozambique

In the **Figure 15**:

Q_{MRin} , Q_{MRAf} and Q_{MRout} = are the water flows in the main stream of ZR at the entrance of Mozambique (V1), after mixing with water from the tributaries of the area affected by coal mining (V4) and at the outfall to Indian Ocean (V5) in (m^3/s) respectively ;

$Q_{(SW+GW)Af}$ and $Q_{(SW+GW)NAf}$ = are the water flows added to the main stream of ZR from the tributaries of the area affected and not affected by coal mining in (m^3/s) respectively (V2);

Q_{PAf}, Q_{PNAf}, Q_{ETAf}, Q_{ETNAf} = are the precipitation in the area affected and not affected, and actual evapotranspiration in the area affected and not affected by coal mining in (m^3/s) respectively;

GW = Unknown groundwater flows.

5.2 Simulation of pH variations in surface water of Zambezi River Basin in Mozambique

The analysis conducted in this sub-chapter is to estimate the pH in the tributaries of the area affcetd by the coal mining which can cause significant impact in the main stream of ZR. For this purpose a model which predicts a pH of the stream resulting in mixing of two streams with known pH and alkalinity was developed.

5.2.1 Surface water model description

The prediction of pH variations was done following the **Figure 17**. The input parameters for the calculations are the total alkalinity of the streams V1, V2, V3; the pH of V1 and V3. The pH of stream V2, water from the area affected by the coal mining, is considered changing due to the effect of AMD, thus affecting the pH of the stream V4 and V5. Different values of pH were assumed for the stream V2, starting from current value which is 7.94 to lower values to evaluate the effect in the stretches V4 and V5 of the main stream of Zambezi River in Mozambique.
All calculations below were done in Ms excel and it was assumed that the streams have constant temperature of 25ºC.

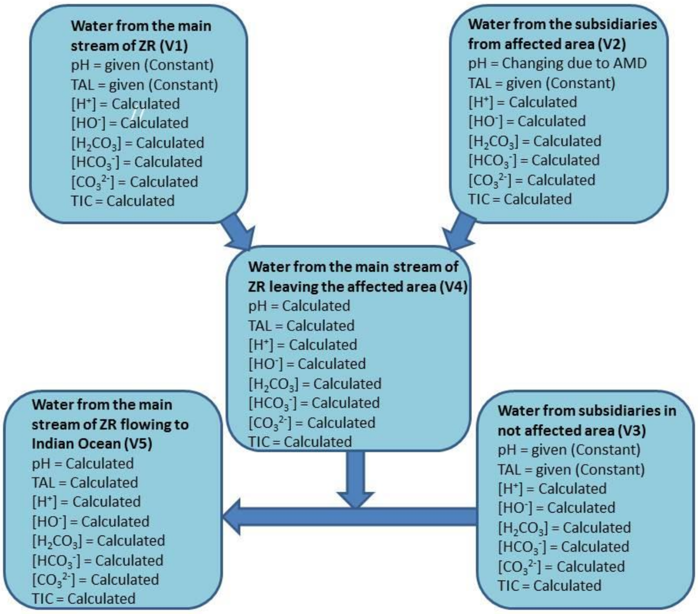

Figure 17 Path to estimate the pH variations in Zambezi River in Mozambique

The first step it was to estimate the initial characteristics (the concentration of carbonate species, TIC, concentrations of H^+ and OH^- ions) of the streams V1, V2 and V3. This was done by employing the equations developed in the **sub-chapter 4.3.2**.

Following to this, the model had to evaluate change of carbonate species, TIC, concentrations of H^+ and OH^- ions in the tributaries of the area affected by the coal mining (V2) when the pH decreases. This was done by employing the equations developed in **sub-chapter 4.3.3**.

The **Figure 17** shows that two streams, water from the main stream of ZR before the area affected by coal mining (V1) and water coming from the area affected by coal mining (V2) are mixed to form the stream V4. The streams have different pH and alkalinity.

In order to predict the characteristics of the resulting stream V4 is important to consider the dilution, mixing and the relationship between alkalinity and pH.

No model computer developed was found solving this problem. This was done by considering dilution, the equations developed in the sub-chapters 4.3.3 and the equations obtained from the analysis of the **Figure 14** as follow.

Before doing any simulation it was necessary to have better understanding of different sections of the **Figure 14**. When the pH is higher than 12 the addition of acid will result in consumption of OH^-. The new concentration of H^+ ions in the main stream $[H^+]_f$ can be calculated by adding to the existing concentration of H^+ ions in the main stream $[H^+]_0$ the concentration coming from the tributaries $\Delta[H^+]$ as shown by the **equation 5.1**. The dilution effect must be considered to calculate both $[H^+]_0$ and $\Delta[H^+]$ in the calculations.

$$[H^+]_f = [H^+]_0 + \Delta[H^+] \qquad (5.1)$$

The second section of the **Figure 14** is when the pH decreases from 12 to 8.3. In this section the reaction presented by the **equation 4.34** governs the reduction of pH and the new concentration of H^+ ions can be estimated by the **equation 5.2** derived from the **equation 4.35**.

$$[H^+]_f = k_{a2} \frac{[HCO_3^-] + \Delta[H^+]}{[CO_3^{2-}] - \Delta[H^+]} \qquad (5.2)$$

In the third section the pH decreases from 8.3 to 4.5. In this section the reaction presented by **equation 4.32** governs the reduction of pH and the new concentration of H^+ ions can be estimated by the **equation 5.3** derived from transformations of **equation 4.33**.

$$[H^+]_f = k_{a1} \frac{[H_2CO_3] + \Delta[H^+]}{[HCO_3^-] - \Delta[H^+]} \qquad (5.3)$$

The fourth and last section starts when pH is equal to 4.5 to lower values. In this section all alkalinity has been consumed and the addition of acid results in direct increase of concentration of H^+ ions and the new concentration of H^+ ions can be estimated by the **equation 5.1**. But in this case $[H^+]_0$ is equal to the concentration of H^+ ions when the pH is equal to 4.5.

In the case of ZR the initial pH for all streams is lower than 8.3 and only the third and fourth sections were considered in the modelling.

The stream V4 is further mixed with water coming from the area considered not affected by the coal mining downstream (V3) to form V5. The same equations used to estimate the characteristics of the stream V4 from V1 and V2 were employed to estimate the characteristics of V5 form V3 and V4.

5.2.2 Results and discussion of surface water Model

The results of calculations of initial characteristics of the streams V1, V2 and V3 are given in the **Table 2B** in the appendix B.

The original pH and alkalinity of the water from the tributaries of the area affected by coal mining (V2) were 7.84 and 192 mg/L (0.00384 eq/L). If the AMD from coal mining affects the water from V2 it is expected that the pH decreases. When the pH decreases the total alkalinity reduces and the concentration of carbonate ions in water changes. The **Figure 18** shows the concentration of carbonate ions and total alkalinity in water of the stream V2 when the pH decreases and the calculations can be found in the **Table 3B** in the appendix B.

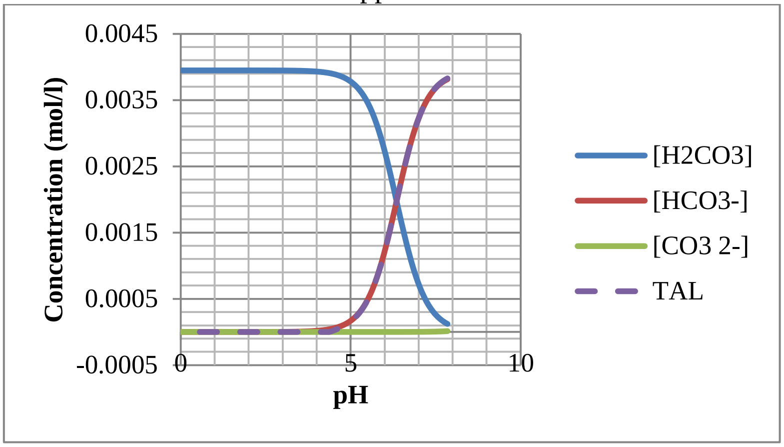

Figure 18 Concentration of carbonate species and total alkalinity in the water of the tributaries of the area affected by coal mining when the pH decreases.

The total alkalinity is shown by a dashed line in the **Figure 18** and is coincident with the curve of HCO_3^-. The tributaries of the area affected by coal mining contributes with some alkalinity to the main stream of ZR when the pH is higher than 4.5. After that point the water from tributaries will not contribute with any alkalinity to the main stream of ZR.

The graph in the **Figure 19** shows the change of characteristics of the stream V4 when the pH of the water coming from the tributaries of the area affected by coal mining decreases. The summary of calculations of the characteristics of the stream V4 is given in the **Table 4B** in the appendix B. The **Figure 19** shows the same behaviour as in the water in the tributaries of the area affected by coal mining; the only difference is in the total inorganic content thus influencing the concentrations of all carbonate species in the water.

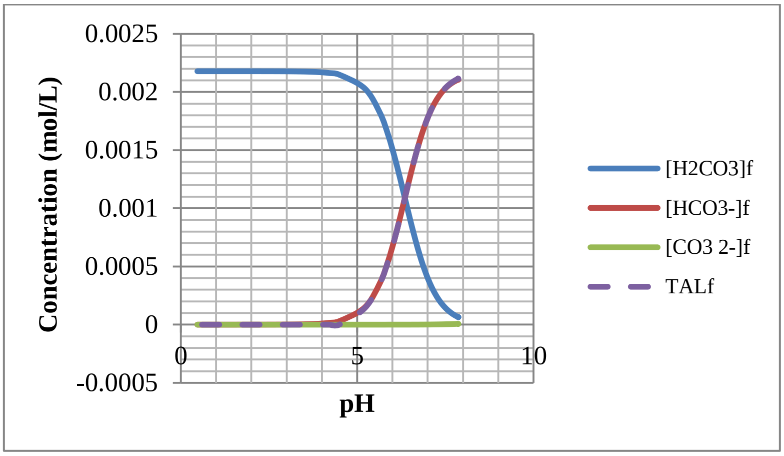

Figure 19 Concentration of carbonate species and total alkalinity in the main stream of Zambezi River when water with lower pH is added from the tributaries of the area affected by coal mining

The graphic in **Figure 20** shows the pH in the main stream of ZR V4 as a function of pH of the tributaries of the area affected by the coal mining. When the pH in the tributaries drops from 7.84 to about 5 the pH in the main stream tends to remain constant and equal to 7.8 due to buffer effect; but when the pH in the tributaries decreases from 5 to about 2.2 the pH of the main stream decreases sharply from 7.8 to 4.5; and when the pH of the water of the tributaries reduces to values below 2.2 the pH in the main stream reduces linearly from 4.5 to 0.5.

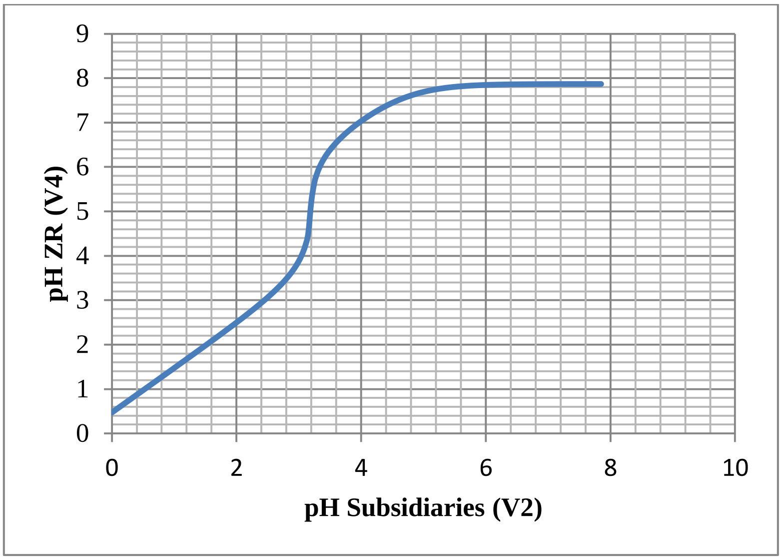

Figure 20 pH of the water of the main stream V4 versus pH of the water from the tributaries of the area affected by coal mining (V2)

The analysis shows that the pH of water of the tributaries of the area affected by coal mining should never drop to values below 5, if the alkalinity of the water of the main stream of ZR and the tributaries of the area affected by coal mining remains the same, because it can cause severe impact to the water quality in the main stream.

The dilution of the water of the main stream of ZR (V4) due to addition of the water coming from the tributaries of the area not affected by the coal mining downstream (V3), **Figure 17**, results in small recovery of pH. The calculation of pH of the water of the main stream of ZR at the outfall (V5) based on the decreasing of pH of the tributaries of the area affected by coal mining (V2) is given in the **Table 5B** in the appendix B. The graph in **Figure 21** shows the relationship between the pH of the water coming from the tributaries of the area affected by the coal mining with the pH of the main stream of ZR immediately after the coal mining area (V4) and at the outfall to Indian Ocean (V5). The dashed line in the **Figure 21** shows the pH in the stream V5 after dilution. The pH of water at the outfall of ZR (V5) will tend to resist more for the dropping of pH compared to the water of ZR immediately after the area affected by coal mining. The total alkalinity of V5 is totally consumed only when the pH of the water of the tributaries of the area affected by the coal mining (V2) reaches about 3, because at that point the pH of V5 drops immediately to values around 4.5.

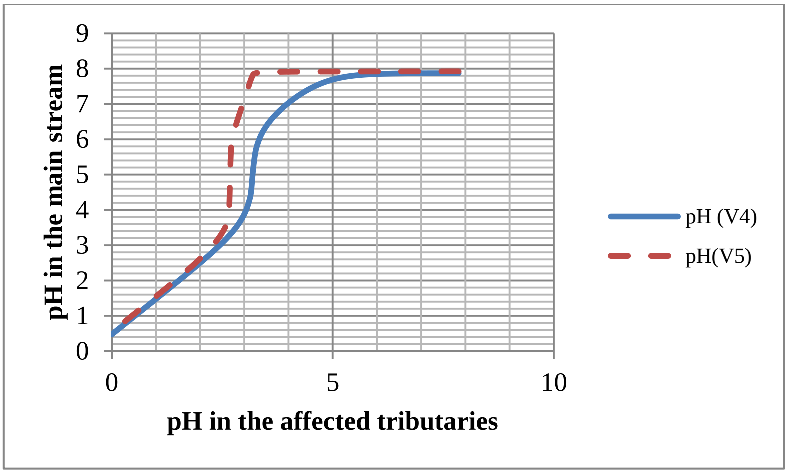

Figure 21 Relationship between the pH of the water from the tributaries of the area affected by coal mining (V2) and the pH of the water of the main stream of Zambezi River immediately after the area affected by coal mining (V4) and at the outfall to Indian Ocean (V5)

The analysis shows to what extent the pH of different stretches of the river can be affected by the changing of pH of the water in the tributaries of the area affected by coal mining (V2). The purpose of the monitoring should be to check if the pH of water in the tributaries of the area affected by coal mining do decrease to values below 6.0: to avoid dissolution of metals; protect the environment and living species in water; and avoid problems of human health.

5.2.3 Uncertainty in the surface water model

There are simplifications which introduce uncertainty to the prediction of pH variation in different stretches of the river considered in the sub-chapter above and they are listed in the **Table 5**.

Table 5 Sources of uncertainty in the prediction of pH changes in different stretches of ZR in Mozambique

Assumption	**Description**	**Justification of the assumption**
The recovery of pH by dissociation of H_2CO_3 and escaping to the atmosphere is neglected.	When the pH is high due to H_2CO_3, unstable acid it dissociating according to the reaction, $H_2CO_3 \Leftrightarrow CO_2 + H_2O$. The CO_2 formed escapes to the atmosphere until the equilibrium between $CO_{2(air)} \Leftrightarrow CO_{2(water)}$ is reached.	The stream of the river is deep enough so that the recovery of pH due to that equilibrium takes a long time to be reached.
The stream bottom is inert. Meaning that no chemical reaction or dissolution of material at bottom of the stream which can interfere in pH variations is taking place.	The bottom of the stream is composed by different minerals and these minerals can dissolve special when the pH is lowered. Due to this dissolution the alkalinity and other important characteristics of water can be affected.	The geology of the stream is complex and diversified. To consider this effect is necessary to do an exhaustive investigation of the geology of the region and at this stage is not possible.
The material dissolved in water does not interfere to the pH variations	There are several ions in water which can react when the pH is lowered and thus interfering in pH variations like precipitation of $Al(OH)_3$, $Fe(OH)_3$.	These elements are neglected in the first approach. Of course is important to consider in future development of the model

Table 5 (Cont.)

Assumption	**Description**	**Justification of the assumption**
The seasonal variation of the flows of the streams of the river was neglected.	There are significant changes in the flow in all streams of the river, either in the main stream or in the tributaries. These may result in high pH in the streams in the dry seasons and lower pH in rain season due to dilution.	This effect is does not have significant relevance as the variation of pH was not taken from the real source of acidity. Hypothetically values were considered. But if the pH is predicted from the source is important to consider the seasonal variations of the flows of the stream.
Biological effect on pH is neglected.	The photosynthesis consumes CO_2 moving the equilibrium $H_2CO_3 \Leftrightarrow CO_2 + H_2O$ to the right thus increasing the pH and the respiration produces CO_2, moving the equilibrium to the left $H_2CO_3 \Leftrightarrow CO_2 + H_2O$ thus reducing the pH.	This effect is neglected because big variations of pH are introduced due to AMD.
The temperature is taken as constant and equal to 25 ºC.	The temperature affects the equilibrium constants k_{a1}, k_{a2} and kw used in the calculations of pH.	The temperature of the water of ZR does not vary a lot and it is close to 25ºC.

In future development of this model some of these assumptions have to be considered to reduce the differences between the predicted values and the observed values. And some of them are extremely important depending on the situation. If there is a need to make a real time prediction is important to consider the seasonal variations in the stream flows for example.

5.3 Estimation of generation of contaminated water from coal mines in Tete

It is quite complicate to estimate the amount of contaminated water generated in coal mines and evaluate its impact to groundwater resources for large areas such as Zambezi River Basin in Mozambique because of the differences of hydrogeological characteristics. Rough estimation of contaminated groundwater generated from the coal mines in both cases, operated and not operated mines, was done considering the most likely hydrogeological condition.

Only a set of data about most likely hydrogeological data in Moatize district was found and is shown in **Figure 22**. The layers and respective transmissivities were found in the Environmental Study of Vale Moçambique, Lda and the thickness of the layers were estimated using **Figure 10** in this report.

5.3.1 **Groundwater model description results and discussion**

For all calculations it was assumed that only Chipanga layer (coal layer) is exploited and the excavations will go a little bit below to this layer.

There are significant differences between the layers presented in geological and hydrogeological models found in literature and summarized in **Figures 10** and **22** respectively. The Chipanga layer which has higher transmissivity compared to the layers above has a pretty clear position in both models and it is located roughly 200 m below the ground surface with average thickness of 36 m. The layers above chipanga layer have a complicated configuration in the conceptual geological model, **Figure 10**, compared to the conceptual hydrogeological model in **Figure 22.** It makes complicated to estimate the thickness of each layer in hydrogeological conceptual model. At the surface there is a weathered layer with very low transmissivity (below 0.05 m^2/d) which can be considered confining layer.

Below the chipanga coal layer there is a siltstone layer which has a high transmissivity compared to chipanga layer and after the siltstone layer there is a Sousa Pinto coal layer. If there is

intention to extract coal from Sousa Pinto coal layer the excavations have to go down to the siltstone layer which is the more productive aquifer. This may result in really high water flowing into the mining excavations.
Some alluviums of about 0-5 meters may occur above the weathering horizon and if any contaminated mining water is pumped to the surface and spread without any treatment may result in contamination of these aquifers. Most probable some of these aquifers have wells where people are withdrawing water for domestic use.
In this evaluation the layers which will be considered to estimate the groundwater seepage are the Chipanga layer and the layers above.

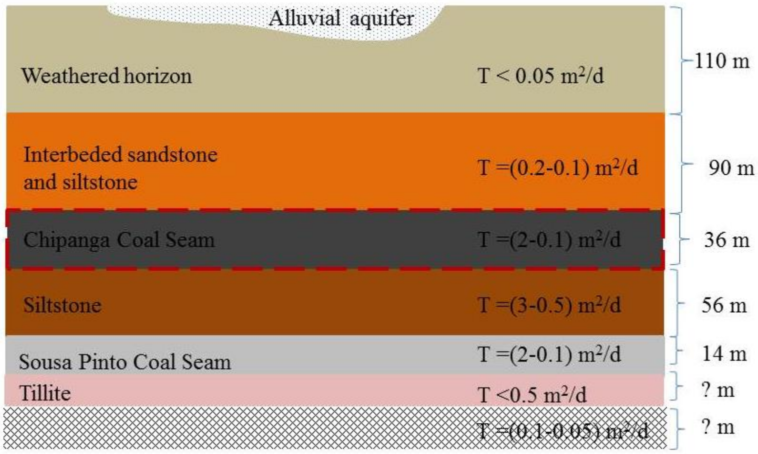

Figure 22 Hydrogeological conceptual Model of Moatize (Used for simulation)

Using the projections of coal production found in MIREM, the development of pits due to coal mining was estimated in terms of volume of the pits, plan surface area of the mining pits and mining area; and side surface area of the pits. The calculations are presented in the **Table 6B** in the appendix B.

Groundwater contamination during the operation of the coal mining

When the mines are being operated the water has to be pumped out of the pits. This is done to allow the excavations and extraction of coal. The water pumped is coming mainly from groundwater but also from precipitation on the mine area. The pit works like a huge well which has to be dried by pumping.

The coal mines in Tete are viewed as one huge mine for all mining area **Figure 23**. Using this assumption, the water pumped out of the mine pits was estimated and was considered to be contaminated water. It was also assumed that the water which has to be pumped out of the pits is coming from two main sources, groundwater seepage to the pits and precipitation minus evapotranspiration. The runoff was neglected because normally there are barriers to avoid the runoff to go into the pits; however this component might be considerable during the rain seasons.

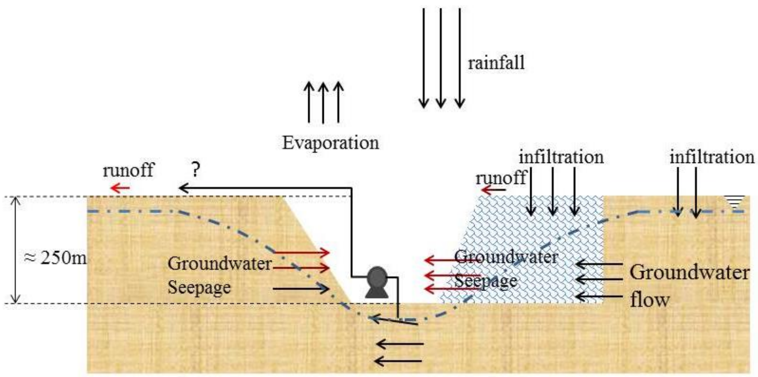

Figure 23 Water flows in operating open coal mine (possible scenario)

The Groundwater seepage to the mining pit was estimated using the **equation 5.4**

$$Q = -KA\frac{dh}{dl} \tag{5.4}$$

Where K is hydraulic conductivity, A is the area available for groundwater flow and dh/dl is the hydraulic gradient. The average conductivity K_{av} was estimated using the **Figure 22** and the **equation 5.5.**

$$K_{av} = \frac{1}{b}\sum_{m=1}^{n} K_m b_m \qquad (5.5)$$

In the equation **5.5**, *b* is the thickness of the layer. The transmissivity is related to conductivity by **equation 5.6**.

$$T = Kb \qquad (5.6)$$

The average conductivity can be calculated using the equation **5.7** which was obtained by combining **equations 5.6** and **5.5**.

$$K_{av} = \frac{1}{b}\sum_{m=1}^{n} T_m \qquad (5.7)$$

The average conductivity (K = 0.0095 m/d) was estimated considering that only the Chipanga Coal Seam (b_1 = 36m; T_{av} = 1.05m/d) and the Interbedded Sandstone and Siltstone layers (b_2 = 90m; T_{av} = 0.15m/d) to have significant contribution to the groundwater seepage into the pits.

It is difficult to estimate the hydraulic gradient but it can be considered relatively high because the water level in the pits have to be kept at levels around 250 m below the ground surface. Three different values of hydraulic gradients were considered: dh/dl =1, dh/dl =1/2 and dh/dl = 1/3.

The area of flow is the total surface area of the sides of the mining pits covering the two layers Chipanga and Interbeded Sandstone and Siltstone. The area of flow was estimated using projections of annual production of coal in Tete shown in the **Table 6B** in the appendix B.

The water which goes into the pits due to rain was estimated using the plan view areas of the pits, the average precipitation and actual evapotranspiration in Tete. The calculations are given in **Table 7B** in the appendix B.

The amount of water to be pumped from the pits to the surface during the mining was estimated as the sum of the amount of groundwater seeping into the pits and the amount of water resulting from rainfall going into the pits, see **Table 7B** in the appendix B.

If the mining is done continuously without abandoning the pits, the pits will increase continuously and the amount of water pumped from the pits to the surface will also increase as the **Figure 24** shows. This is extreme case and not realistic because some pits will be abandoned during the period of 2011 to 2028. The abandoned pit will be treated as a closed mines discussed following.

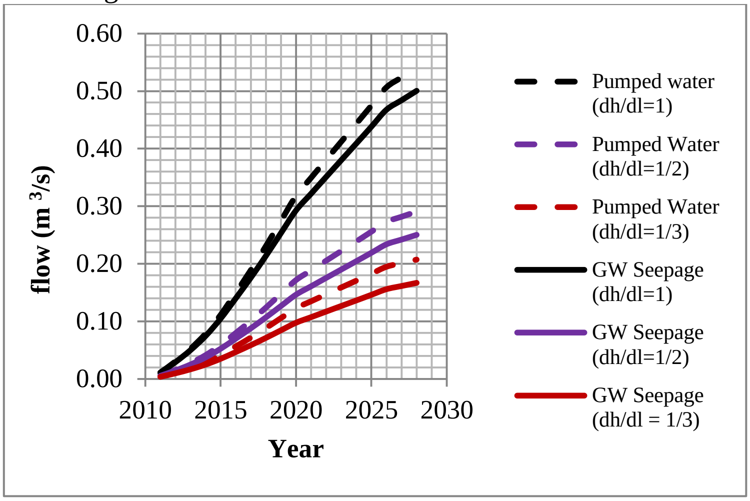

Figure 24 Projection of groundwater seepage into the pits and water to be pumped from the pits to the surface during the operation of the mines from 2011 to 2028

The mining water is not the only water which can result in AMD. The tailing from coal processing normally stored in the landfills can generate additional AMD. The AMD produced from the landfills can infiltrate directly to the groundwater or it may be transported as a runoff to the surface water if the landfills are not properly constructed and managed.

The water pumped from the mining sites can be used for different purposes in the mines but at the end it is spread on ground surface. In general there is a low permeable layer at the surface in the geology of Tete and this will limit the water infiltrating back to the deep aquifers. The alluvial aquifers are the most vulnerable for contamination. But there will be always part of contaminated water infiltrating back to the deep groundwater and the other part joining the surface water. Due to these

mechanisms it is important to treat properly all mine water and leachates from the landfills of tailings before sending it back to natural environment.
Severe consequences can be caused to human health if the water spread reaches alluvial aquifers in which the local population have wells to withdraw water for domestic use.

Groundwater contamination in not operated coal mines

When the open coal extraction is finished the mines are closed and huge pits are left on the ground. These pits are filled up by groundwater and rainwater until the groundwater level is equal to the water table in dry seasons or bit higher than the water table in the rain seasons because the water is not pumped anymore. At this stage the contaminated water from the pits infiltrates directly to the groundwater. The possible scenario is shown in **Figure 25**.

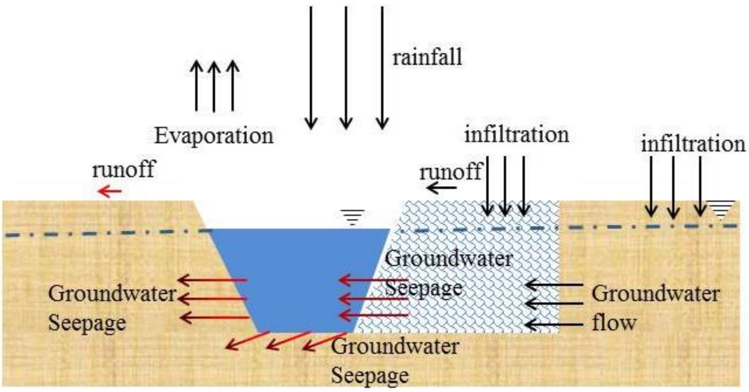

Figure 25 Water flows in closed mine (possible scenario)

In this case the flow of contaminated water is the sum of groundwater seeping into the pits to the water added by rain through all mining area. The runoff can be neglected. The same equations as in operating coal mines are used to estimate the groundwater seepage.
The **equation 5.4** was used to estimate the amount of groundwater seeping into the pits. The area of flow of groundwater into the pits is half of the area considered in the case

of operating mine because in this case in one half of the area the water is flowing into the pits and in other half the water is flowing out of the pit, following the groundwater flow. The conductivity is the same as in the operating mine because it depends on the geological conditions. The hydraulic gradient is also complicated to estimate as the area considered is extremely large. It can be taken as following the relief of the region, but it is also complicated to estimate the slope of the relief. This analysis is more suitable to be done in a restrict areas.

But in order to have a rough estimation of the contaminated water added to the groundwater when the mines are closed different hydraulic gradients were assumed. In order to have reasonable assumption of hydraulic gradient it was compared with slope of ground surface which is around 0.001. These slopes can vary a lot from mountains to planar areas, but this error is minimized by choosing four different values of hydraulic gradients and analysing the changing of groundwater seeping into the pits.

To estimate the contribution of rainfall in contaminated water added to the groundwater the same data of precipitation and evapotranspiration used in the case of operating mines was used and the area considered in this case was all the mine area.

The amount of water added to the groundwater if the mines are closed immediately after the extraction of coal in the period from 2011 to 2028 is shown in **Figure 26** and the calculations are given in the **Table 8B** in the appendix B. Four different hydraulic gradients were assumed, considering the extreme cases of very steep gradient of 10% to very mild gradient of 0.01%. The result show that the contribution of groundwater seeping into the pits is very small related to the total amount of contaminated water added to the groundwater. This because the contribution of rainfall is extremely high compared to the groundwater seepage. In the case of mild hydraulic gradient (from 0.1%) below the contribution of groundwater seeping into the pits can be neglected compared to the amount of water from rainfall see **Figure 26 c)** and **d).**

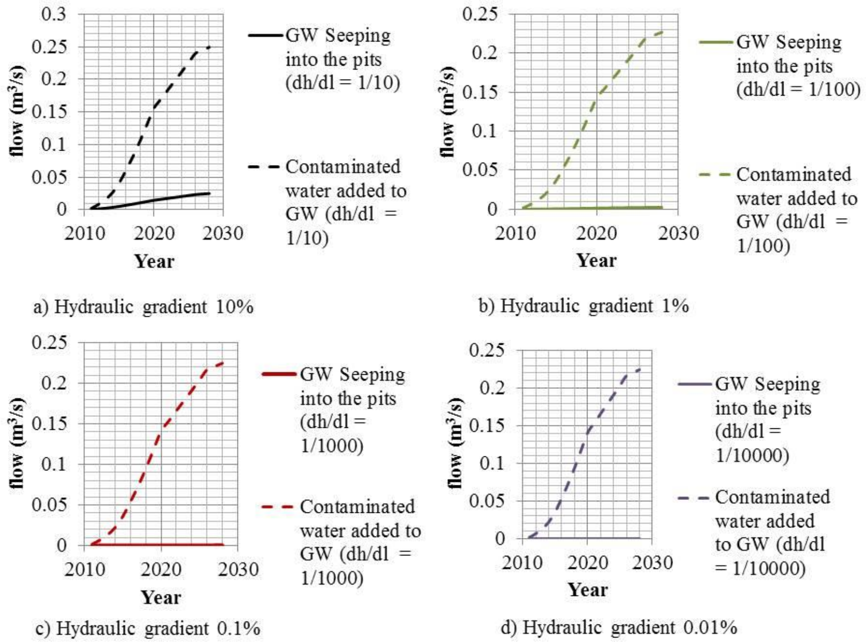

Figure 26 Projections of contaminated water added to the GW from closed coal mines in Tete (2011-2028)

If the pH of the water in the pits is very low it can cause significant impact to the groundwater. The future studies should also be focused on contaminated groundwater plume migration, the radium of influence of the acid water in the pits of closed mines. To determine these parameters it is important to consider more restrict area, to have more detailed knowledge about the geology of the region and a complete characterization of contaminated groundwater.

5.3.2 Effect of number of pits to the amount of contaminated water generated in coal mines

Assuming one mine for all Tete introduces a significant error to the estimation of the amount of groundwater seeping in to the pits in both cases, in operated and not operated mines.

The contribution of rainfall is much lower than the contribution of groundwater seepage into the pit in the total water pumped from the pits in operating mines. Due to this analysis of the effect of the number of the pit was done considering only the groundwater seepage. Higher hydraulic gradient dh/dl = 1 was chosen to consider the maximum possible generation of contaminated groundwater.

The **Figure 27** shows that there is a significant increase of the amount of water generated when the number of pits increases. The most probable scenario is to have more than eight mines as discussed in sub-chapter 3.4. Considering extreme case of having 16 pits being operated at the same time the amount of contaminated water generated will be approximately 6 m^3/s and the amount of water added from rain can be neglected.

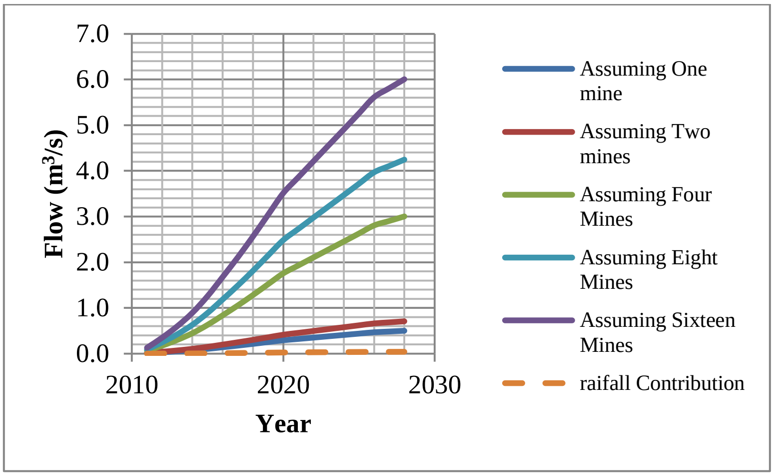

Figure 27 Effect of number of pits to the generation of contaminated water during the operation of the mines

Similar analysis was done to the case of not operated mines. In the sub-chaper 5.3 in which it was discussed contaminated groundwater in not operated (closed) mines it was shown that the amount of contaminated water generated is mainly coming from the rainfall and the contribution of groundwater seepage was very low. As the number of pits increases the contaminated water coming from groundwater also increase, the most convenient analysis was done to the total amount of contaminated water generated. Higher hydraulic gradient dh/dl = 0.1 was assumed to get the maximum possible contaminated water generation.

The **Figure 28** shows that when the number of pits increase the contribution of groundwater seepage to the contaminated water generated in closed mines become significant. The highest amount of water generated considering the case of 16 pits in Tete province is about 0.85 m^3/s. Most of this water will be directly added to the groundwater because the water is not pumped to the surface when the mines are closed.

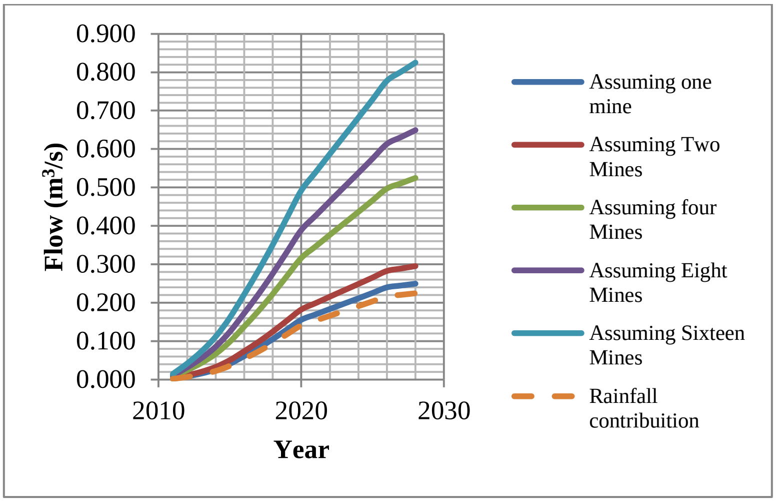

Figure 28 Effect of number of pits to the generation of contaminated in closed mines

Considering the effect of number of pits there is a significant increase of contaminated water generation in both cases, operating and closed mines. When the mines are operated the contaminated generated will most likely contaminate the tributaries and the alluvial aquifers and when the mines are closed the contaminated water will be contaminate mainly groundwater aquifers.

5.3.3 Uncertainty in groundwater model

There are several sources of uncertainty in the calculations done above. The most important ones are listed in **Table 6**.

Table 6 Sources of uncertainty in the calculations of contaminated groundwater in Tete

Assumption	Description	Justification of the assumption
The conceptual hydrogeological model of Tete is uniform and has same configuration as in Moatize, **Figure 22**.	The geology of Tete is quite complex and it makes also complex the hydrogeological conceptual model. Better configuration of hydrogeological conceptual model can be obtained by modelling very small areas.	The idea now is to have a general idea of negative impact of coal mining in all ZRB in Tete. The lack of hydrogeological data about other areas of Tete forced to assume that all Tete has its geology similar to Moatize which is not true. Different values assumed for hydraulic gradient may minimize the error made by this assumption.
The following hydraulic gradients (1, 1/2 and 1/3) were assumed to estimate the water seeping into the pit, in the case of operating mines.	When the mines are operated it is expected that the water has to be lowered until depths around 250 meters and this will create very high hydraulic gradient. In this case very high values of hydraulic gradients had to be chosen.	Choosing high hydraulic gradients will give the result in critical condition. If it is shown that no impacts will be caused there is higher probability of not having impacts in the reality.

Table 6 (Cont.)

Assumption	Description	Justification of the assumption
The following hydraulic gradients (10%, 1%, 0.1% and 0.01%) were assumed to estimate the water seeping into the pits, in the case of closed mines	The hydraulic gradient when the mines are closed will be lower than in the case of operated mines because the pits are supposed to be full with water. The water will come into the pits from one side and will infiltrate from other side following the groundwater flow. The hydraulic gradient will be close to the hydraulic gradient of the aquifer.	The value assumed for hydraulic gradient are close to the topographical slope because the hydraulic gradient of the aquifers normally follow the topography. A very big range, form 10% to 0.001% of hydraulic gradient was assumed to check the influence of hydraulic gradient to the groundwater seepage.
The water flows into the pits only by the sides of the pits. No water is flowing from the bottom.	The water seeping into the pits come from all sides of the pits. But it is expected that the water seeping from the bottom of the pits will be smaller than that which is seeping from the sides.	As the water flowing from the sides of the pits is higher than that flowing from the bottom, it is not expected to introduce significant error to the model. This may be significant in the case of operating mines if the water is pumped below the bottom surface of the mine.

These assumptions have to be considered in future development of the model and some of them may be improved by modelling small areas with more accurate data.

5.4 Effect of contaminated water from the mines to the water of the tributaries of the area affected by coal mining

To check if there is a significant effect of contaminated water water pumped from the pits of the mines to the water of the tributaries of the area affected by the coal mining it was assumed that all water coming from the pits is added to the water of the tributaries. It was also assumed the highest value of contaminated water coming from the pits of the mines (6 m^3/s) estimated in previous sub-chapter and very low pH (pH =1).

At pH = 1 the alkalinity of water is totally consumed and the contribution of alkalinity of water from the mines can be neglected. The flow of water pumped from the pits of the mines (6 m^3/s) is extremely low compared to the flow of water in the tributaries of the area affected by the coal mining (V2 = 1193 m^3/s). This makes reasonable to assume that the amount of H_2CO_3 in the water from the mines is low compared to the amount of H_2CO_3 in the water of the tributaries of the area affected by the coal mining (V2). The concentration of H_2CO_3 in the water of tributaries of the area affected by coal mining after mixing with contaminated water from the pits of the mines is assumed to be equal to the concentration of H_2CO_3 in the tributaries before mixing with contaminated water from the pits.

Using these assumptions the characteristics of the water of the tributaries of the area affected by the coal mining after addition of contaminated water from the mines were calculated and are shown in the **Table 7**.

The results in the **Table 7** show that there is no significant change in the pH and alkalinity of water of the tributaries of the area affected by the coal mining after addition of contaminated water from the mining pits. As no significant impact is expected in the water of the tributaries of the area affected by the coal mining, no significant impact can be expected also in the main stream of Zambezi River.

Table 7 Evaluation of impact of water from the coal mining pits to the water of the tributaries of the area affected by coal mining

Parameter	**Water of the tributaries**	**Water from the mining pits**	**Water of the tributaries after mixing with water from the mining pits**
Flow (m^3/s)	1193	6	1199
pH	7.85	1	7.12
[H+] (mol/l)	1.4E-08	1.0E-01	7.5E-08
[OH-](mol/l)	7.1E-07	1.0E-13	1.3E-07
[CO3 2-](mol/l)	1.3E-05	0.0	1.3E-05
[HCO3-](mol/l)	3.8E-03	0.0	3.3E-03
[H2CO3](mol/l)	6.1E-05	-	5.6E-04
TAL (mol/l)	3.8E-03	0.0	3.3E-03

However particular attention has to be given to the tributaries located in the mines because in this study all tributaries in the area affected by coal mining were viewed as one. In the reality there are number of tributaries and only few of them passes through the mines. For sure these tributaries do not have enough water and alkalinity to resist to the addition of contaminated water from the mines.

Significant impact is expected in the small tributaries which passes through the mines and in located points where the small impacted tributaries connects to the main stream of ZR.

6. Proposal for Water Quality Monitoring

The water quality monitoring proposed in this chapter considers minimizing the usage of resources by avoiding duplicating the analyses done in the water at the same area by different companies. This can be done creating a mechanism to share the results of water quality analyses between the companies.

As discussed before the institution responsible for water quality monitoring in Zambezi River Basin (ZRB) in Mozambique is ARA-Zambeze. But there are other institutions playing important roles in water quality monitoring in ZRB in Mozambique such as National Institute for Fishing Investigation of Songo (IIP-Songo), coal mining companies, domestic water supply companies, agriculture companies and industries.

ARA-Zambeze has problem of lack of resources to do a complete water quality monitoring in ZRB in Mozambique. Of course there is a need of creating laboratories to make water quality analyses inside the ARA-Zambeze but these laboratories should be created mainly for operative oversight and to analyse water from very restricted points, where seems really important and there is no other company doing it.

In order to evaluate the water quality degradation due to coal mining it is important to establish communication between the coal mines and ARA-Zambeze. ARA-Zambeze should evaluate the water quality monitoring proposed by the companies and propose improvements to meet its needs of information for the general monitoring. After agreeing which parameters, with which frequency and in which points should be monitored the companies should report to ARA-Zambeze the results of their analyses. ARA-Zambeze can compile data from different companies for general assessment; develop predictions of future water quality changes and measures to mitigate the negative impacts.

ARA-Zambeze should schedule a periodical operative oversight in all companies to check the water quality analyses and to sample water in the monitoring points of the companies to analyse in the laboratories of ARA-Zambeze and compare with the results provided by the companies.

ARA- Zambeze should prepare annual and/or monthly reports of water quality, predictions of future changes of water quality in

ZRB in Mozambique; propose measures to mitigate the negative impacts and submit to the stakeholder mentioned above. ARA-Zambeze should schedule periodical meetings with important stakeholders to discuss the problems regarding water quality in the river basin.

Particular attention has to be given in the small tributaries passing through the mines because they are the most likely to be impacted.

There are institutions which need resources to improve their capacity in order to respond to the need of water quality monitoring, taking into consideration the development of coal mining. The IIP-Songo is a crucial example. The IIP-Songo should extend the periodical analyses of fish to the area affected by coal mining. To minimize the usage of resources, the fish monitoring should be restricted to the most vulnerable areas. The vulnerable areas should be identified and constantly updated based on the historical data of fish monitoring and periodical reports provided by ARA-Zambeze. The results of fish monitoring should be reported to ARA-Zambeze including the discussion of the impacts of water quality degradation to fish population of the river, possible reasons of the changings in fish population and propose measures to reduce the impacts.

The stakeholders (coal mining, domestic water supply, agriculture and industrial companies) should fill the reporting forms provided by ARA-Zambeze and submit in a required periodicity. These companies have also the obligation to suggest mitigation procedures for possible impacts to be discussed in annual meetings scheduled by ARA-Zambeze.

All stakeholders should have the obligation to participate in annual meeting scheduled by ARA-Zambeze. Some mitigation measures have to be funded by the companies involved in the activities affecting water quality of the river basin. The companies have also obligation to report the critical changes in water quality parameters which are not included in the reporting forms provided by ARA-Zambeze.

ARA-Zambeze should update the water quality monitoring procedures and water quality reporting forms in case it seems necessary. It is important to underline that both surface and groundwater should be considered in general water quality monitoring coordinated by ARA-Zambeze.

The **Table 8** shows the different stakeholders and the proposed role in water quality monitoring in ZRB in Mozambique.

Table 8 Important Stakeholder in water quality monitoring in ZRB in Mozambique and proposed roles

Stakeholder	Role	Resources
ARA-Zambeze	Collect and process the results of data supplied by the stakeholders	• Data processing room equipped with computers; • Skilled personnel.
	Prepare a shot-forms for water quality reports for important stakeholder to make uniform the periodically data reports by the companies.	• Skilled personnel
	Monitor water quality in restricted points and do the operative oversight.	• Water quality analysing laboratory; • Budget for the analyses; • Skilled personnel.
	Prediction of water quality changes.	• Computer model to predict water quality changes for ZRB in Mozambique.
	Publish monthly and/or annual reports of water quality degradation of ZRB.	• Skilled personnel.
	Schedule annual meetings with important stakeholders.	• Budget for the meetings.
	Propose mitigation measures for water quality changes and implement emergency actions.	• Presence of complete department of emergency actions and mitigation programs.
	Update the water quality monitoring procedure if it seems necessary.	• Skilled personnel.
	Find resources to implement a global mitigation measures.	
	Prepare annual in meetings to discuss water quality changes in the river basin	

Table 8 (Cont.)

Stakeholder	Role	Resources
IIP-Songo	Identify and monitor fish population in vulnerable areas based on historical data and reports of ARA-Zambeze.	• Equipment for fish monitoring • Skilled personnel • Budget
	Report the records of fish monitoring to ARA-Zambeze.	• Skilled personnel
	Propose mitigation measures and to find resources for implementation of mitigation measures.	
	Participate in meeting scheduled by ARA-Zambeze.	
Coal mining companies	Report water quality records in their monitoring area according to the short-forms provided by ARA-Zambeze.	
	Propose and participate in mitigation measures of water quality changes.	
	Participate in meeting scheduled by ARA-Zambeze.	
Domestic water supply companies, Agriculture companies and Industries	Report water quality records in their monitoring area according to the short-forms provided by ARA-Zambeze.	
	Participate in meeting scheduled by ARA-Zambeze.	

6.1 Parameters to be considered in general monitoring

The **Table 1B** in the appendix B is a list of physical and chemical parameters which can be considered in water quality monitoring in a river basin. This table was produced based on Mozambican legislation and in the table of water quality parameters available different references such as Lenntechs website. The table do not include organic compounds and pesticides and disinfectants and disinfectants by-products. Information about these parameters can be found in the Lenntechs website in the following reference (Lenntech, 1993).
There is no need to monitor continuously all the parameters presented in the **Table 1B** in the appendix B affected. The most important parameters to be considered in rivers affected by coal mining are pH, alkalinity, colour, turbidity, total suspended solids, total dissolved solids, conductivity and leaching metals (Farrell-Poe, 2000). In addition to this is important to monitor the concentration of aluminium, iron, manganese and sulphate. The leaching metals to be analysed are determined by the geology of the area affected by the mining and they can be identified by analysing the historical date of water quality. All harmful metals have to be analysed in the beginning of the monitoring, see **Table 1B** in the appendix B, but priority has to be given to Ba, Cr, Cu, Ni, Zn and Pb as discussed in the sub-chapter 3.3 about the chemistry of coal of Tete .Other parameters may be considered in future if it seems relevant.

6.2 Water quality monitoring in the coal mining companies

The water quality monitoring procedures in the coal mining companies are not well known because it was not possible to get data directly from them. Some information about the water quality monitoring in Vale Moçambique Lda were found in its Environmental Study Report available in National Mining Directorate (DNM), but there are some limitations to interpret the information from this reports because of unclear figures and legends. This was mainly caused by the version black and white available.

The coal mining companies should consider the monitoring of surface and groundwater quality separately. A detailed and clear description of the sampling points, both for surface and groundwater should be included in Environmental Study Reports and water quality monitoring programs. The records of water quality monitoring should be available publically and not confidential as they seem to be at present.

6.2.1 Surface water quality monitoring in the coal mines

From the Environmental Study Report of Vale Moçambique, Lda, the map showing the selected points for surface water quality monitoring was produced and given in the **Figure 29.** The points selected by Vale Moçambique, Lda seem to be well located for the purpose of the monitoring. However is not possible to confirm is this monitoring plan is being implemented because it was not possible to get any information directly from the company.

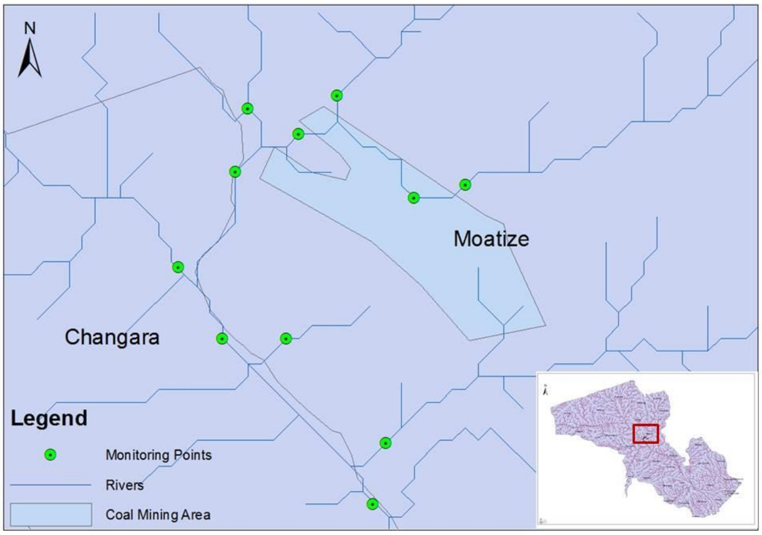

Figure 29 Disposition of monitoring points of Vale Moçambique, Lda, adapted from: (Vale Moçambique Lda, 2010)

A similar configuration of water quality monitoring should be adopted by other companies. The general example to select monitoring points to monitor surface water is given in *A Practical Guide to the Design and Implementation of Freshwater Quality Studies and Monitoring Programmes* published on behalf of United Nations Environment Programme and the World Health Organization. This manual also includes the procedures to do the sampling and analyses of water quality parameters.
Nothing can be said about other coal mining companies because no data was found. In future it is important to communicate with the companies to know what is really being done for water quality monitoring.
It is important to emphasize that the sampling points should be selected following water quality monitoring guides to guarantee that the samples are collected in the appropriate distances and depths.

6.2.2 Groundwater quality monitoring in the coal mines

In general nothing can be said about how groundwater monitoring is being done by the mining companies. Vale Moçambique, Lda made a groundwater quality assessment and is described in its Environmental Study Report but the problems of illustrations in the printed version available in DNM makes difficult to understand what is being done. Six sections are considered in the groundwater monitoring in Vale Moçambique Lda concession area. The positive thing is that in all sections sampling wells are installed in different layers which allow doing the sampling in different aquifers which can be affected.
There are no closed ruled to do the groundwater monitoring it depends on the hydrogeological characteristics and the purpose of the monitoring. The **Figure 30** shows an example of location of sampling wells in groundwater monitoring. In general the wells should be placed upstream and downstream the mining area following the groundwater flow and one well on each likely affected aquifer. It may happen that there is no need to place sampling wells in all hydrogeological layers. When the layers have really low storativity and transmissivity (confining layers);

and/or the layer is below the area affected by the coal mining. Placing sampling wells in these layers may mean extra unnecessary work and cost.

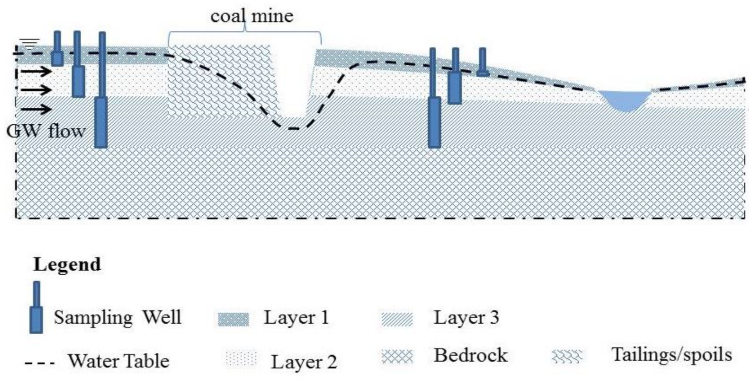

Figure 30 Example of groundwater monitoring wells in coal mine (possible scenario)

It is important to have good knowledge of hydrogeological characteristics of the area to be monitored in order to place the monitoring wells in the correct positions and distances. It is also recommended to consult the groundwater monitoring guides to select the most appropriate distance to install the sampling wells and periodicity of sampling.

7. Integrated Water Resource Management in Zambezi River Basin

Integrated water resources management (IWRM) means to have a cyclic working plan. The cycle includes defining policies, analysing the problems of IWRM, choosing strategies, defining IWRM plan, implementing IWRM plan and evaluation (assessing progress and revise the plan).

The major sources of problems in water management in the rivers are caused by dams' management and change of water quality due to human activities such as agriculture, industry, mining, livestock, etc. These activities have impact in human health, biodiversity in the river basin and human activities downstream the area affected.

The cycle of IWRM is strongly depended on assessment which includes the results of the analyses of water quality parameters obtained by applying monitoring program. The water quality and water quality trends are important input to develop management actions which included reducing or eliminating the sources of pollution and recovering or mitigating the already impacted water.

ZRB is an international river basin and the water quality in Mozambique is greatly affected by the quality of water coming from the neighbourhood countries. It makes communication between ARA-Zambeze with other river basin organizations in ZRB very important. The results obtained from water quality analyses should be shared between the countries and is important that they are uniform to allow comparison. The general monitoring of water quality should be coordinated by ZAMCOM to guarantee uniformity.

On the other hand ARA-Zambeze has to work in coordination with the companies which have direct influence in the water quality inside Mozambique like coal mines, industries, domestic water suppliers, agriculture companies, etc. The communication between ARA-Zambeze with the companies will minimize the usage of resources and improve the water quality monitoring within the river basin in Mozambique.

8. Future Studies

The lack of resources, low communication between the stakeholders and poor legislation limits greatly the development of water quality monitoring considering the effect of coal mining in Tete Province. It is important create a prediction system of general influence of coal mining activity in water quality of Zambezi River Basin (ZRB) by developing the prediction mechanism presented in this document. In order to have a prediction system and sustainable water quality monitoring is important to develop the following investigations:

- Coal mining development and possible impacts to water resources, biodiversity, agriculture, human health and other activities downstream the ZRB in Mozambique;
- Development and calibration of model of mixing of streams of rivers which predicts pH of the resulting stream;
- Development and calibration of model which predicts pH variations during the water flow in the river;
- Development and calibration of model which predicts the pH variations for all ZRB in Mozambique;
- Determination of the radius of influence of coal mine in the groundwater aquifer;
- Development of surface water quality monitoring considering coal mining in Tete province;
- Development of groundwater monitoring considering the development of coal mining in Tete province;
- Investigation of AMD generation in Tete;
- Proposal of improvement in legislation of water quality in Mozambique.

8.1 Description of the studies

The nine topics presented in **Table 8** have seven basic final technical outcomes, (1) Predict the negative impacts of coal mining in water resources in ZRB in Mozambique; (2) a technical description of AMD formation in Tete; (3) Software which can be used to predict the pH variation in ZRB in Mozambique, this it can be easily extended to all ZRB or applied in other river basins; (4) General procedure to estimate a safe distance to place wells near the coal mines; (5) recommendations to do the surface and groundwater monitoring in coal mines; (6) Establishment surface water quality monitoring in ZRB in Mozambique; and (7) Improvement the legislation of water quality in Mozambique.

Table 9 Description of topics for future studies

Ord.	Title	Objective	Possible Partners	Activities/resource
1	Coal mining development and possible impacts to water resources, biodiversity, agriculture, human health and other activities downstream the ZRB in Mozambique.	To describe the development of coal mining in Tete and predict possible negative impacts in water resources and activities affected by water quality in Mozambique.	LU; EMU; ARA-Zambeze; Ministry of Agriculture; Ministry of public buildings and habitations; and Ministry of health	Field work (2 up to 4 weeks in Tete and Sofala/ Zambezia if necessary);
2	Development and calibration of model of mixing of streams of rivers which predicts pH of the resulting stream.	To develop a computer model to estimate the pH of water resulting in mixing of two streams with different characteristics	LU; EMU.	Computer software to develop the model (to be selected); Computer modelling course(s) (to be selected);Create a laboratorial prototype to calibrate the model;
3	Development and calibration of model which predicts pH variations during the water flow in the river.	To develop a model to predict changing on pH of water in the river, depending on the stream velocity, temperature and depth considering the alkalinity and equilibrium $CO_{2(air)} \Leftrightarrow CO_{2(water)}$.	LU; EMU.	Computer software to develop the model (to be selected); Computer modelling course(s) (to be selected); Create a laboratorial prototype to calibrate the model;

Table 9 (Cont.)

Ord.	Title	Objective	Possible Partners	Activities/resources
4	Development and calibration of model which predicts the pH variations for all ZRB in Mozambique.	To develop a computer model to predict pH of the river of ZRB using the mixing (2) model and transport (3) models developed previously.	LU; EMU; ARA-Zambeze	Computer software to develop the model (to be selected); Create a laboratorial prototype to calibrate the model; Filed trip (up to 4 weeks in Tete)
5	Determination of the radius of influence of coal mine in the groundwater aquifer.	To develop a procedure to estimate the radius of influence of coal mining to groundwater to recommend the location public wells.	LU; EMU; Coal Mining company (to be selected)	Groundwater model computer model (to be selected); Calibrate the model based on a field data from coal mine; Filed trip (up to 4 weeks)
6	Development of surface water monitoring program considering coal mining in Tete province.	To select the most appropriate sampling points for surface water quality monitoring based on coal mining development and applicability of computer developed in model (4)	LU; EMU; ARA-Zambeze	ArcGIS; Model developed in (4); Filed trip (up to 4 weeks in Tete).

Table 9 (Cont.)

Ord.	Title	Objective	Possible Partners	Activities/resources
7	Development of groundwater monitoring considering the development of coal mining in Tete.	To develop evaluate groundwater monitoring for selected coal mine and suggest improvements.	LU; EMU; coal mining Company (to be selected).	Field trip (4 weeks in Tete).
8	Investigation of AMD generation in Tete.	To investigate AMD generation under different conditions.	LU; EMU; Coal mining company	Field trip to collect the samples; Create a laboratorial physical model.
9	Proposal of improvement in legislation of water quality in Mozambique to meet the needs of actual development of coal mining.	To analyse the Mozambican Legislation and propose changes to empower the stakeholders participation and data exchange between ARA-Zambeze and the coal mining companies.	LU; EMU; Ministry of Mineral Resources; Ministry for Coordination of Environmental issues; ARA-Zambeze.	Field work in Tete (two weeks).

9. Conclusion

Zambezi River Basin is an international river basin which sustains life of about 30 million people. The average flow of the main stream of the river when it enters Mozambique is about 2330 m^3/s and at the outfall to the Indian Ocean it is about 4134 m^3/s. This makes both the activities taking place in the upstream countries and inside Mozambique interfering greatly with its water quality.

Nowadays the coal mining is developing faster in the area of the Zambezi River Basin in Mozambique. There are three huge coal basins identified in Tete province and there are about 30 companies holding licenses for prospection and extraction of coal in these basins. The Chicôa-Mecúcoè coal basin is located more to the west of Cahora-Bassa dam and there is no coal mine in operation in this basin until now. The other two basins, Sanângoè-Mefídezi and Moatize-Minjova, are located more to the east of the Cahora-Bassa dam and there are already seven mines in operation in these coal basins. The coal basins are located near to the main stream of Zambezi River and this may influence the water quality of the river, its tributaries and groundwater aquifers which pass through the mine area.

A water balance in the river showed that the main stream of Zambezi River Basin receives about 44% of its water from the tributaries in Mozambique and 29% is received from the area affected by the coal mining. This is a significant amount of water to interfere in the water quality of the main stream of the river.

If the acid mine drainage from the coal mines comes into contact with ground or surface water, it can contaminate by reducing the pH and increasing the content of sulphate, iron, aluminium, manganese and heavy metals.

Prediction of changing of pH of the main stream of Zambezi River by changing the pH of the water coming from the tributaries of the area affected by the coal mining was done based on the results of water balance, current alkalinity and pH. It was observed that significant impact in the main stream of Zambezi River can be expected only when the pH of the water from the tributaries of the area affected by coal mining is below 5. After the area affected by the coal mining, the water of the main stream of Zambezi River is diluted by water received from the tributaries of the area not affected downstream. This result in a small recovery of pH and a significant impact on the pH of the water of the main stream in that area can only be expected when the pH of the water coming from the tributaries of the area affected by coal mining is below 3.

Following this, the amount of contaminated water generated in the mining pits in all mines in Tete was estimated. The highest flow of contaminated water which is expected to be generated from coal mines in Tete is about 6 m^3/s.

If the contaminated water generated in the coal mines (6 m^3/s, assuming pH =1) is added directly to the tributaries of the area affected by the coal mining with average flow of about 1198 m^3/s, without any treatment no significant change on pH is expected. Particular attention has to be given to the small tributaries near the coal mines and at the points where these affected tributaries connects to the main stream during planning of the monitoring of water quality.

In general the pH of water of the river and its tributaries should not drop to values below 6 at any point because it may result in direct negative impact at that point. Even if the pH is further recovered there is no guarantee that the content of metals and other parameters of the water will be recovered to values which cannot impact the environment, biodiversity and threaten the human health.

When the mines are operated there is high probability to contaminate the alluvial aquifers and the surface water because the mine water is pumped to the surface. When the mines are closed the pumping stops and the contaminated water infiltrates directly to the deep groundwater aquifers and affects them. If the contaminated water pumped from the mines during the operations is infiltrated to alluvial aquifers it may result in deterioration of its water. If there are wells in the alluvial aquifers it may result in problems of public health.

There is a need of improvement of Mozambican water legislation to face the actual development of coal mining and to guarantee success in the implementation of a water quality monitoring program in Zambezi River Basin. Further studies are necessary to establish a prediction system and sustainable monitoring program of water quality changes in Zambezi River Basin in Mozambique but it is important to empower the stakeholders' participation to guarantee the success in implementation of these tools to safeguard the water quality of the river basin.

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Appendix A – Maps of coal mining licenses

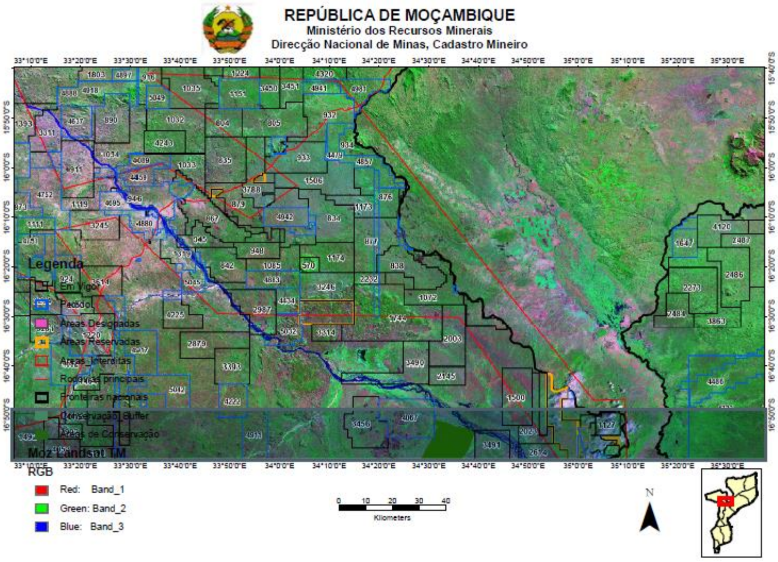

Figure 1A Licenses in Moatize - Section 1

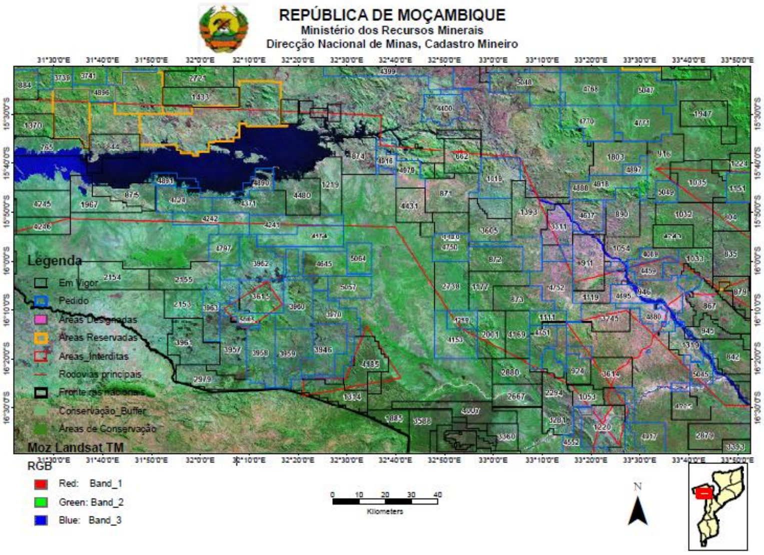

Figure 2A Licenses in Moatize - Section 2

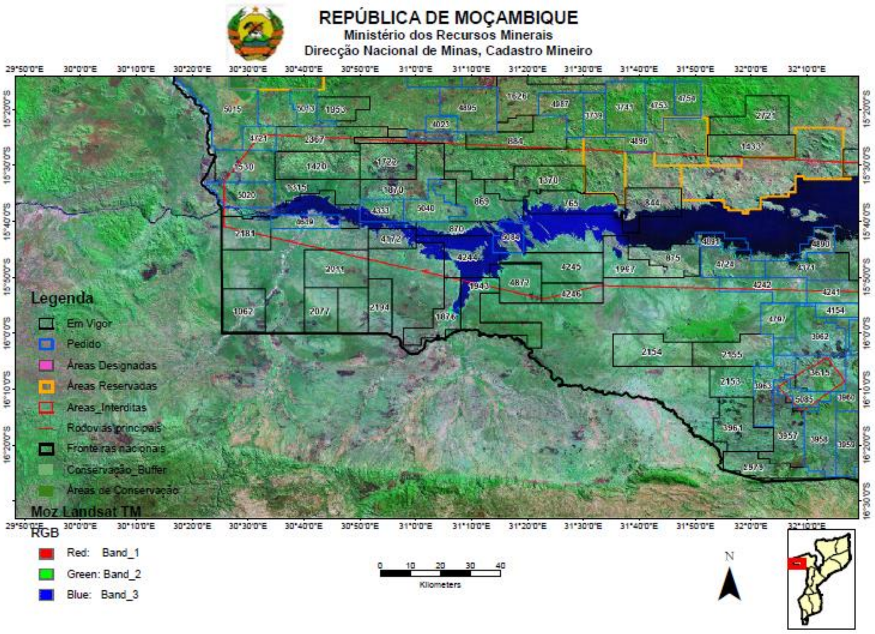

Figure 3A Licenses in Moatize - Section 3

Appendix B – Tables with water quality parameters and results of calculations of the models

Table 1B – Summary table of physical and chemical parameters (Normal found in fresh water/ surface water/groundwater and maximum limits by WHO and Mozambican legislation)

Parameter	**Symbol**	**Normal found in fresh water/ Surface water/Groundwater**	**Health based guideline by the WHO**	**Mozambican Legislation**
Alkalinity	**-**	**-**	**Not mentioned**	**-**
Aluminium	Al	-	0.2 mg/l	-
Ammonia	NH_4	<0.2 mg/l (up to 0.3 mg/l in anaerobic waters)	No guideline	1.5 mg/l
Antimony	Sb	< 4 µg/l	0.005 mg/l	0.005 mg/l
Arsenic	As	-	0.01 mg/l	0.01 mg/l
Asbestos	-	-	No guideline	-
Barium	Ba	-	0.3 mg/l	0.7 mg/l
Berillium	Be	< 1 µg/l	No guideline	
Boron	B	< 1 mg/l	0.3 mg/l	0.3 mg/l
Calcium	Ca	-	-	50 mg/l
Cadmium	Cd	< 1 µg/l	0.003 mg/l	0.003 mg/l
Chloride	Cl	-	250 mg/l	250 mg/l
Chromium	Cr^{+3},Cr^{+6}	< 2 µg/l	0.05 mg/l	0.05 mg/l
Colour	-	-	Not mentioned	15 TCU
Conductivity	-	-	Not mentioned	50-2000 µhmo/cm
Copper	Cu	-	2 mg/l	1 mg/l
Cyanide	CN^-	-	0.07 mg/l	0.07 mg/l
Dissolved Oxygen	O_2	-	No guideline	-
Fluoride	F	< 1.5 mg/l (up to 10)	1.5 mg/l	1.5 mg/l
Hardness	mg/l $CaCO_3$	-	No guideline	
Hydrogen Sulphide	H_2S	-	No guideline	-
Iron	Fe	0.5-50 mg/l	No guideline	0.3 mg/l
Lead	Pd	-	0.01 mg/l	0.01 mg/l
Magnesium	Mg^{2+}	-	-	50 mg/l
Manganese	Mn	-	0.5 mg/l	0.1 mg/l
Mercury	Hg	< 0.5 µg/l	0.001mg/l	0.001 mg/l

Table 1B (Cont.)

Parameter	Symbol	Normal found in fresh water/ Surface water/Groundwater	Health based guideline by the WHO	Mozambican Legislation
Molybdenum	Mb	<0.01 mg/l	0.07 mg/l	0.07 mg/l
Nickel	Ni	< 0.02 mg/l	0.02 mg/l	-
Nitrate and Nitrite	NO_3^-, NO_2^-	-	50 mg/l total nitrogen	-
Nitrite	NO_2^-	-	-	3 mg/l
Turbidity	-	-	Not Mentioned	5 NTU
Organic matter	-	-	-	2.5 mg/l
pH	-	-	No guideline	6.5-8.5
Phosphorous	-	-	-	0.1 mg/l
Selenium	Se	<< 0.01 mg/l	0.01 mg/l	0.01 mg/l
Silver	Ag	5-50 mg/l	No guideline	200 mg/l
Sulphate	SO_4^{2-}	-	500 mg/l	500 mg/l
Inorganic tin	Sn	-	No guideline	-
TDS	-	-	No guideline	1000 mg/l
Uranium	U	-	1.4 mg/l	-
Zinc	Zn	-	3 mg/l	3.0 mg/l

Table 2B. Initial characteristics of streams V1, V2, V3, V4 and V5

Characteristics of water in Zambezi River before the affected area (V1)

Parameter	**Value**	**Units**
Flow	2330	cum/s
pH	7.6	Standards Units
TAL	62	mg/L CaCO3
[H+]	2.51E-08	mol/L
[OH-]	3.98E-07	mol/L
[CO3 2-]	2.30E-06	mol/L
[HCO3-]	0.00124	mol/L
[H2CO3]	3.49E-05	mol/L
TALn	0.00124	eq/l
TIC	0.00127	mol/L

Characteristics of water from affected Tributaries (V2)

Parameter	**Value**	**Units**
Flow	1193	cum/s
pH	7.85	Standards Units
TAL	192	mg/L CaCO3
[H+]	1.41E-08	mol/L
[OH-]	7.08E-07	mol/L
[CO3 2-]	1.26E-05	mol/L
[HCO3-]	0.00381	mol/L
[H2CO3]	6.06E-05	mol/L
TALm	0.00384	mol/L
TIC	0.00389	mol/L

Characteristics of water in Zambezi River after the affected area (V4)

Parameter	**Value**	**Units**	**Obs.**
Flow	3523	cum/s	
pH	7.87	Standards Units	varying with pH of V2
TAL	0.00209	mg/L CaCO3	varying with pH of V2
[H+]	1.35E-08	mol/L	varying with pH of V2
[OH-]	7.40E-07	mol/L	varying with pH of V2
[CO3 2-]	5.73E-06	mol/L	varying with pH of V2
[HCO3-]	0.00209	mol/L	varying with pH of V2
[H2CO3]	6.35E-05	mol/L	varying with pH of V2
TIC	0.00216	mol/L	

Characteristics of water from not affected Tributaries (V3)

Parameter	**Value**	**Units**
Flow	611	cum/s
pH	7.85	Standards Units
TAL	0.00384	mg/L CaCO3
[H+]	1.41E-08	mol/L
[OH-]	7.08E-07	mol/L
[CO3 2-]	1.26E-05	mol/L
[HCO3-]	0.00381	mol/L
[H2CO3]	6.06E-05	mol/L
TIC	0.00389	mol/L

Table 2B. (Cont.)

Characteristics of water in Zambezi River in the outfall to Indian Ocean (V5)

Parameter	**Value**	**Units**	**Obs.**
Flow	4134	cum/s	
pH	7.92	Standards Units	varying with pH of V2
TAL	0.00236	mg/L CaCO3	varying with pH of V2
[H+]	1.20E-08	mol/L	varying with pH of V2
[OH-]	8.36E-07	mol/L	varying with pH of V2
[CO3 2-]	6.75E-06	mol/L	varying with pH of V2
[HCO3-]	0.00234	mol/L	varying with pH of V2
[H2CO3]	6.31E-05	mol/L	varying with pH of V2
TIC	0.00241	mol/L	

Table 3B Calculations of changing carbonate species and TAL with pH in the stream V2

pH	[H+]	Alpha [H2CO3]	Alpha [HCO3-]	Alpha [CO3 2-]	[H2CO3]	[HCO3-]	[CO3 2-]	TAL
7.85	1.41E-08	3.07E-02	9.66E-01	3.20E-03	1.19E-04	3.76E-03	1.24E-05	3.77E-03
7.5	3.16E-08	6.63E-02	9.32E-01	1.38E-03	2.58E-04	3.62E-03	5.36E-06	3.63E-03
7.15	7.08E-08	1.37E-01	8.62E-01	5.70E-04	5.34E-04	3.35E-03	2.21E-06	3.35E-03
6.8	1.58E-07	2.63E-01	7.37E-01	2.18E-04	1.02E-03	2.87E-03	8.46E-07	2.87E-03
6.45	3.55E-07	4.44E-01	5.56E-01	7.33E-05	1.73E-03	2.16E-03	2.85E-07	2.16E-03
6.1	7.94E-07	6.41E-01	3.59E-01	2.11E-05	2.49E-03	1.40E-03	8.21E-08	1.39E-03
5.75	1.78E-06	8.00E-01	2.00E-01	5.26E-06	3.11E-03	7.78E-04	2.05E-08	7.76E-04
5.4	3.98E-06	9.00E-01	1.00E-01	1.18E-06	3.50E-03	3.91E-04	4.59E-09	3.87E-04
5.05	8.91E-06	9.52E-01	4.75E-02	2.49E-07	3.70E-03	1.85E-04	9.69E-10	1.76E-04
4.7	2.00E-05	9.78E-01	2.18E-02	5.11E-08	3.80E-03	8.47E-05	1.99E-10	6.48E-05
4.35	4.47E-05	9.90E-01	9.86E-03	1.03E-08	3.85E-03	3.83E-05	4.01E-11	0.00E+00
4	1.00E-04	9.96E-01	4.43E-03	2.07E-09	3.87E-03	1.72E-05	8.05E-12	0.00E+00
3.65	2.24E-04	9.98E-01	1.98E-03	4.14E-10	3.88E-03	7.71E-06	1.61E-12	0.00E+00
3.3	5.01E-04	9.99E-01	8.86E-04	8.27E-11	3.88E-03	3.45E-06	3.22E-13	0.00E+00
2.95	1.12E-03	1.00E+00	3.96E-04	1.65E-11	3.89E-03	1.54E-06	6.42E-14	0.00E+00
2.6	2.51E-03	1.00E+00	1.77E-04	3.30E-12	3.89E-03	6.88E-07	1.28E-14	0.00E+00
2.25	5.62E-03	1.00E+00	7.91E-05	6.58E-13	3.89E-03	3.07E-07	2.56E-15	0.00E+00
1.9	1.26E-02	1.00E+00	3.53E-05	1.31E-13	3.89E-03	1.37E-07	5.10E-16	0.00E+00
1.55	2.82E-02	1.00E+00	1.58E-05	2.62E-14	3.89E-03	6.13E-08	1.02E-16	0.00E+00
1.2	6.31E-02	1.00E+00	7.05E-06	5.22E-15	3.89E-03	2.74E-08	2.03E-17	0.00E+00
0.85	1.41E-01	1.00E+00	3.15E-06	1.04E-15	3.89E-03	1.22E-08	4.05E-18	0.00E+00
0.5	3.16E-01	1.00E+00	1.41E-06	2.08E-16	3.89E-03	5.47E-09	8.08E-19	0.00E+00

Table 4B Calculations of carbonate species, TAL and pH of the water of the main stream of ZR (V4) immediately after the affected area based on the changing of pH of the water coming from the tributaries of the area affected by coal mining

pH(V2)	Alpha [H2CO3]	Alpha [HCO3-]	Alpha [CO3 2-]	Δ[H+]	Δ[H+]'	[H2CO3]i	[HCO3-]i	[CO3 2-]i	[H2CO3]f	[HCO3-]f	[CO3 2-]f	[H+]f	pH (V4)	TALf
7.85	2.94E-02	9.67E-01	3.35E-03	4.78E-09		6.35E-05	2.09E-03	7.22E-06	6.35E-05	2.09E-03	5.73E-06	1.35E-08	7.87	2.09E-03
7.5	2.94E-02	9.67E-01	3.35E-03	1.07E-08		6.34E-05	2.09E-03	7.22E-06	6.34E-05	2.09E-03	7.22E-06	1.35E-08	7.87	2.10E-03
7.15	2.94E-02	9.67E-01	3.35E-03	2.40E-08		6.34E-05	2.09E-03	7.22E-06	6.35E-05	2.09E-03	7.22E-06	1.35E-08	7.87	2.10E-03
6.8	2.94E-02	9.67E-01	3.34E-03	5.37E-08		6.35E-05	2.09E-03	7.21E-06	6.35E-05	2.09E-03	7.22E-06	1.35E-08	7.87	2.09E-03
6.45	2.95E-02	9.67E-01	3.34E-03	1.20E-07		6.35E-05	2.09E-03	7.20E-06	6.36E-05	2.09E-03	7.21E-06	1.36E-08	7.87	2.09E-03
6.1	2.96E-02	9.67E-01	3.32E-03	2.69E-07		6.36E-05	2.09E-03	7.17E-06	6.39E-05	2.09E-03	7.20E-06	1.36E-08	7.87	2.09E-03
5.75	2.99E-02	9.67E-01	3.29E-03	6.02E-07		6.39E-05	2.09E-03	7.10E-06	6.45E-05	2.09E-03	7.17E-06	1.38E-08	7.86	2.09E-03
5.4	3.05E-02	9.66E-01	3.22E-03	1.35E-06		6.45E-05	2.09E-03	6.94E-06	6.59E-05	2.08E-03	7.10E-06	1.40E-08	7.85	2.09E-03
5.05	3.19E-02	9.65E-01	3.07E-03	3.02E-06		6.59E-05	2.08E-03	6.62E-06	6.89E-05	2.08E-03	6.94E-06	1.47E-08	7.83	2.09E-03
4.7	3.51E-02	9.62E-01	2.78E-03	6.76E-06		6.89E-05	2.08E-03	5.99E-06	7.57E-05	2.08E-03	6.62E-06	1.62E-08	7.79	2.08E-03
4.35	4.21E-02	9.56E-01	2.28E-03	1.51E-05		7.57E-05	2.08E-03	4.92E-06	9.08E-05	2.06E-03	5.99E-06	1.96E-08	7.71	2.07E-03
4	5.78E-02	9.41E-01	1.61E-03	3.39E-05		9.08E-05	2.06E-03	3.47E-06	1.25E-04	2.03E-03	4.92E-06	2.73E-08	7.56	2.03E-03
3.65	9.30E-02	9.06E-01	9.28E-04	7.58E-05		1.25E-04	2.03E-03	2.00E-06	2.01E-04	1.95E-03	3.47E-06	4.57E-08	7.34	1.96E-03
3.3	1.72E-01	8.28E-01	4.20E-04	1.70E-04		2.01E-04	1.96E-03	9.06E-07	3.70E-04	1.79E-03	2.00E-06	9.23E-08	7.03	1.79E-03
2.95	3.48E-01	6.52E-01	1.28E-04	3.80E-04		3.71E-04	1.79E-03	2.77E-07	7.51E-04	1.41E-03	9.06E-07	2.37E-07	6.62	1.41E-03
2.6	7.42E-01	2.58E-01	9.41E-06	8.51E-04		7.51E-04	1.41E-03	2.03E-08	1.60E-03	5.56E-04	2.77E-07	1.28E-06	5.89	5.55E-04
2.25	1.00E+00	4.21E-04	1.87E-11	1.90E-03	1.05E-03	1.60E-03	5.56E-04	4.03E-14	2.16E-03	9.09E-07	4.03E-14	1.05E-03	2.98	0.00E+00
1.9	1.00E+00	1.30E-04	1.78E-12	4.26E-03	2.36E-03	2.16E-03	9.09E-07	3.85E-15	2.16E-03	2.81E-07	3.85E-15	3.41E-03	2.47	0.00E+00
1.55	1.00E+00	5.11E-05	2.75E-13	9.54E-03	5.28E-03	2.16E-03	2.81E-07	5.94E-16	2.16E-03	1.10E-07	5.94E-16	8.69E-03	2.06	0.00E+00
1.2	1.00E+00	2.17E-05	4.94E-14	2.14E-02	1.18E-02	2.16E-03	1.10E-07	1.07E-16	2.16E-03	4.68E-08	1.07E-16	2.05E-02	1.69	0.00E+00
0.85	1.00E+00	9.46E-06	9.42E-15	4.78E-02	2.65E-02	2.16E-03	4.68E-08	2.03E-17	2.16E-03	2.04E-08	2.02E-17	4.70E-02	1.33	0.00E+00
0.5	1.00E+00	4.19E-06	1.84E-15	1.07E-01	5.93E-02	2.16E-03	2.04E-08	3.98E-18	2.16E-03	9.03E-09	4.03E-18	1.06E-01	0.97	0.00E+00

Table 5B Calculations of carbonate species, TAL and pH of the water of the main stream of ZR at the outfall to Indian Ocean (V5) based on the changing of pH of the water coming from the tributaries of the area affected by coal mining

pH(V2)	pH (V4)	Alpha [H2CO3]	Alpha [HCO3-]	Alpha [CO3 2-]	Δ[H+]	Δ[H+]'	[H2CO3]i	[HCO3-]i	[CO3 2-]i	[H2CO3]f	[HCO3-]f	[CO3 2-]f	[H+]f	pH(V5)	TALf
7.85	7.87	2.61E-02	9.70E-01	3.79E-03	1.15E-08		6.31E-05	2.34E-03	6.75E-06	6.31E-05	2.34E-03	6.75E-06	1.20E-08	7.92	2.36E-03
7.50	7.87	2.61E-02	9.70E-01	3.79E-03	1.15E-08		6.30E-05	2.34E-03	9.15E-06	6.30E-05	2.34E-03	9.15E-06	1.20E-08	7.92	2.36E-03
7.15	7.87	2.61E-02	9.70E-01	3.79E-03	1.15E-08		6.30E-05	2.34E-03	9.15E-06	6.30E-05	2.34E-03	9.15E-06	1.20E-08	7.92	2.36E-03
6.80	7.87	2.61E-02	9.70E-01	3.79E-03	1.15E-08		6.30E-05	2.34E-03	9.15E-06	6.30E-05	2.34E-03	9.15E-06	1.20E-08	7.92	2.36E-03
6.45	7.87	2.61E-02	9.70E-01	3.79E-03	1.16E-08		6.30E-05	2.34E-03	9.15E-06	6.30E-05	2.34E-03	9.15E-06	1.20E-08	7.92	2.36E-03
6.10	7.87	2.61E-02	9.70E-01	3.79E-03	1.16E-08		6.30E-05	2.34E-03	9.15E-06	6.31E-05	2.34E-03	9.15E-06	1.20E-08	7.92	2.36E-03
5.75	7.86	2.61E-02	9.70E-01	3.79E-03	1.17E-08		6.31E-05	2.34E-03	9.14E-06	6.31E-05	2.34E-03	9.14E-06	1.20E-08	7.92	2.36E-03
5.40	7.85	2.61E-02	9.70E-01	3.79E-03	1.20E-08		6.31E-05	2.34E-03	9.14E-06	6.31E-05	2.34E-03	9.14E-06	1.20E-08	7.92	2.36E-03
5.05	7.83	2.61E-02	9.70E-01	3.79E-03	1.25E-08		6.31E-05	2.34E-03	9.14E-06	6.31E-05	2.34E-03	9.14E-06	1.20E-08	7.92	2.36E-03
4.70	7.79	2.61E-02	9.70E-01	3.79E-03	1.38E-08		6.31E-05	2.34E-03	9.14E-06	6.31E-05	2.34E-03	9.14E-06	1.20E-08	7.92	2.36E-03
4.35	7.71	2.62E-02	9.70E-01	3.78E-03	1.67E-08		6.31E-05	2.34E-03	9.14E-06	6.31E-05	2.34E-03	9.14E-06	1.20E-08	7.92	2.36E-03
4.00	7.56	2.62E-02	9.70E-01	3.78E-03	2.33E-08		6.31E-05	2.34E-03	9.13E-06	6.31E-05	2.34E-03	9.13E-06	1.20E-08	7.92	2.36E-03
3.65	7.34	2.62E-02	9.70E-01	3.78E-03	3.89E-08		6.31E-05	2.34E-03	9.13E-06	6.32E-05	2.34E-03	9.13E-06	1.20E-08	7.92	2.36E-03
3.30	7.03	2.62E-02	9.70E-01	3.78E-03	7.86E-08		6.32E-05	2.34E-03	9.12E-06	6.33E-05	2.34E-03	9.12E-06	1.20E-08	7.92	2.36E-03
2.95	6.62	2.63E-02	9.70E-01	3.76E-03	2.02E-07		6.33E-05	2.34E-03	9.11E-06	6.35E-05	2.34E-03	9.11E-06	1.21E-08	7.92	2.36E-03
2.60	5.89	2.68E-02	9.70E-01	3.70E-03	1.09E-06		6.35E-05	2.34E-03	9.08E-06	6.46E-05	2.34E-03	9.08E-06	1.23E-08	7.91	2.36E-03
2.25	2.98	4.01E-01	5.99E-01	9.43E-05	8.99E-04		6.46E-05	2.34E-03	8.92E-06	9.64E-04	1.44E-03	8.92E-06	2.97E-07	6.53	1.46E-03
1.90	2.47	1.00E+00	2.21E-04	5.14E-12	2.91E-03	2.01E-03	9.67E-04	1.45E-03	2.27E-07	2.41E-03	5.34E-07	1.24E-14	2.01E-03	2.70	0.00E+00
1.55	2.06	1.00E+00	6.83E-05	4.91E-13	7.41E-03	4.50E-03	2.41E-03	5.34E-07	1.24E-14	2.41E-03	1.65E-07	1.18E-15	6.51E-03	2.19	0.00E+00
1.20	1.69	1.00E+00	2.68E-05	7.56E-14	1.75E-02	1.01E-02	2.41E-03	1.65E-07	1.18E-15	2.41E-03	6.47E-08	1.82E-16	1.66E-02	1.78	0.00E+00
0.85	1.33	1.00E+00	1.14E-05	1.36E-14	4.00E-02	2.26E-02	2.41E-03	6.47E-08	1.82E-16	2.41E-03	2.74E-08	3.28E-17	3.91E-02	1.41	0.00E+00
0.50	0.97	1.00E+00	4.96E-06	2.59E-15	9.05E-02	5.05E-02	2.41E-03	2.74E-08	3.28E-17	2.41E-03	1.20E-08	6.33E-18	8.96E-02	1.05	0.00E+00

Table 6B Characterization of the development of coal mines (Volume of pits, plan surface of pits, plan surface of mine area, side surface of the pits)

Year	Coal Production	Crude Coal	Volume of coal extracted	Thickness of Coal layer	Surface Area affected by coal Extraction	Cumulative Affected area	Depth of the pits	Plan view area of Pits	Cumulative area of pits	Side Area of the pits available for groundwater seepage	Cumulative S
	m(ton=1000Kg)	Coal Production/0.48	V=m*1000/density (≈800kg/cum) =(cum)	Assuming Chipanga layer (b=36m)	Aaf = V/b1		The Chipanga layer is approximately at H=250 m	Ap=V/H (sqm)	(sqm)	Assuming square pits S=4xsqrt(Ap)x(b1+b2) [sqm]; b1 (36m) and b2 (90 m) are thickness of the aquifers	(sqm)
2011	2 857 000	5 952 083	7 440 104	36	206 670	206 670	200	37 201	37 201	97 209	97 209
2012	8 370 766	17 439 096	21 798 870	36	605 524	812 194	200	108 994	146 195	166 392	263 601
2013	10 816 027	22 533 389	28 166 737	36	782 409	1 594 603	200	140 834	287 029	189 140	452 741
2014	15 044 500	31 342 709	39 178 386	36	1 088 288	2 682 892	200	195 892	482 920	223 069	675 810
2015	22 867 810	47 641 271	59 551 589	36	1 654 211	4 337 102	200	297 758	780 678	275 019	950 828
2016	30 517 958	63 579 079	79 473 849	36	2 207 607	6 544 709	200	397 369	1 178 048	317 708	1 268 536
2017	31 997 479	66 661 415	83 326 769	36	2 314 632	8 859 342	200	416 634	1 594 682	325 318	1 593 854
2018	35 829 841	74 645 501	93 306 876	36	2 591 858	11 451 199	200	466 534	2 061 216	344 249	1 938 103
2019	39 029 868	81 312 225	101 640 281	36	2 823 341	14 274 541	200	508 201	2 569 417	359 293	2 297 395

Table 6B (cont.)

Year	Coal Production	Crude Coal	Volume of coal extracted	Thickness of Coal layer	Surface Area affected by coal Extraction	Cumulative Affected area	Depth of the pits	Plan view area of Pits	Cumulative area of pits	Side Area of the pits available for groundwater seepage	Cumulative S
	m(ton=1000Kg)	Coal Production/0.48	V=m*1000/density (≈800kg/cum) =(cum)	Assuming Chipanga layer (b=36m)	Aaf = V/b1		The Chipanga layer is approximately at H=250 m	Ap=V/H (sqm)	(sqm)	Assuming square pits S=4xsqrt(Ap)x(b1+b2) [sqm); b1 (36m) and b2 (90 m) are thickness of the aquifers	(sqm)
2020	38 770 081	80 771 003	100 963 753	36	2 804 549	17 079 089	200	504 819	3 074 236	358 095	2 655 490
2021	20 995 934	43 741 529	54 676 912	36	1 518 803	18 597 892	200	273 385	3 347 621	263 522	2 919 013
2022	21 205 889	44 178 935	55 223 669	36	1 533 991	20 131 883	200	276 118	3 623 739	264 837	3 183 849
2023	21 000 000	43 750 000	54 687 500	36	1 519 097	21 650 980	200	273 438	3 897 176	263 548	3 447 397
2024	20 800 000	43 333 333	54 166 667	36	1 504 630	23 155 610	200	270 833	4 168 010	262 290	3 709 687
2025	21 300 000	44 375 000	55 468 750	36	1 540 799	24 696 409	200	277 344	4 445 354	265 424	3 975 111
2026	21 600 000	45 000 000	56 250 000	36	1 562 500	26 258 909	200	281 250	4 726 604	267 286	4 242 397
2027	6 700 000	13 958 333	17 447 917	36	484 664	26 743 573	200	87 240	4 813 843	148 863	4 391 261
2028	6 700 000	13 958 333	17 447 917	36	484 664	27 228 237	200	87 240	4 901 083	148 863	4 540 124
Total	376 403 153	784 173 236	980 216 544	-	27 228 237	256 305 834	-	4 901 083	-		

Table 7B Calculations of projections of groundwater seepage into the pits of coal mine and the amount of water pumped out of the pits during the operation of the mines in Tete (2011-2028)

Year	Cumulative Plan view area of the pits (sqm)	Cumulative flow areas in the pits (sqm)	Rainfall water into the mining pits (cum/s)	Groundwater seepage to the pits assumed dh/dl = 100/100m [cum/s)	Groundwater seepage to the pits assumed dh/dl = 100m/200m [cum/s)	Groundwater seepage to the pits assumed dh/dl = 100m/300m [cum/s)	Total flow into the pits (dl/dl=100 m/100m)	Total flow into the pits (dl/dl=100 m/200m)	Total flow into the pits (dl/dl=100 m/300m)
2011	37201	97209	0.0003	0.011	0.005	0.004	0.011	0.006	0.004
2012	146195	263601	0.0012	0.029	0.015	0.010	0.030	0.016	0.011
2013	287029	452741	0.0024	0.050	0.025	0.017	0.052	0.027	0.019
2014	482920	675810	0.0040	0.074	0.037	0.025	0.078	0.041	0.029
2015	780678	950828	0.0064	0.105	0.052	0.035	0.111	0.059	0.041
2016	1178048	1268536	0.0097	0.140	0.070	0.047	0.150	0.080	0.056
2017	1594682	1593854	0.0131	0.176	0.088	0.059	0.189	0.101	0.072
2018	2061216	1938103	0.0170	0.214	0.107	0.071	0.231	0.124	0.088
2019	2569417	2297395	0.0212	0.253	0.127	0.084	0.274	0.148	0.106
2020	3074236	2655490	0.0253	0.293	0.146	0.098	0.318	0.172	0.123

Table 7B (cont.)

Year	Cumulative Plan view area of the pits (sqm)	Cumulative flow areas in the pits (sqm)	Rainfall water into the mining pits (cum/s)	Groundwater seepage to the pits assumed dh/dl = 100/100m [cum/s)	Groundwater seepage to the pits assumed dh/dl = 100m/200m [cum/s)	Groundwater seepage to the pits assumed dh/dl = 100m/300m [cum/s)	Total flow into the pits (dl/dl=100 m/100m)	Total flow into the pits (dl/dl=100 m/200m)	Total flow into the pits (dl/dl=100 m/300m)
2021	3347621	2919013	0.0276	0.322	0.161	0.107	0.349	0.188	0.135
2022	3623739	3183849	0.0299	0.351	0.175	0.117	0.381	0.205	0.147
2023	3897176	3447397	0.0321	0.380	0.190	0.127	0.412	0.222	0.159
2024	4168010	3709687	0.0344	0.409	0.204	0.136	0.443	0.239	0.171
2025	4445354	3975111	0.0366	0.438	0.219	0.146	0.475	0.256	0.183
2026	4726604	4242397	0.0390	0.468	0.234	0.156	0.507	0.273	0.195
2027	4813843	4391261	0.0397	0.484	0.242	0.161	0.524	0.282	0.201
2028	4901083	4540124	0.0404	0.500	0.250	0.167	0.541	0.291	0.207

Table 8B Calculations of projections of groundwater seepage into the pits of coal mines and the amount of water added to the groundwater in closed mines in Tete (2011-2028)

Year	Cumulative area of affected area by mining	Cumulative area of GW flow into the pits	Rainfall into the pits (cum/s)	Groundwater seepage to the pits assumed dh/dl = 0.1[cum/s)	Groundwater seepage to the pits assumed dh/dl = 0.01[cum/s)	Groundwater seepage to the pits assumed dh/dl = 0.001[cum/s)	Groundwater seepage to the pits assumed dh/dl = 0.0001[cum/s)	Contaminated water added to the GW (dh/dl = 0.1)	Contaminated water added to the GW (dh/dl = 0.01)	Contaminated water added to the GW (dh/dl = 0.001)	Contaminated water added to the GW (dh/dl = 0.0001)
2011	206 670	48 604	0.002	5.358E-04	5.358E-05	5.358E-06	5.358E-07	0.002	0.002	0.002	0.002
2012	812 194	131 800	0.007	1.453E-03	1.453E-04	1.453E-05	1.453E-06	0.008	0.007	0.007	0.007
2013	1 594 603	226 370	0.013	2.495E-03	2.495E-04	2.495E-05	2.495E-06	0.016	0.013	0.013	0.013
2014	2 682 892	337 905	0.022	3.725E-03	3.725E-04	3.725E-05	3.725E-06	0.026	0.022	0.022	0.022
2015	4 337 102	475 414	0.036	5.240E-03	5.240E-04	5.240E-05	5.240E-06	0.041	0.036	0.036	0.036
2016	6 544 709	634 268	0.054	6.991E-03	6.991E-04	6.991E-05	6.991E-06	0.061	0.055	0.054	0.054
2017	8 859 342	796 927	0.073	8.784E-03	8.784E-04	8.784E-05	8.784E-06	0.082	0.074	0.073	0.073
2018	11 451 199	969 051	0.094	1.068E-02	1.068E-03	1.068E-04	1.068E-05	0.105	0.095	0.095	0.094
2019	14 274 541	1 148 698	0.118	1.266E-02	1.266E-03	1.266E-04	1.266E-05	0.130	0.119	0.118	0.118
2020	17 079 089	1 327 745	0.141	1.464E-02	1.464E-03	1.464E-04	1.464E-05	0.155	0.142	0.141	0.141

Table 8B (cont.)

Year	Cumulative area of affected area by mining	Cumulative area of GW flow into the pits	Rainfall into the pits (cum/s)	Groundwater seepage to the pits assumed dh/dl = 0.1[cum/s)	Groundwater seepage to the pits assumed dh/dl = 0.01[cum/s)	Groundwater seepage to the pits assumed dh/dl = 0.001[cum/s)	Groundwater seepage to the pits assumed dh/dl = 0.0001[cum/s)	Contaminated water added to the GW (dh/dl = 0.1)	Contaminated water added to the GW (dh/dl = 0.01)	Contaminated water added to the GW (dh/dl = 0.001)	Contaminated water added to the GW (dh/dl = 0.0001)
2021	18 597 892	1 459 506	0.153	1.609E-02	1.609E-03	1.609E-04	1.609E-05	0.169	0.155	0.153	0.153
2022	20 131 883	1 591 925	0.166	1.755E-02	1.755E-03	1.755E-04	1.755E-05	0.184	0.168	0.166	0.166
2023	21 650 980	1 723 699	0.179	1.900E-02	1.900E-03	1.900E-04	1.900E-05	0.198	0.180	0.179	0.179
2024	23 155 610	1 854 844	0.191	2.045E-02	2.045E-03	2.045E-04	2.045E-05	0.211	0.193	0.191	0.191
2025	24 696 409	1 987 555	0.204	2.191E-02	2.191E-03	2.191E-04	2.191E-05	0.226	0.206	0.204	0.204
2026	26 258 909	2 121 199	0.216	2.338E-02	2.338E-03	2.338E-04	2.338E-05	0.240	0.219	0.217	0.217
2027	26 743 573	2 195 630	0.220	2.420E-02	2.420E-03	2.420E-04	2.420E-05	0.245	0.223	0.221	0.221
2028	27 228 237	2 270 062	0.224	2.502E-02	2.502E-03	2.502E-04	2.502E-05	0.250	0.227	0.225	0.225