Examensarbete
TVVR 13/5008

Treatment methods for water pollution from coal mining in Moatize (Mozambique)

Estêvão A. J. Pondja

May 2013

Division of Water Resources Engineering
Department of Building and Environmental Technology
Lund University

Treatment methods for water pollution from coal mining in Moatize (Mozambique)

Supervisor: Kenneth M Persson

Examiner: Magnus Persson

Key words: Acid mine drainage, treatment of acid mine drainage, coal mine in Moatize, open pit mining, passive and active treatment, Moatize district in Tete province.

Acknowledgments

This work was only possible to achieve thanks to the knowledge and support received from professors and colleagues during my studies at Lund University. I would like to first thank God for health and protection that he gave me during my studies at Lund University.

My special thanks go to my supervisors Professor Kenneth Persson and Professor Nelson Matsinhe who contributed richly for the materialization of this work. I am grateful also to Professor Rolf Larsson for knowledge that he has been transmitted and for his support in bureaucratic and logistical issues.

Also I thank my family, especially my dear mother Isabel Nhantumbo, my brothers and my girlfriend Ezelina Bila for moral support. I want to thank all Professors and staff from Lund University for the knowledge transmitted during my studies at Lund University.

Abstract

Moatize district located in Tete province in the center of Mozambique has one of the largest unexploited coal deposits of the world with a capacity of 2.5 billions of tones. Recently many multinational coal mine companies started exploitation of coal in Moatize. Coal exploitation has economical, social and environmental impacts. The main environmental impact is generation of acid mine drainage (AMD) which can pollute surface and groundwater.

The aim of this work was to describe and assess the main impact of mining activities on water resource in Moatize and to describe treatment methods for polluted water.

The methodology used was literature review and visits realized in different institutions of Mozambique.

Different active and passive methods for AMD were described throughout the report.

It can be conclude that the impact of AMD in Moatize will not significantly affect the Zambezi river due to its big flow but it can be severe in small tributaries because some of them pass through the mining section. Water pollution can affect the population of Moatize negatively because they depend in agriculture and fishing to survive. There were not enough data to decide which treatment method can be applied for Moatize, but based on data from an old mine from Moatize it was possible to conclude that aerobic wetland and lime-limestone neutralization could be used.

It is recommended to collect extensive data from mining companies in Moatize to make more detailed investigation about different treatment methods.

Abbreviations

AMD – Acid mine drainage
ARA- Regional water administration (administração regional de águas)
ARD – Acid rock drainage
ALD – Anoxic limestone drains
DO – Dissolved oxygen
EPA – Environmental protection agency
EC – Electrical conductivity
Fe – Total dissolved iron
HDS – High density sludge
MICOA – Ministerio Para a Coordenação da Acção Social (Ministry of environment)
Mtpa – Millions of tonnes per annum
Q – Flow rate
ROM – Run of mine
SS – Suspended solids
SAPS – Successive alkalinity producing systems
TDS – Total dissolved solids

Contents

1. Introduction

Mozambique is a country rich in mineral resources such as coal, gas and heavy sands. The mining industry in Mozambique has been grown quickly in recent years due to recent discoveries of coal deposits and natural gas. These findings have attracted much foreign investment, especially in the energy sector (gas and coal).

Many mining companies have opened mines recently in Mozambique and it brings positive and negative aspects. The positive aspect is that the country will grow economically but on the other hand these mining activities will affect adversely the environment, polluting the surface water and groundwater. People living in the area where those minerals are located have been reallocated to other places. These people were living close to the rivers because they depend a lot of agriculture, but with this reallocation process due to mining activities they are living far from water courses which make life difficult for them.

There are many types of mining companies in Mozambique but coal mining has been growing considerable in recent years.

This work will be focus on coal mining activities in Tete province due to potential of contamination of Zambezi river basin which is the biggest in the country.

In Tete province, particularly in Moatize, there is located one of the largest unexploited mineral coal deposits of the world with an estimated capacity of about 2.5 billion tones (José & Sampaio, 2011).

The mega mining project going on in Tete are mostly open-pit mining and these projects will affect the aquatic environment and fauna adversely due to removal of large amounts of land that can alter the flora and fauna and adversely affect existing fish in rivers around (José & Sampaio, 2011). Sediment can be transported to the water courses during operation of coal mining and it means that suspended solids will increase (José & Sampaio, 2011).

Mining companies nowadays are using very sophisticated equipment to process coal. This means that the amount of coal to be processed will increase and water consumed during the processing will also increase (José & Sampaio, 2011). As result of these increases the amount of tailings will increase. The issue here is that tailings normally contain chemical products such as cyanides, pyrite (sulfide) and metals which can reach water courses (José & Sampaio, 2011). The exposed surface of mining is also a potential source of metals (José & Sampaio, 2011). Due to the presence of sulfides in coal, wastewater from coal mining contain sulfate which can pollute the water courses (José & Sampaio, 2011). The main environmental problem of coal mining is the acid mine drainage which will be discussed further in this report.

This report will be focus on Moatize (Tete) district because it contains two mega coal mining companies operating there. The companies are Vale Mozambique (with headquarter in Brazil) and Rio Tinto (with headquarter in Australia). There are other companies which are doing research and prospecting in Moatize. The exploration of coal in Moatize by Vale Mozambique and Rio Tinto has been done using open pit mining (José & Sampaio, 2011).

The coal mining companies in Tete province which are operating and which are in advanced phase to start their operations are listed in table 1 (Rosenfeld, 2012). The coal produced in Tete province is coking coal which is used during steel production and thermal coal which is used to produce electricity (Rosenfeld, 2012). The production in table 1 are in Millions tons per annum (Mtpa).

Table 1: Estimation of production of mining companies in Tete (Rosenfeld, 2012).

Mine name	Location	Owner	Date of start production	Maximum coking coal production capacity (Mtpa)	Maximum thermal coal production capacity (Mtpa)
Benga	Benga (Moatize)	Rio Tinto	2012	6.0	4.0
Zambeze	Moatize	Rio Tinto	2014	13.5	9.0
Moatize phase 1	Moatize	Vale	2011	8.58	2.6
Moatize phase 2	Moatize	Vale	2015	8.58	2.6
Ncondezi	Ncondezi	Ncondezi	2014	0.0	10.5
Revuboe	Moatize	Revuboe	2015	5.1	3.4
ENRC Estima	Moatize	ENRC	2013	6.0	4.0
Jindal	Moatize	JSPL	2013	3.0	2.0
Minas de Moatize	Moatize	Beacon Hill	2011	0.72	1.64

1.1 Research questions

To carry out this study the following research question will be used:

- How contamination of water resources due to coal mining activities occurs in the study area?
- What are the main impacts of coal mining pollution in environment and for people living in the study area?
- What treatment can be given to the contaminated water from coal mining and what are the advantages and disadvantages of each method?

1.2 Objectives

General objective

The main objective of this work is to describe the main impact of mining activities on water resource in lower Zambezi river basin (Moatize) and to describe treatment methods for polluted water.

Specific objectives

The specific objectives are:

- to describe the study area;
- to describe contamination process in water resource due to coal mining activities;

- to identify different treatment method for contaminated water;
- to propose the best method among the identified methods.

1.3 Methodology

The methodology used for this work was basically:
- Visit in some institutions in Mozambique to collect relevant information for the work. The visited institutions are: Regional Water Administration (ARA Zambezi - Tete), Fisheries Research Institute in Tete, Ministry for Coordination of Environmental Action (MICOA – Maputo), Ministry of Mineral Resources (Maputo) and mining companies (Vale and Rio Tinto in Tete province). During the visits it was possible to interact with different experts from different fields and also it was possible to speak with people living in the study area.

It was not possible to go inside of the coal mining installation of Vale Mozambique and Rio Tinto because they didn´t allow the author of this report due to bureaucratic issues.

One limitation of this work could be lack of information of this two mining companies operating in Moatize and another limitation could be lack of information of water quality in the study area due to lack of resource of ARA-Zambezi which is responsible for water management in this part of Zambezi river basin. ARA-Zambezi can only perform physical analysis of water but chemical analysis they don´t perform due to lack of funds to buy necessary

equipment to perform this task.
- Literature research: different articles and books were consulted in order to clarify the research questions.

1.4 Problem description

During coal mining activities the surrounding environment is normally polluted. There are different types of pollution that can occur during mining activities: atmospheric pollution due to dust present in mines, different types of solid waste generation and water resource pollution. The main environmental problem of coal mining is the generation of acid mine drainage.

Acid rock drainage (ARD) is a term used to describe the general process of acid water drainage from rocks in general but when it comes to mining, acid rock drainage is known as acid mine drainage (AMD) and it refers to the drainage resulting from mining activities (INAP, 2013). Acid rock drainage can occur in nature due to weathering of minerals containing sulfides (e.g: pyrite) and also can occur due to oxidation of elemental sulfur (INAP, 2013). Acid rock drainage can also occur due to anthropogenic reasons such as mining. During this report the term acid mine drainage (AMD) will be used because the reports deals with pollution in coal mine.

Mining activities accelerate process of weathering of reactive sulfide because they increase the reactive surface area of reactive component when huge volume of material containing sulfide is exposed to air and water (INAP, 2013). Pyrite (FeS_2) is one of the most relevant mineral when it comes to acid mine drainage generation due to its concentration, distribution and grain size (INAP, 2013).

1.4.1 Oxidation process of pyrite

Sulfide minerals are formed in absence of oxygen in ore minerals deposits and it means that they are formed in reduced conditions (INAP, 2013). Sulfide minerals can become unstable when exposed to oxygen from atmosphere, when exposed to mining water which contains oxygen, excavation, mineral processing and other activities which involve removing of earth, thus exposing minerals containing sulfide (INAP, 2013). Figure 1 below show oxidation process of pyrite in a simplified manner and the reactions in the figure 1 do not represent the real mechanisms, they are schematic reaction just to facilitate the perception of this process (INAP, 2013).

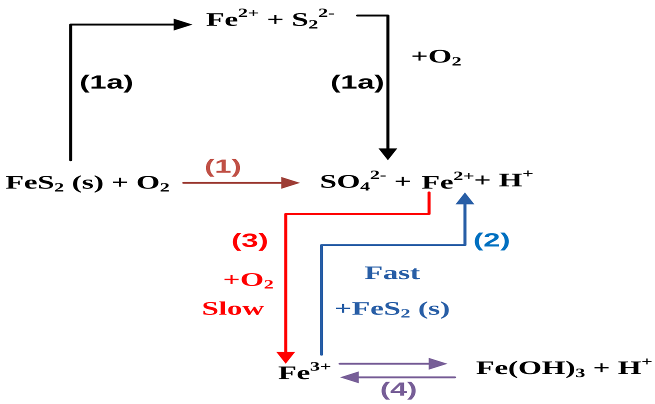

Figure 1: Pyrite oxidation process (INAP, 2013).

Pyrite in contact with water and oxygen reacts (direct oxidation) forming acid solution, with the general reaction shown in equation 1 (INAP, 2013).

$$FeS_2 + \frac{7}{2}O_2 + H_2O = Fe^{2+} + 2SO_4^{2-} + 2H^+ \quad (1)$$

Reaction (1) can occur in the presence of microorganisms, or in absence, and in most case oxygen acts as oxidant

(INAP, 2013). Instead of direct oxidation, pyrite can dissolve as shown in figure 1 in process (1a). It is also possible to oxidize pyrite using oxygen dissolved in water but due to low solubility of oxygen in water the amount of oxygen is low in water and it makes the process very inefficient but ferric iron (Fe^{3+}) dissolved in water can oxidize pyrite as shown in equation 2 (INAP, 2013).

$$FeS_2 + 14Fe^{3+} + 8H_2O = 12Fe^{2+} + 2SO_4^{2-} + 16H^+ \quad (2)$$

For generation and replenishment of Fe^{3+} it is necessary to allow reaction (2) happen and it is done through oxidation of Fe^{2+} as shown in equation (3) (INAP, 2013).

$$Fe^{2+} + \frac{1}{4}O_2 + H^+ = Fe^{3+} + \frac{1}{4}H_2O \quad (3)$$

Reaction (2) is faster than reaction (3) and it generates more acidity per mole of pyrite oxidized yet significant amount of Fe^{3+} can be generated only in acidic condition and this is one limitation of reaction (2) (INAP, 2013).

For oxidation of pyrite, reaction (1) first takes place at neutral or higher pH and when sufficient acidic conditions have been established reaction (2) will take place at pH close to 4.5 or lower (INAP, 2013). The last reaction is (3) and happens in order to replenish Fe^{3+} (INAP, 2013).

To generate Fe^{3+} it is necessary to have oxygen as shown in reaction (2) and aerobic bacteria (Acidithiobacillus genus) which catalyze this reaction (INAP, 2013).

It is possible to remove Fe^{2+} from solution through oxidation and hydrolysis under slightly acidic condition to alkaline conditions and the product is an insoluble hydroxide as shown in equation (4) (INAP, 2013).

$$Fe^{2+} + \frac{1}{4}O_2 + 2\frac{1}{2}H_2O = Fe(OH)_3 + 4H^+ \quad (4)$$

Combining reaction (1) and (4) at pH higher than 4.5, reaction (5) takes place and the amount of acidity in reaction (5) when compared to reaction (1) will be doubled (INAP, 2013).

$$FeS_2 + \frac{15}{4}O_2 + \frac{7}{2}H_2O = Fe(OH)_3 + 2SO_4^{2-} + 4H^+ \quad (5)$$

In mine waters there are a lot of microorganisms and in acidic conditions they use to be the only living organisms. Ferrooxidans are oxidizing iron bacteria and thiooxidans are sulfur oxidizing bacteria.These two types of bacteria are very important in sulfide oxidation and in formation of acid mine drainage (INAP, 2013).

1.4.2 Impact of acid mine drainage in the environment

The main impacts of AMD in the environment are: metals will be released to the environment and when they reach streams fish may die; due to presence of metals and low pH in rivers fishes through their gills will breathe in a contaminated environment resulting in chronic toxicity of fishes (Jennings, et al., 2008). The fish contamination can also be due to contaminated sediment and food and this contamination is basically due to high content of metals in water (Jennings, et al., 2008).

One of the main product of pyrite oxidation is iron hydroxide ($Fe(OH)_3$) which precipitates in the streams and gives a red/orange color to the water and it can cover the surface of sediments and streambeds contributing for destructions of habitat (Jennings, et al., 2008). Table 2 below shows different parameter available in acid mine drainage and its impact in the environment.

Table 2: Typical AMD characteristics and its impact (Silvas, 2010).

Parameter	Typical chemical species associated	Concentration range in (mg/l) with exception of pH	Impact in the environment
pH	H_2SO_4	2 - 4	Dissolution and metal mobilization.
Iron	Fe^{3+},Fe^{2+}, iron hydroxide and Fe_2O_3	100 – 3,000	Discoloration and turbidity of water; Increases in pH; Precipitation of Fe^{2+}.
Heavy metal	Mg,Cu,Cd,Zn,Pb,Hg,As	1 -200	Reduction of flora and fauna; Drinking Water quality reduction
Total solids	Ca, Mn,Al,SO_4^{2-},etc.	100 – 30,000	Drinking Water quality reduction

2. Study area

Mozambique is located in southeast of Africa and it has total surface area of 799.380 km^2 (Cumbe, 2007). It makes border with the Indian ocean, and six countries, namenly: South Africa, Malawi, Zambia, Zimbabwe, Tanzania and Swazland (figuere 2) (Cumbe, 2007). Mozambique is situated between latitudes 10°27´ south and 26°52´ south and in longitudes 30°12´ east and 40°51´ east (figure 2) (Cumbe, 2007).

Mozambique has eleven provinces: Maputo, Maputo city (which is the capital), Gaza, Inhambane, Sofala, Manica, Tete, Zambezia, Nampula, Cabo Delgado and Niassa. Mozambique has a total population of 22.4 million, a population density of 28 peop/Km^2 and agriculture is the basic of survival of the population (Global, AICEP Portugal, 2010). According to the population census of 2007, about 70% of the population lives in rural area and 30% in urban areas (Global, AICEP Portugal, 2010). The rate of iliteracy has been decreasing and in 2010 it was about 50% (Global, AICEP Portugal, 2010). The GDP is 942 USD percapita and the percentage of population living with less than 2 USD per day is about 82% (Stiftung, 2012).

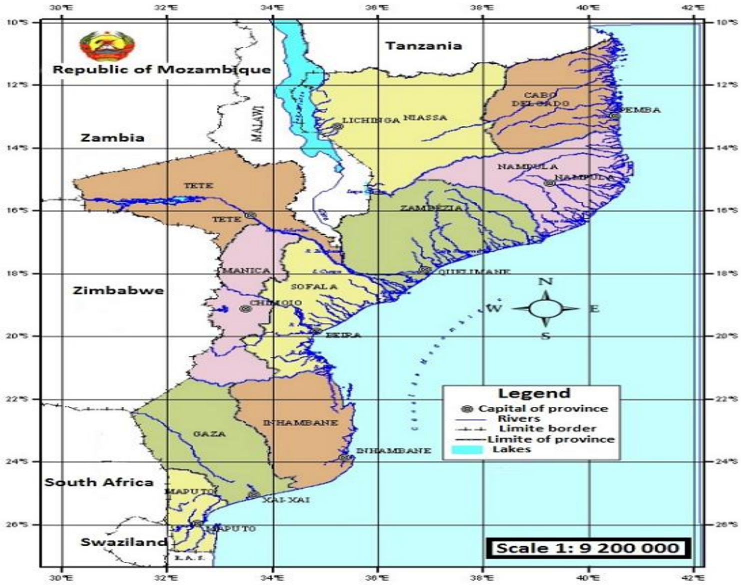

Figure 2: Map of Mozambique (Cumbe, 2007).

2.1 District of Moatize in Tete province

Moatize district which is 20 km far from the city of Tete is located NE of provincial capital city Tete between parallels 15 ' 36" and 16' 38" south latitude and between the meridians 32 ' 16" and 34' 28" east longitude (José & Sampaio, 2011).

The population of Moatize according to the population census of 2007 is about 113.000 inhabitants and the total surface is 8.455 Km^2 which corresponds to a population density of 13.4 pop/Km^2 (José & Sampaio, 2011). The district of Moatize is divided in 9 localities: Moatize, Benga, Mpanzu, Msungo, Kambulatsitsi, Mecungas, Zóbué, Capridzanje and Ncodeze (José & Sampaio, 2011).

The biggest coal reserve in Mozambique is located in Moatize in Tete province and thanks to this coal reserve it is expected that Mozambique will become the second largest coal producer in Africa after South Africa (José & Sampaio, 2011).

The coal in Tete province can be found in the following districts: Moatize, Mutarara, Changara, Cahora Bassa , Mágoé, and in the city of Tete (JSPL Mozambique Minerals, LDA, 2011). Most of coal exploration and licenses in Tete province are located between 15^{o} 52´ 00 S and 33^{o} 54´ 36.00 E (Hatton & Fardell, 2011). This province has been reported as one of the last biggest undeveloped coking coal basin in the world (Hatton & Fardell, 2011). There are 40 coal mining companies in Mozambique that hold licenses and 95% of those are located in Tete province (Hatton & Fardell, 2011). The study area is located in Moatize district where are located two mega companies operating in this area (figure 3).

This study area was chosen because most of coal mining companies operating in Tete are located in Moatize in the vicinity of the Zambezi River. There are some small rivers which pass through mining sections of Vale and Rio Tinto mining companies and they are potential recipients of pollutants coming from mining activities. It was not possible to have data from location of wastewater discharge of Vale and Rio Tinto in the Zambezi River or in one of its tributary due to lack of information. As shown in figure 3 there are others coal mining companies making studies inside Moatize making this region a potential area for surface and groundwater pollution.

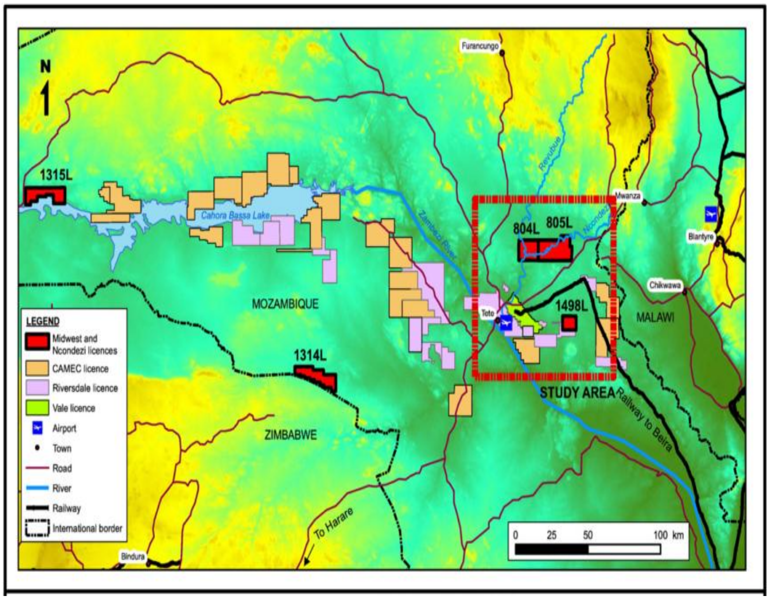

Figure 3: Location of licenses in Tete and study area (Hatton & Fardell, 2011).

2.2 Climate and Geology of Moatize

The Moatize climate is semi-arid and sub-tropical (Golder Associates Africa, 2010). The rainfall is low but evaporation and temperatures are high (Golder Associates Africa, 2010). There are three seasons which can be found along the year: hot wet season starting from October or middle of November till middle of March or beginning of April characterized by summer rains; dry and cool winter season which starts in May and end in August and finally a hot dry season which starts on September and end by the end of October or beginning of November (Golder Associates Africa, 2010). The average rainfall is about 644 mm/year and the average potential evapotranspiration is about 1,626 mm/year (José & Sampaio, 2011). The highest rainfall occurs mostly during periods between December of one year to February of the following year, and the average temperature is in the range of 27 ^{o} C, and the mean annual maximum and minimum temperature are 33 to 21 ^{o} C respectively (José & Sampaio, 2011).

Geologically, the sediment of karoo age is constituted by shales, sandstones, conglomerates and coal seams (Golder Associates Africa, 2010). This sediments were divided from the top to the bottom in Matinde formation, serie produtiva and tellite series. Matinde is the highest karoo formation in Moatize and it is constituted by sandstones and conglomerates (Golder Associates Africa, 2010). Carbonaceous shale and coal with high ash content also occur in Matinde formation but they are not valuable economically (Golder Associates Africa, 2010). The productive serie includes Minjova-Moatize basin and coal seams with economical value is present here. It comprises of mudstone, shales, carbonaceous shales and siltstone intercalated with seams of coal (Golder Associates Africa, 2010). The coal is contained in multi seams coal and stratigraphically named in figure 4 from the youngest to the oldest. The most important coal seam is Chipanga because it has economical value and it has the biggest reserve (thicker and extensive) (Golder Associates Africa, 2010). The basal series of karoo are formed by tellite series in Moatize and the topography can varies from 10 to 130 m(Golder Associates Africa, 2010).

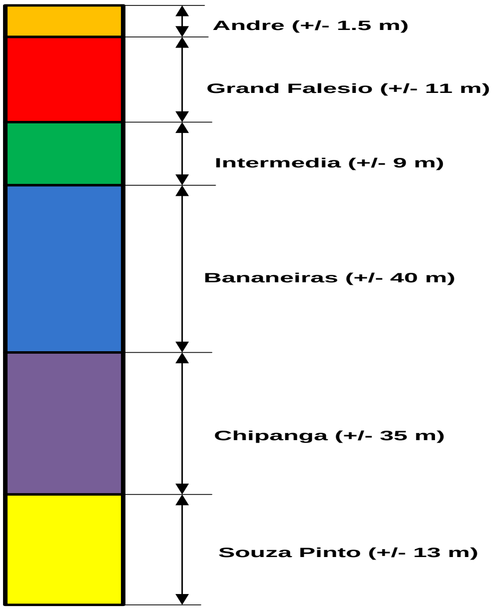

Figure 4: Moatize coal stratigraphy (Golder Associates Africa, 2010).

Moatize coal deposit is the biggest in Mozambique and it consist of siltstone and sandstones which were originated from sedimentary rocks (José & Sampaio, 2011).

2.3 Description of water resource in the study area

The study area is located in the lower Zambezi in Mozambique and it makes the risk of water pollution due to mining activities high.

Zambezi river basin is one of the biggest river basins in Africa and stretches over 8 countries: Mozambique, Angola; Botswana, Malawi, Namibia, Tanzania, Zimbabwe and Zambia (Ashton, et al., 2001). The source of Zambezi is located in Zambia and it discharge in Indian Ocean in Mozambique (Jessen & Silva, 2008). This river basin is one of the most important of southern Africa and has an area of 1,281,800 km^2 (Ashton, et al., 2001) with total course of 2,700 km (Jessen & Silva, 2008). Mozambique occupies 11% of the total basin area and the population is about12.4% of total population of the country (Ashton, et al., 2001). Zambezi River is divided in upper, middle and lower Zambezi (figure 5).

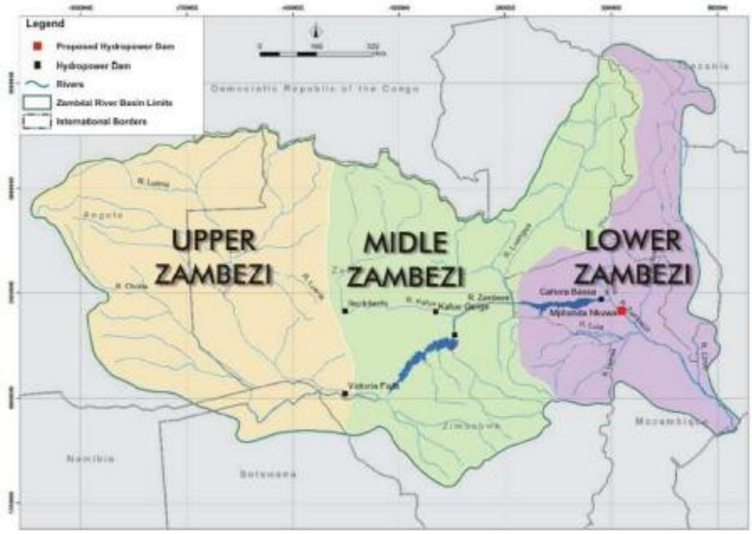

Figure 5: Division of Zambezi river basin in 3 parts (Southern Waters , 2011).

The upper Zambezi has an area of 507,200 km^2 and it includes sub catchment of Angola, Zambia, Namibia and Botswana (Jessen & Silva, 2008). The mean annual precipitation in upper Zambezi is about 1000 mm, the average annual runoff is about 88 mm and the maximum flow is about 17,286 m^3/s (with 10,000 years of return period) (Jessen & Silva, 2008). The middle Zambezi has an area of 543,200 km^2 approximately and it includes Victoria Falls, Kafue and Cahora Bassa (Jessen & Silva, 2008). The mean annual precipitation in middle Zambezi is about 916 mm, the average annual runoff is about 87 mm and the maximum flow is about 30,000 m^3/s (with 10,000 years of return period) (Jessen & Silva, 2008). The lower Zambezi has a total stretch of 650 km and it starts in Cahora Bassa till Indian Ocean (Jessen & Silva, 2008). The main tributaries at this part of the river are Revuboe, Luenha , Luia and Chire. Moatize is part of lower Zambezi meaning that this work will be focus on this part of river basin. The precipitation for different zones in Zambezi river basin ranges from 500 mm in the south west to 2000 mm in the north east. It is presented in figure 6 below.

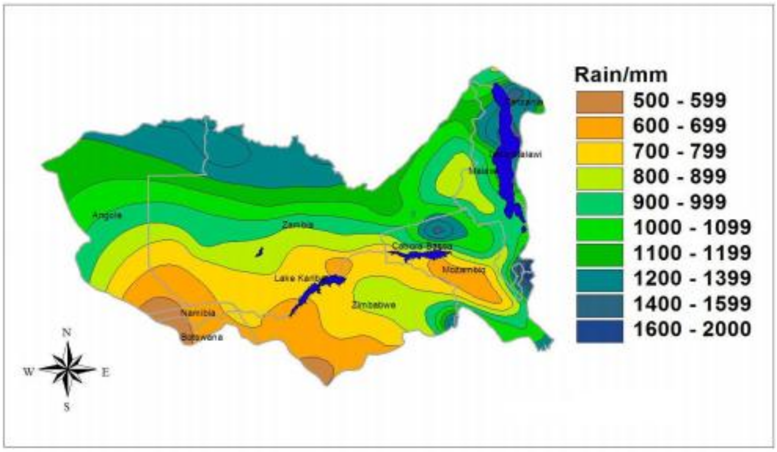

Figure 6: Average annual precipitation in Zambezi river basin (Southern Waters, 2011).

2.4 Water quality in lower Zambezi (Tete)

The institution responsible for management of water resource in Zambezi river basin in Mozambique is ARA-Zambezi (Administração Regional de Águas). ARA Zambezi means regional water administration and this institution belongs to government of Mozambique. ARA-Zambezi has been making analysis of water along Zambezi river basin in Mozambique but with some limitation. There are no measurements of chemicals water parameters due to lack of resources. Table 3 shows water quality of rivers in Moatize area before mining activities started.

Table 3: Water quality of some rivers passing through Moatize (Vale Moçambique, 2010).

Parameters	Units	Zambezi (Tete)	Revuboe	Muarazi	Nharenga	Nhacomba
Fe^{3+}	mg/l	0.001	0.137	0.031	0.026	0.002
Al^{3+}	mg/l	0.02	0.080	0.105	0.015	0.009
Mn^{2+}	mg/l	0.001	0.0015	0.002	0.001	0.01
pH	------	7.87	7.5	7.51	7.5	7.7
Total Alkalinity	mg/l as $CaCO_3$	62	82.00	206	150	60
TDS	mg/l	92.5	68.10	459.5	234	106
Dissolved oxygen	mg/l O_2	5.20	4.08	2.92	4.33	6.14
SO_4^{2-}	mg/l	4.7	1.45	26	17.6	3.2

Moatize river is located inside the concession area of Vale mining company and it can be diverted to avoid water going to pits (Golder Associates Africa, 2010). This river is characterized by low water quality due to anthropogenic reasons, geological situation and low water availability. The table 4 below represents the water quality in 4 (M1,M2,M3 and M4) different points of Moatize river. The samples were taken in 2005 between September and December which is a rainy season (Vale Moçambique, 2010). Point M3 represents samples taken downstream and M1,M2 and M4 are points located along the river. The alkalinity, TDS and sulfate concentration are high downstream of the river (point M3).

Table 4: Water quality in Moatize river at 4 different points (Vale Moçambique, 2010).

Parameters	Units	M1	M2	M3	M4
Fe^{3+}	mg/l	0.03	0.371	0.001	0.03
Al^{3+}	mg/l	0.115	0.095	0.030	0.31
Mn^{2+}	mg/l	0.001	0.003	0.003	0.001
pH	------	7.72	7.24	8.00	7.73
Total Alkalinity	mg/l as $CaCO_3$	222	250	370	70
TDS	mg/l	74.5	93	1173	121
Dissolved oxygen	mg/l O_2	3.71	3.73	6.19	5.26
SO_4^{2-}	mg/l	6.3	137.8	837.5	26

2.5 Description of relevant water parameters for characterization of AMD

In coal mining industry it is possible to find three types of pollutants: physical, chemical and biological contaminants. It is important to notice that biological pollutants which are referred here are from domestic wastewater from the offices and buildings in the mining company and it must be connected to the municipal sewer (Dharmappa, et al., 2002). Table 5 below shows this classification (Dharmappa, et al., 2002)

Table 5: Typical pollutants and parameter from coal mining wastewater (Dharmappa, et al., 2002).

Physical	Chemical		Biological
	Organics	**Inorganic**	
Suspended solids	Coal	Heavy metals	Bacteria
pH	pH	pH	
Turbidity	Grease and oils	Acids	Viruses
Color	Soaps and detergents	Alkalis	Protozoes and invertebrates
Temperature	Rubber	Cyanide	
Taste	Dyes	Anions: PO^{-}_{4},SO^{2-}_{4},HCO^{-}_{3}, Cl^{-},NO^{-}_{3}, etc	
Odor	Phenolic compounds	Cations: Mn,Fe, Ca,K,Na,Mg, etc	

Not all parameters presented in table 5 will be discussed, only those relevant for AMD.

pH

pH is an indication of molar concentration in solution of hydrogen ions. It is defined using equation 6 (Dharmappa, et al., 2002):

$$pH = -\log_{10}^{[H^*]} \qquad (6)$$

Solubility of metals in water depends quite a lot on pH values, for example low pH values results in solubility of species in water but high pH values results in precipitation of metals oxides in water (Dharmappa, et al., 2002).

Temperature

When it comes to biochemical activities, temperature is a very important indicator. A rise of $10^{o}C$ in temperature results in duplication of biochemical activity between the range of $5^{o}C$ to $30^{o}C$ (Dharmappa, et al., 2002). There are very few mining companies which add heat to their effluent meaning that thermal pollution is not a problem for coal mining in Moatize (Dharmappa, et al., 2002).

Suspended solids (SS)

For receiving waters the parameter that from a visible manner gives an indication of pollution is concentration of solids in suspended form. Fractions of un-dissolved substances that can be retained in a fiber filter paper with pore size of 0.45µm are called suspended solids (Dharmappa, et al., 2002). The general limit could be 30 mg/l for coal mining but it is important to know that this value can change from country to country (Dharmappa, et al., 2002).

Total dissolved solids (TDS)

Total dissolved solids represent the total amount of solids that are dissolved in water sample. There is a parameter which is related with TDS called electrical conductivity (EC) (Dharmappa, et al., 2002). EC represents the ability of a solution to carry electrical current and one of the characteristics of coal mining effluent is the high level of mineralization (Dharmappa, et al., 2002). EC is very easy to measure using an instrument and it can in average be related with TDS using equation 7 according to Department of Resource and Energy from Australia (Dharmappa, et al., 2002):

$$TDS = 0.62 * EC \quad (7)$$

Where: TDS is in mg/l and EC is in µS/cm

The typical values of EC can be seen in table 6 below. As shown in this table, the EC for mining water is high due to high amount of dissolved salts.

Table 6: Typical values of EC for different source of water (Dharmappa, et al., 2002).

Water source	EC (µS/cm)
Sea water	35000
Mining water	1000 – 10000
River	200 – 800
Tap water	60 – 100
Distilled water	0.5 – 2

Alkalinity

The amount of negative ions that can react in water to neutralize ions of hydrogen is called alkalinity. It is also known as the ability of water to neutralize acids and the main elements are HCO_3^- (bicarbonate) ,CO_3^{2-} (carbonate) and OH^- (hydroxide ion) (Dharmappa, et al., 2002). For mining waters if alkalinity is high it means that there is a possibility to avoid acid waters (low pH) caused by biochemical reaction of sulfur compounds with water (Dharmappa, et al., 2002).

Acidity

In mine water acidity results from dissolution of sulfuric acid or carbon dioxide in water and as result, pH drops and metals will dissociates in solution. It is important to emphasize that before discharging mining wastewater pH must be adjusted (Dharmappa, et al., 2002).

Sulfates

There is sulfate in natural water due to interaction between water and mineral deposits such as gypsum. Pyrites can oxidize biologically forming dissolved sulfates and thus increasing the concentration of sulfates (Dharmappa, et al., 2002). High concentration of sulfates in water has an unpleasant taste and it has laxative effect on consumers.

Metals

Non toxic metals such as Mg, Fe, Mn , Ca, Na ,K can be found in coal mining in different concentrations (Dharmappa, et al., 2002). The hardness of water is added due to the presence of Mg and Ca but discoloration of water is cause by presence of Fe and Mn (Dharmappa, et al., 2002).

Toxic metals such as Al, Zn, and Ba can also be found in coal mining waters but in small concentrations (Dharmappa, et al., 2002). If discharge from mining water are not controlled it can has significant impact on the environment due to the presence of heavy metals (Dharmappa, et al., 2002). As said before, pH is a key issue when it comes to solubility of metals. For alkaline conditions there is a tendency of metals to form compounds with carbonates and hydroxides which precipitates out (Dharmappa, et al., 2002). But for acid conditions metal compounds that are soluble in water are formed.

3. Legislation

The constitution of Republic of Mozambique establishes the right of living in equilibrated environment and also the right to protect it (JSPL Mozambique Minerals, LDA, 2011). The government and local authorities are responsible to adopt politics for environmental protection and reasonable use of natural resource.

3.1 General aspects of environmental legislation

The Ministry for Coordination of Environmental Action (MICOA) is responsible to guarantee conservation and sustainable use of natural resource, coordination of environmental activities and emission of environmental license (JSPL Mozambique Minerals, LDA, 2011).

Before the emission of an environmental license in Mozambique the environmental law establishes that preventive requirements must be fulfilled.

The permissible levels of pollution were established by the government through the environmental law. The regulation of environmental quality was approved on June 2004 and it regulates the quality of water, air, effluent emission and soil for industriy (Assembleia da República de Moçambique, 2004).

The environmental law foresees creation of environmental protection areas to ensure the protection and preservation of natural resource as well as maintaining the improvement of ecosystem with ecological and socio-economic value (JSPL Mozambique Minerals, LDA, 2011).

3.2 Environmental management of mining activities in Mozambique (included in mining law)

The objective of this management is to ensure that the right of use and exploitation of minerals must be done in harmony with the best and safety mining practices observing the environmental quality patterns established by the environmental law (Assembleia da República de Moçambique, 2002).

The main instruments of the environmental management under the application of mining law are: environmental impact assessment; environmental management program; environmental management plan; environmental monitoring program; mine closure program; environmental audit; control program risk and emergence situation (Assembleia da República de Moçambique, 2002).

3.3 Water law

The water law stipulates that activities which directly or indirectly lead to water contamination, accumulation of solid waste or other contaminants can only be realized through especial authorization (JSPL Mozambique Minerals, LDA, 2011).

3.4 Regulation of patterns of environmental quality and effluent emission

This regulation aims to establish regulation of patterns of environmental quality and effluent emission in order to control and maintain the permissible level of concentration of pollutants in the environment (Assembleia da República de Moçambique, 2004). These regulations are applied for all public and private activities that can pollute the environment directly or indirectly. Compete to MICOA to monitor compliance of the provisions contained in this regulation (Assembleia da República de Moçambique, 2004). Table 7 below shows the admissible limits for wastewater in coal mining for Mozambique according to the law.

Table 7: Admissible limits of wastewater discharge for coal mining industry in Mozambique.

Parameter	Value
pH	6-9
Total suspended solids	35-50 mg/l
Oil and fat	10 mg/l
Mercury	3.5 mg/l

The parameters for wastewater discharge are not complete, for istance; there is no information for sulfate, metals and cyanates. This is limitation of this law and it means that the mining componies will not be controlled when it comes to parameters that are not specified by the law. According to environmental assessment studies from Vale Moçambique and Rio Tinto they will use South African laws to overcome this situation. Information from table 8 could be added in the Mozambican legislation (table 7) in order to avoid emission of AMD from coal mine. Data from table 8 were established by environmental protection agency (EPA) of the United States of America.

Table 8: Effluent limitation for coal mine wastewater (Ford, 2003).

Parameter	**Total metal concentration (average daily values for 30 days)**
Fe	3.5 mg/l
Mn	2.0 mg/l
pH	6-9

4. Coal extraction and their environmental impact in Moatize

Coal extraction can be done using underground mining or surface mining. There are two type of surface mining which are very popular in surface coal mining: strip mining and open pit mining. This work will concentrate in open pit because this is the method used by Vale Mozambique and Rio Tinto in Moatize.

4.1 Open pit mining

Open pit mining is performed making excavation from surface to have access of the ore and this is the most applied method for large scale operation (Water affairs and Forestry, 2008). Ore benches are blasted, drilled and loaded in trucks which take coal to the surface. The pit is not filled again with soil which means that a huge pit will be in the mined area at the end of coal exploitation (Water affairs and Forestry, 2008)

Normally open pit mining is applied for coal deposits that are relatively deep and it results in a pit that is below the groundwater table, meaning that groundwater must be pumped out of the pit to allow mining to take place (Water affairs and Forestry, 2008). When mining is over, pumps are switched off and a pit lake will be formed (Water affairs and Forestry, 2008).

In figure 7 below it is possible to see typical open pit coal mining in activity and when it is not any longer in activity. During mining activities sulfide minerals are exposed to oxygen and water creating condition for AMD generation. Precipitation and groundwater tend to fill the pit but to allow mining activities going on, water is pumped out from the pit to the surface. When the mine is closed, pumps are switched of and the pit will be full of water, contributing for generation of AMD.

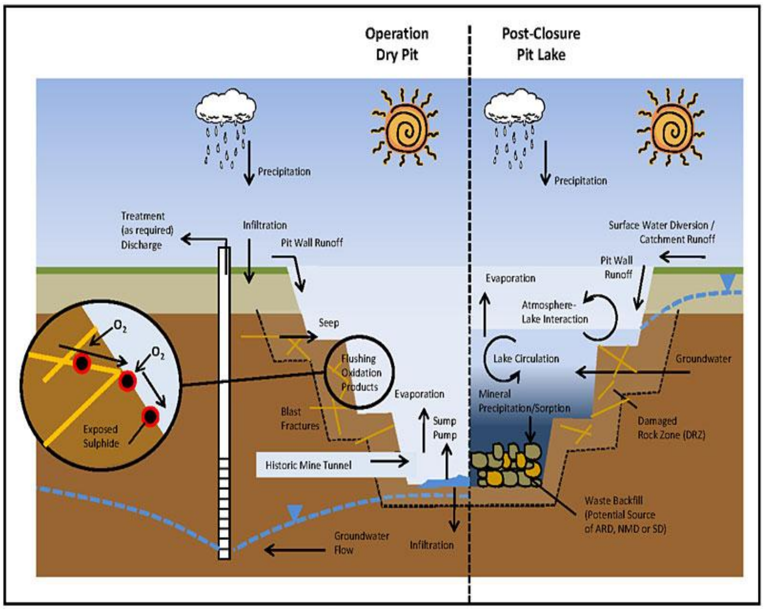

Figure 7: Open pit mining during operation and after post closure (INAP, 2013).

4.2 Coal process at Rio Tinto mining

The simplified flow diagram of coal production at Rio Tinto mining company in Benga (Moatize) can be seen in the figure 8 below. Coal is extracted from mining and transported in conveyors to a crushing, after that it is washed in a washing station and after that, different types of coal are piled up and tailings are deposited in tanks. There are two types of coal that are produced at Benga: cooking coal and thermal coal (Riversdale Moçambique Limitada, 2009). During coal processing different types of liquid and solid waste are generated and they are potential source of AMD.

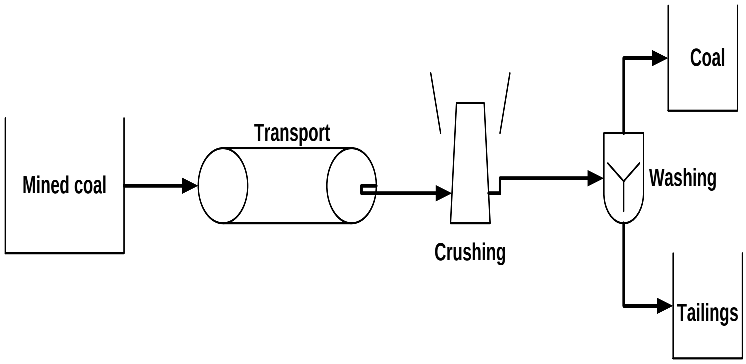

Figure 8: Coal production simplified diagram of Rio Tinto (Riversdale Moçambique Limitada, 2009).

4.2.1 Waste management during mining activities at Rio Tinto

Waste resulting from different activities in coal mining must be managed in a proper manner in order to reduce risk of water pollution. During mining activities at Rio Tinto mining company in Benga, different types of waste will be produced as shown in figure 9 (Riversdale Moçambique Limitada, 2009). There are two landfills available inside the mining company, one at the 25 m depth and other 90 m. Other waste landfill will be available inside the excavated area when it has enough depth (Riversdale Moçambique Limitada, 2009). The overburden which is waste covering the coal seam will be deposited in these landfill. The coarse waste resulting from coal washing will be dumped in waste landfill for overburden and also in the mined area (Riversdale Moçambique Limitada, 2009). The fine waste which is also coming from coal washing process will be deposited in tanks for fine waste and liquids during the first 5 years and after that, it will be dumped in landfills and in the excavated area (Riversdale Moçambique Limitada, 2009). Domestic waste will be dumped in a specific landfill for this type of waste. Hazardous waste such as used oils will be treated according to the Mozambican regulation (Riversdale Moçambique Limitada, 2009).

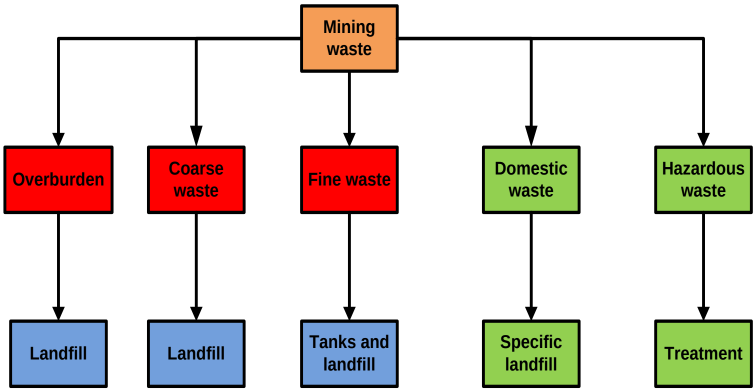

Figure 9: Waste management at Rio Tinto in Benga (Riversdale Moçambique Limitada, 2009).

4.2.2 Water management at Rio Tinto mining

Water pollution during mining operation phase and even for closed operation phase is one of major issues when it comes to water resource contamination. Precaution to avoid water pollution such as acid mine drainage have be done during the conception of Rio Tinto mining project in Benga and the following measures have been taken to avoid AMD (Riversdale Moçambique Limitada, 2009):

- A flood protection wall (berm) 5 m high and made by compacted earth was built to protect the open mining area from flood which can come from Revuboe tributary;

- Ditches for storm water runoff control were built around the landfills and around mining installation to deviate clean storm water from places where mining activities are going on;

- Basins to control pollution were built: polluted runoff and dirty rain water will be deposited in these basins and this water will be recycled and used for dust control;

- Drainage channel and water pumps will be introduced inside the pits to collect mining water and transport it to a basin located at the surface;

- Treatment of different waste: waste containing coal will not be mixed with other types of waste;

- Domestic wastewater treatment plant for mining employees will be built;

- Protective plastic thick coating will (plastic liner) be putted below the waste pile in order to avoid contaminated water that will come from waste seepage to drain to subsoil and groundwater;

- Industrial wastewater treatment plant will be built to treat contaminated water such as water coming from mining operations till reaches the limits established by the law.

4.2.3 Impact on Water resource

The great threat for water pollution in coal mining is acid mining drainage. For the case of Benga coal mining which belongs to Rio Tinto the potential source of AMD are: accumulation of mine water in the excavated areas; dirty places around units of treatments and process of coal;

landfills for deposition of overburden and coarse waste; basin for deposition of fine liquid waste; treated effluents from domestic wastewater.

In case of intensive precipitation, there is a risk of fill the excavated pits polluting rivers downstream. In the first 2 km the excavation will reach 200 m below the sea level and for deeper section it will reach 400 m of depth (Riversdale Moçambique Limitada, 2009). Water will be extracted from the pits by pumps to the surface and then it will be collected in basins to reduce dust in the mining. The rivers that can be affected are Zambezi and Reuben and creeks of Nhacomba and Nharenga (Riversdale Moçambique Limitada, 2009).

4.3 Coal process in Vale Mozambique mining in Moatize

The Vale concession (867 C) in Moatize is located 20 Km north-east of Tete city. The company was projected to last 35 year and to produce 26 Mt/a of ROM (run of mine) and after processing it will end up with 2 Mt/a of thermal coal with 27.2 MJ/Kg and 8.5 Mt/a of cooking coal with 10.5% of ash (Golder Associates Africa, 2010). The vale concession is between Muarazi and Rovuboe rivers as shown in figure 10 and they drain south-west directly to Zambezi River (Golder Associates Africa, 2010). Moatize river is the main tributary of Rovuboe and it is seasonal river with no flow in dry season (Golder Associates Africa, 2010). Rovuboe has low flow during dry season and it is perennial river (Golder Associates Africa, 2010). The Moatize-Minjova coal basin is 20 km long and 7 km wide and it is characterized by normal faults (Golder Associates Africa, 2010). Due to faults 6 mining coal field sections were created as shown in figure 10 (Golder Associates Africa, 2010). The smallest mining section is 1 and it has Moatize River passing through it. In the past some mining activities were done in this section in lower Chipanga coal seam (Golder Associates Africa, 2010). The section 2a has low elevation and flat area and no previous work were done in this section (Golder Associates Africa, 2010). Section 3 is relatively flat with low elevation. Section 4 is located in the southern part of Moatize village (Golder Associates Africa, 2010). Section 5 is characterized by presence of faults and dykes and it is close to Rovubue River. Section 6 is characterized by undulation and Moatize river pass through it (Golder Associates Africa, 2010).

The method which has been used is open pit mine with trucks and shovels and the production is basically 26 Mt/a ROM feed to the plant of processing with 52Mbcm/a primary waste (Golder Associates Africa, 2010). The stripping ratio is 1.95 bcum/t ROM and the average material movement is about 71Mbcm/a which makes Moatize operation a high volume mining (Golder Associates Africa, 2010).

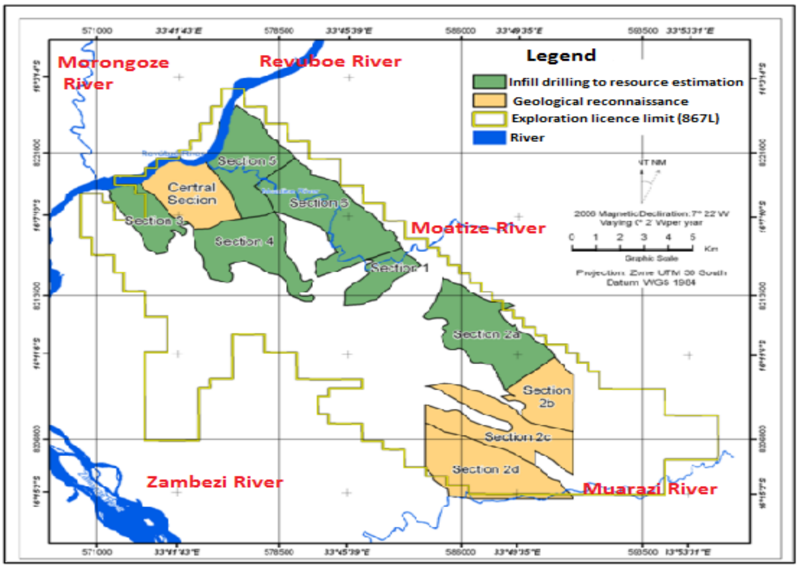

Figure 10: Mining section in Vale mining company in Moatize (Golder Associates Africa, 2010).

4.3.1 Water management

During mining activities surface and groundwater will be affected in Moatize resulting in the following impacts: interruption of surface water flow pattern, reduction of volume of surface runoff and reduction of water quality in the environment (Golder Associates Africa, 2010). The mine company has 15 days per year allocated to stop operation due to rainfall (Golder Associates Africa, 2010). The strategy for water management is the following: construction of dikes to control surface water; diversion of upstream water flow of Moatize River; water from pits will be used for coal processing; water in pits will be treated by sedimentation pond; sumps to manage rainfall runoff; the pits will be filled with waste and coarse reject from the coal plant; flow will be dispersed and slowly by using riprap pads (Golder Associates Africa, 2010). To prevent inflows to the pits in section 1; 5 and 6 Moatize River can be dewatered before mining (Golder Associates Africa, 2010). The source of AMD can be: tailings impoundment, waste rock dump, milling area, haulage roadways, and contaminated surface (INAP, 2013).

5. Treatment methods for AMD from coal mining

During mining activities generation of water with poor quality start from the beginning till the closure of the mine exploration. Treatment of mine effluent is required to meet standard limit established by law. The type of mine effluent that requires treatment are (Kuyucak, 2006): **acid mine drainage** - waste rock and tailing from coal mine can generate acid with high content of metals (Fe, Mn, Al etc.) due to presence of sulfide mineral, mainly pyrite (FeS_2) and pyrrhotite (FeS) which can react with oxygen and water producing acid water if enough buffer mineral such as calcite ($CaCO_3$) or alkali are not present to neutralize the generated acid water; **mine dewatering -** during coal extraction explosives made by different materials such as nitrate and ammonia are used to blast the rock. During mine dewatering the solution that is produced may contain TSS, ammonia, nitrate, and ions of metals in significant concentration; **process water** - coal is processed using different type of chemicals (hydrochloric acid, cyanide and sulfuric acid) it means that the resulting wastewater may contain acids and cyanide; **tailing reclaim water and mineral processing -** a sulfur oxyanions which are called thiosalts (thiosulphate, sulfate, sulfide and polythionates) are produced during grinding and flotation of coal in alkaline medium. If the technology used during grinding and flotation cannot prevent generation of thiosalts then it is necessary to have an alternative treatment system for thiosalts (Kuyucak, 2006).

Pollutant present in mine effluent such as metals, acidity, NH_4^-/NO_3^-, cyanide, TSS and thiosalts can be removed by chemical, physical or biological treatment (Kuyucak, 2006). The design and selection of adequate treatment system for a certain site depends on the objective of the treatment which is defined based on water quality, costs and flow rate

(Kuyucak, 2006). The key properties of coal water mine drainage are: acidity, alkalinity, sulfate content, metal content (Fe, Al and Mn), microbe (INAP, 2013). In order to build a mine water treatment facility for coal mine it is important to know some practical mine site features that can influence construction, maintenance and operation of the facility: topography and layout, climate, space, source of pollution feeding the facility and location of users of treated water (INAP, 2013). It is necessary to think about management of sludge and brine resulting from the treatment facility (INAP, 2013).

Flow rate is one of the most critical parameters when it comes to design of treatment facility because decreasing annual flow which requires treatment it will result in reduction of capital and operating costs of the facility. A clever way to reduce the flow rate which requires treatment is by separation of clean water from contaminated water (INAP, 2013).

5.1 Treatment of AMD

5.1.1 Active treatment

Active treatment are treatment technologies which uses engineered systems and requires continuous intervention of human being for operation, maintenance, monitoring and it needs external source of energy such as electrical power (INAP, 2013).There are a lot of active treatment methods for AMD but the most common are: aeration, neutralization (including chemical precipitation), metal removal, chemical precipitation, membrane process, ion exchange and biological sulfate removal (INAP, 2013). The active treatment methods which will be discussed in this report are: aeration, neutralization and membrane process because these methods are quite used in coal mining worldwide.

Aeration

The objective of aeration is to oxidize dissolved Fe^{2+} because it is one of the principal pollutants of AMD. If water has more than 50 mg/l of Fe^{2+} it means that this water must be aerated (INAP, 2013). It is good to aerate water because aeration increases level of oxygen promoting oxidation of iron and manganese and it increase chemical treatment efficiency and reduce costs (INAP, 2013). During aeration dissolved carbon dioxide from mine water coming from underground will be released resulting in rise of pH and reagent cost reduction (INAP, 2013).

Neutralization

In order to precipitate metals AMD can be neutralized by different chemicals such as sodium and calcium hydroxide and carbonate of sodium and calcium. Neutralization and precipitation is quite used due to its feasibility to treat huge volume of contaminated water; low cost and due to its simplicity (Kuyucak, 2006). When metal hydroxide reaches their solubility limit they precipitate and this occur at certain pH (Kuyucak, 2006).

Quick lime (CaO) and hydrated lime ($Ca(OH)_2$) are quite used for neutralization of AMD due to its abundance and high reactivity (Kuyucak, 2006). During neutralization process acid water is neutralized and metals such as Fe^{2+},Fe^{3+},Al,Cu,Zn, and Pb are precipitated in the form of metal hydroxides (Kuyucak, 2006). The resulting sludge of this process is a mixture of metal hydroxide and gypsum ($CaSO_4$). Equation 8 below shows the main reaction of neutralization process using lime (Kuyucak, 2006).

$$Ca(OH)_2 + Me^{2+} / Me^{3+} + H_2SO_4 \Leftrightarrow Me(OH)_2 / Me(OH)_3 + CaSO_4 + H_2O \quad (8)$$

Sludge with $Fe^{3+}$is more stable than sludge with Fe^{2+} and that is why air is used during neutralization to oxidize Fe^{2+}

to Fe^{3+}. Clarifiers or thickener are used to settle the produced sludge and if solid content is less than 1 mg/l filters of sand can be used to polish more the treated water (Kuyucak, 2006).

The content of solids in sludge (sludge density) is strongly affected by the concentration of metals in water and the type of treatment process applied. Solid content in sludge can vary from 1 to 30% and to avoid formation of huge volumes the process is optimized by adjusting process parameters (neutralization rate, oxidation rate, ratio of Fe^{2+}/Fe^{3+},ions concentration, temperature, sludge age, crystals formation and sludge recycling) in order to get denser sludge (Kuyucak, 2006).

The current method used to treat AMD by neutralization in order to get compacted sludge compared with other liming traditional method is known as high density sludge (HDS) (Kuyucak, 2006). In this process different neutralization reactors are used and they are aerated to oxidize Fe^{2+} to Fe^{3+} and pH is controlled (Kuyucak, 2006). Treated water coming from the reactors is flocculated with a polymer and the resulting solid liquid solution is separated in a thickener of clarifier (figure 11) (Kuyucak, 2006). The sludge produced in thickener or clarifier is recycled and used with lime as neutralization agent (figure 11). The produced sludge has high solid content (10-30%) when compare with a process without sludge recirculation (Kuyucak, 2006). Sludge can be used in different manner, it can be mixed with lime before going to the process or it can be used alone to neutralize partially AMD (Kuyucak, 2006). Nowadays mining companies have a tendency to use HDS or to change existing plant to HDS in order to improve effluent and sludge quality, reduce costs and to increase the amount of water that is recovered (Kuyucak, 2006).

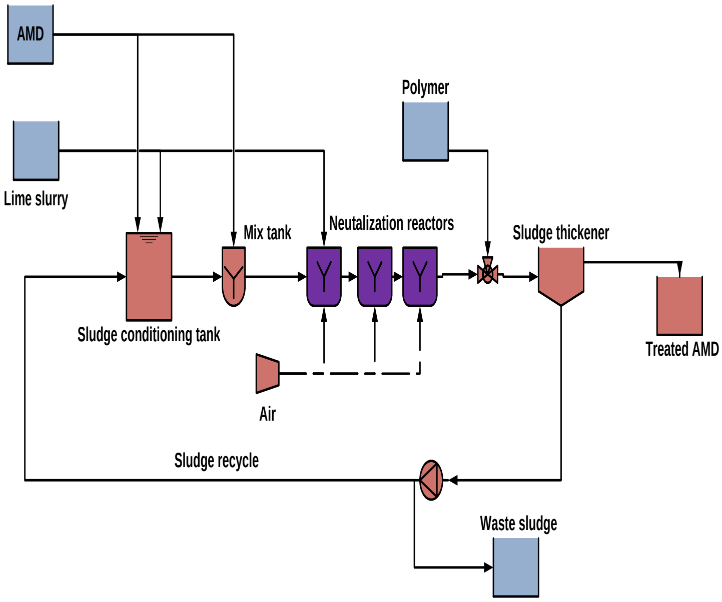

Figure 11: Configuration of basic HDS (INAP, 2013).

The configuration of HDS of shown in figure 11 is the standard process used at industrial scale for treatment of AMD using lime neutralization due to the following reasons: low cost of lime; lime is used efficiently; it requires small site for sludge disposal due to high density of waste sludge; good water/solid separation; very solid process with capacity to treat AMD with different characteristics (variable flow, metals loading and acidity) (INAP, 2013). Treatment of AMD using neutralization with configuration of HDS process is the most used technology and innovation of the original process has been developed and used worldwide (INAP, 2013).

Limestone has been used for so many years in coal mine industries to treat AMD because it is the cheapest material available to treat AMD, it´s easy to handle and is the safest chemicals to treat AMD (INAP, 2013). For coal mine the contaminant of concern is iron or aluminum and limestone is very effective for this situation (INAP, 2013). The application of limestone is limited because it has low solubility and it has tendency to form external coating of $Fe(OH)_3$ during treatment of AMD (INAP, 2013).

HDS can be achieved by using limestone to neutralize AMD instead of lime under certain conditions (Kuyucak, 2006). Limestone react with acid water dissociating and releasing carbon dioxide as shown in equation 9 and 10 below (Kuyucak, 2006):

$$CaCO_{3(S)} + H_2SO_{4(aq)} \Leftrightarrow CaSO_{4(S)} + H_2O + CO_{2(g)} \quad (9)$$

$$CaCO_{3(S)} + Fe_2(SO_4)_{3(aq)} + 3H_2O \Leftrightarrow 3CaSO_{4(S)} + 2Fe(OH)_{3(S)} + 3CO_{2(g)} \quad (10)$$

The carbon dioxide that is released forms carbonate ions and the formed carbonate ions buffer the pH to an upper limit of 6.5 and as consequence of this, removal of some metals cannot be possible because it requires pH greater than 6.5. To overcome this situation a combination of limestone and lime can be used as shown in figure 12 below:

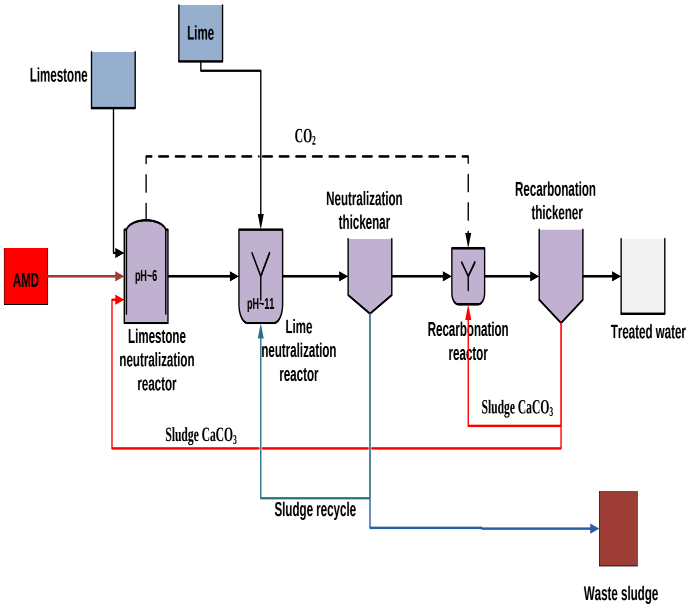

Figure 12: AMD treatment plant using combination of limestone and lime (INAP, 2013).

This process has three different steps which are: pre-neutralization with limestone which is little bit cheap, the second step is neutralization with lime in order to reach a certain pH which is determined by the specific metal to be removed and the last step is adjustment of pH and re-carbonation which is done using carbon dioxide produced in the limestone neutralization reactor (INAP, 2013).

When it comes to selection of appropriate neutralization agent for a specific water treatment from mining the following key parameters must be take into account: type of material to handle (including transportation, storability and dosing); knowledge about the hazardous material; reliability and availability of suppliers; efficiency of neutralization; process consequence like coating, clogging and scaling of the equipment and cost (INAP, 2013). The key aspect of treatment of AMD is neutralization and hydrolysis and different types of alkali and processes are employed. Table 9 below shows different types of alkali and materials to treat AMD (INAP, 2013).

Table 9: Materials and alkali applied for AMD treatment (INAP, 2013)

Neutralization agent (Alkali)	Necessity (ton of alkali/ton of acidity)*	Efficiency of neutralization (% of applied alkali)	Cost (USD/tones bulk)**
Limestone ($CaCO_3$)	1	30 - 50	10 -15
Hydrated lime ($Ca(OH)_2$)	0.74	90	60 -100
Un hydrated lime (CaO)	0.56	90	80 - 240
Soda Ash (Na_2CO_3)	1.06	60 - 80	200 - 350
Caustic Soda (NaOH)	0.8	100	650 - 900
Magna lime (MgO)	0.4	90	Project specific
Fly ash	Material specific	-	Project specific
Kiln dust	Material specific	-	Project specific
Slag	Material specific	-	Project specific

*acidity is expressed as $CaCO_3$; **market prices of January 2009

To select necessary alkali to treat a certain AMD it is necessary to think about collateral damage of the produced residue, cost of alkali and the objective of treatment (removal of metals) (INAP, 2013). The table 9 can be used to determine amount of alkali necessary to neutralize a certain amount of acid and to estimate alkali cost to perfome the task. If for example it was necessary to neutralize 200 ton of acid it would be necessary 164 ton of hydrated lime (200*0.74/0.90=164 ton) (INAP, 2013). Figure 13 and table 9 can help to design a site specific neutralization system for Moatize, but AMD flow rate and water chemistry are necessary to design the required treatment system. To select appropriate neutralization agent it is important to known the concentration of iron and manganese and the flow rate (figure 13). Manganese is very soluble at pH 4.5 to 8 and it makes removal of manganese difficult. The best way to remove Mn is by raising pH to values above 9 in order to oxidize Mn^{2+} to Mn^{3+} or Mn^{4+} and thus the insoluble Mn carbonate or Mn oxide can be removed (Trumm, 2010).

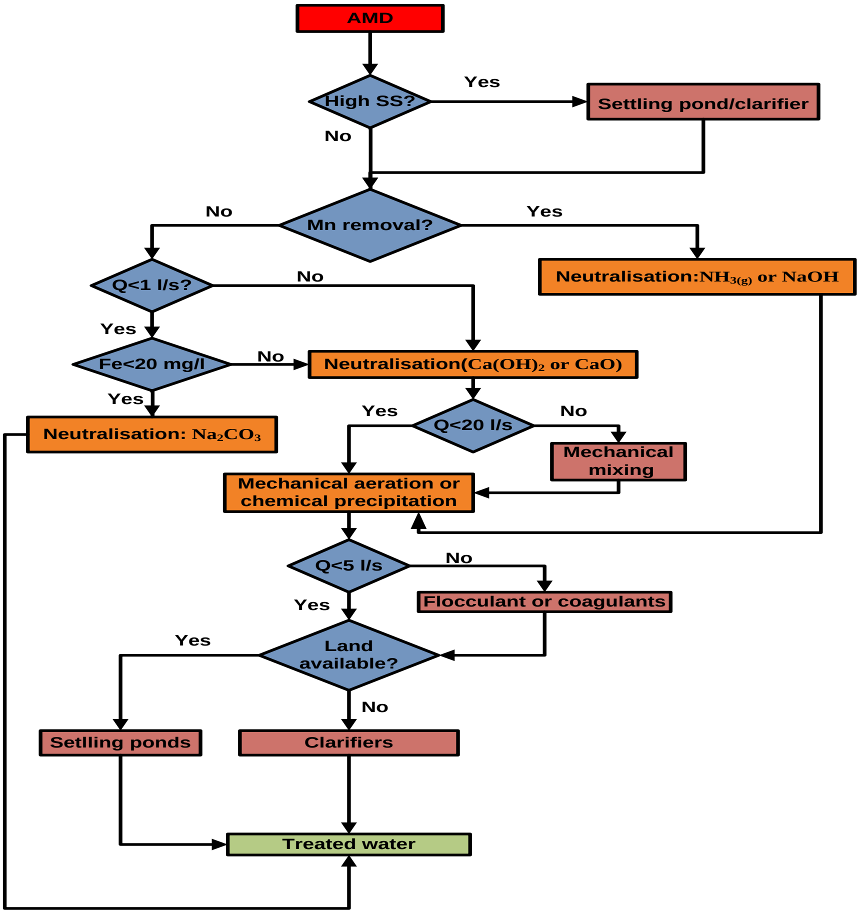

Figure 13: Diagram to design site specific AMD treatment system (Trumm, 2010).

Membrane process

Membrane process can be used to treat saline and brackish AMD and there are too many membrane technologies used in mine industry (INAP, 2013). The challenge of using membrane technologies has becoming greater due to problem of fouling and scaling caused by metals, sulfates and carbonates present in AMD (INAP, 2013). A byproduct of membrane process is brine and sludge but mine industries using membrane technology have developed membrane desalination technology with high recovery capacity. Figure 14 shows a membrane desalination technology with high recovery capacity to treat AMD (INAP, 2013). To limit membrane scaling first a pre-treatment with lime is done to remove metal and gypsum that has been supersaturated; the next step is a pre-treatment to remove suspended solids that has left using micro or ultra filtration; next step is a pre-treatment to adjust pH to a regime that there is no scaling and addition of anti-scaling product; then a membrane treatment happens in a reverse osmosis or nano filtration device; and finally a post treatment for byproducts is done using different techniques (INAP, 2013). For mine water about 60 to 70% of clean water recover can be achieved if a single pass membrane treatment is used. To decrease brine handling, brine streams needs to be treated and figure 14 shows some techniques to treat brine streams such as evaporation or crystallization (INAP, 2013).

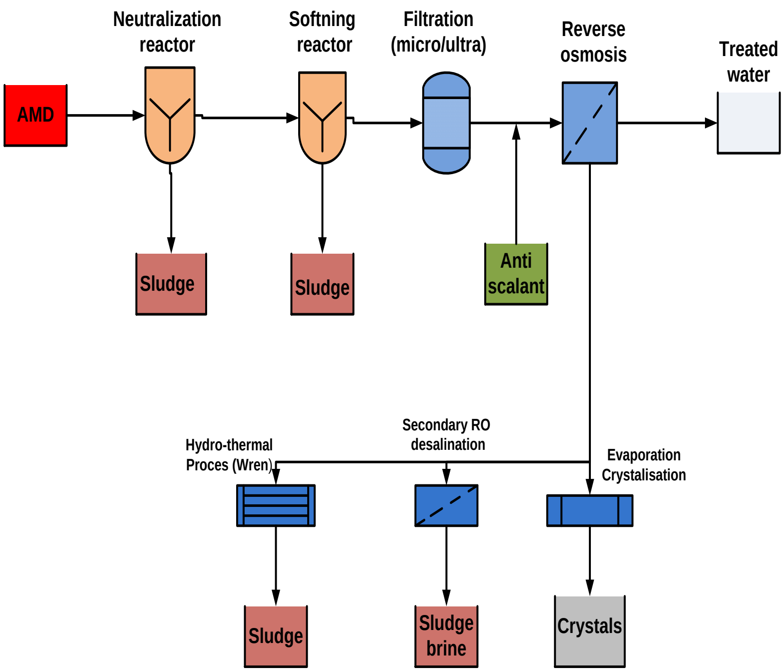

Figure 14. Membrane treatment plant for AMD (INAP, 2013).

5.1.2 Passive treatment

Passive treatment is known as process that doesn't need regular human intervention (operation and maintenance). It is made by natural material such as clay, soil and broken rock, plants, manure and wood (INAP, 2013).

"Passive treatment is a process of sequentially removing metals or/and acidity in a natural-looking, man-made bio-system that capitalizes on ecological and geochemical reactions" (INAP, 2013). The great advantage of this process is that it can last for many years with limited human intervention and once constructed it doesn't need chemical or electrical power to work (INAP, 2013). There are different types of passive treatment but the most known are:

aerobic wetlands, anaerobic wetlands, anoxic limestone drains, open limestone drains and reducing and producing alkalinity system (INAP, 2013).

When it comes to design of passive treatment system for AMD the critical parameters are the flow, water quality characteristics of AMD and land availability (Zipper, et al., 2011).

Aerobic wetlands

The simplest type of passive treatment is the aerobic wetland but it cannot treat efficiently certain type of water (Zipper, et al., 2011). It is used to treat net alkaline water which has high content of iron and the capacity to neutralize acidity is limited (Zipper, et al., 2011). Mine water is aerated while it is flowing slowly through vegetation and dissolved iron is oxidized and the oxidation product will precipitate (Zipper, et al., 2011). As result of precipitation of iron the pH will drop due to generation of H^+ ions and effluent water can have pH lower than influent water even if the iron concentration is higher (Zipper, et al., 2011). Aerobic wetlands can also remove Mn but oxidation of Mn starts when oxidation of Fe is completed (Zipper, et al., 2011). To remove Mn using aerobic wetlands it is necessary to have big area to allow completely Fe oxidation and beginning of Mn oxidation or it can be done by adding another wetland cell (Zipper, et al., 2011). Figure 15 shows a typical aerobic wetland were aquatic plants (cattails) transport oxygen through the roots to the subsurface to help oxidation process (Zipper, et al., 2011). Composted organic matter or natural soil can be used as substrate and water level between 10 to 30 cm are used to maintain aerobic condition and to allow cattails to growth in order to help in wetland performance (Zipper, et al., 2011).

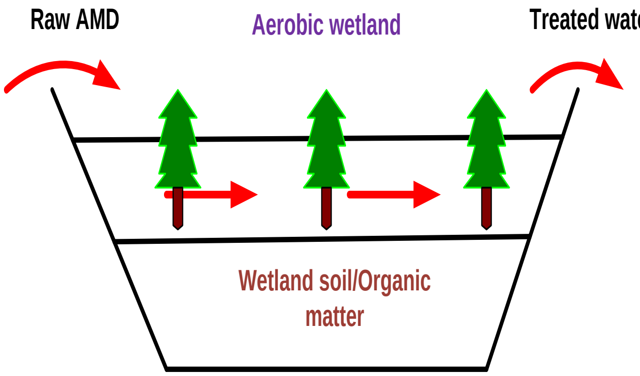

Figure 15: Cross section of a simplified aerobic wetland (Zipper, et al., 2011).

Anaerobic wetland

Anaerobic wetland is a modification of aerobic wetland where bed of limestone and a layer of biodegradable organic matter are added in order to allow treatment of acid water (Zipper, et al., 2011). The limestone bed is added bellow the substrate or it can be mixed together and added in order to enhance alkalinity generation as HCO_3^- (Zipper, et al., 2011). Under anoxic condition (low oxygen) sulfate can be reduced in presence of biodegradable organic matter, and this process evolves microbes (Zipper, et al., 2011). Sulfate reducing bacteria use oxygen present in SO_4^{2-} that enters to the system under anoxic condition to reduce it to H_2S gas or to solid sulfide by biodegradation of organic matter in a metabolic process (Zipper, et al., 2011). Equation 11 below show a common situation of this process:

$$SO_4^{2-} + 2CH_2O \Rightarrow H_2S + 2HCO_3^- \qquad (11)$$

If metals (M) are present in the solution the reductions process leads to sulfide metal product as shown in equation

12 below and metal sulfides are deposited in substrate (Zipper, et al., 2011).

$$M + SO_4^{2-} + CH_2O \Rightarrow MS + HCO_3^- \quad (12)$$

Alkalinity can also be generated by reaction between acid water with limestone present below the substrate as shown in equation 13 below (Zipper, et al., 2011).

$$CaCO_3 + H^+ \Rightarrow Ca^{2+} + HCO_3^- \quad (13)$$

The three equations shows the production of bicarbonate ions which are source of alkalinity and they can raise pH by neutralization of H^+ (equation 14) and thus contributing for precipitation of soluble metals present in acid water (Zipper, et al., 2011).

$$HCO_3^- + H^+ \Rightarrow H_2O + CO_2(aq) \quad (14)$$

Anaerobic processes are also knew as composted wetland due to production of alkalinity by substrate (Zipper, et al., 2011). The circular arrows shown in figure16 represent diffusion of water in substrate during alkalinity generation in anaerobic wetland.

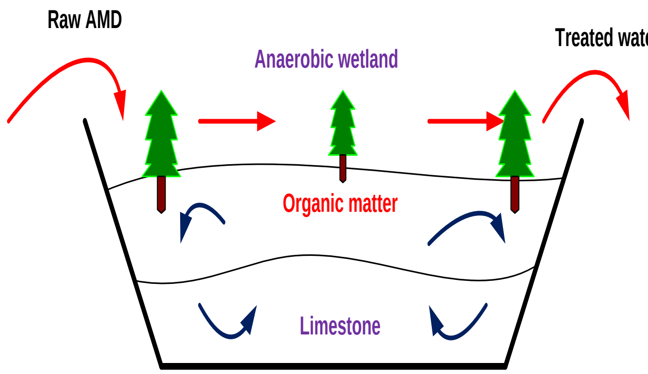

Figure 16: cross section of anaerobic wetland (Zipper, et al., 2011).

Anoxic limestone drain

Anoxic limestone drains (ALD) (figure 16) are used to treat AMD by dissolution of limestone and generation of alkalinity (bicarbonate) (Zipper, et al., 2011). The contact between AMD and oxygen is avoided by capping ALD with compacted soil or clay and the effluent water goes to a settling pond where there is pH adjustment and precipitation of metals (Zipper, et al., 2011). When ALDs are working properly they are more cost-effective than wetlands but they cannot treat all AMD because if there is significant amount of Fe^{3+}, Al and O_2 in water it will clog when pH reach 4.5 or above due to precipitation of metal hydroxides (Zipper, et al., 2011). To avoid clogging the influent concentration of Al, Fe^{3+} and dissolved O_2 must all be low than 1 mg/l (Zipper, et al., 2011). One advantage of the ALD is that coating and armoring of Fe hydroxide cannot occur under anoxic condition because Fe^{2+} cannot precipitate as $Fe(OH)_2$ at pH below 6.

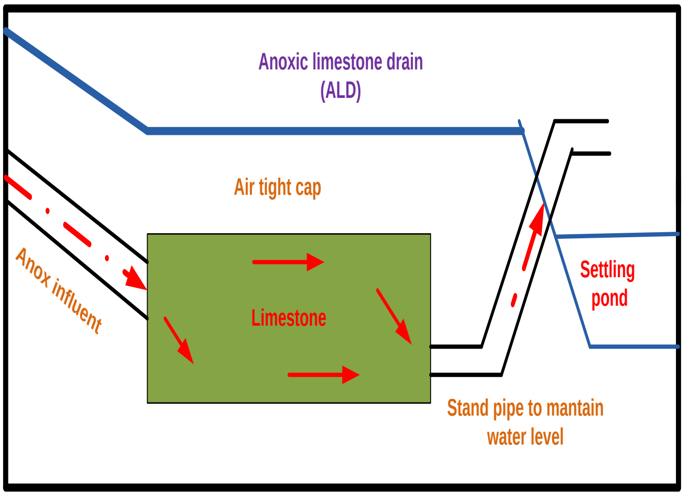

Figure 17: Cross section of ALD system (Zipper, et al., 2011).

Vertical flow system

Vertical flow system or successive alkalinity producing system (SAPS) is a combination of ALD and anaerobic wetland and the objective is to compensate the limitation of each method (Zipper, et al., 2011). As shown in figure 17 the components of this system are drainage system, layer of organic matter and layer of limestone. When AMD enter to the system it flows vertically downward where it finds organic layer to remove dissolved O_2 through aerobic bacteria which use as energy source biodegradable organic matter and sulfide bacteria generate alkalinity by reducing sulfate to sulfide (Zipper, et al., 2011). The organic matter layer must be able to reduce dissolved O_2 for less than 1 mg/l to avoid limestone armoring and to allow reduction of sulfate (Zipper, et al., 2011). The limestone layers allow dissolution of $CaCO_3$ by acid water and water in anoxic condition will produce more alkalinity. Finally water is discharged to a settling pond to neutralize acid and precipitate metals (Zipper, et al., 2011). When influent AMD has significant amount of Fe^{3+} and sediments it is necessary to make a pre-treatment in a aerobic wetland or settling pond to avoid accumulation of solids in the surface of organic layer (Zipper, et al., 2011). For the case of high acidic influent it is necessary to split the system in several vertical flows which can be separated by different settling ponds (Zipper, et al., 2011). A long term performance of this system can degrade organic layer and metal flocs (Fe^{3+},Al) can accumulate in the surface of limestone layer (Zipper, et al., 2011). To avoid this situation it is necessary to install a flushing valve in the system (Zipper, et al., 2011).

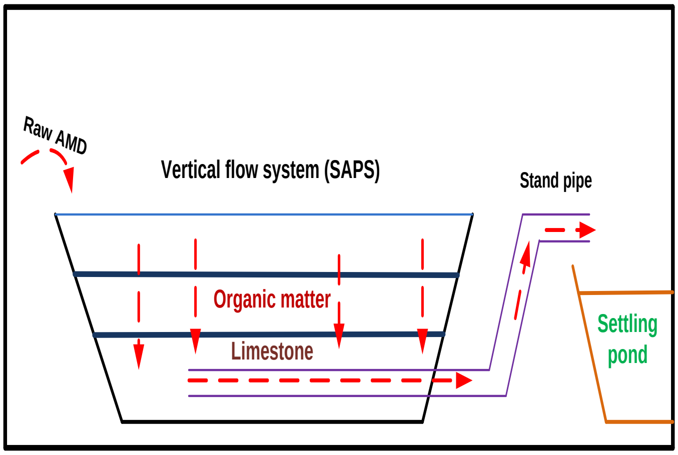

Figure 18: Cross section of a Vertical flow system (Zipper, et al., 2011).

There are many types of passive treatment methods for AMD and it is important to know how to select the appropriated treatment method. Figure 19 shows a diagram which helps during selection of passive treatment of AMD. First thing that should be done before selecting a passive treatment method is to measure flow rate and chemical composition of water. Samples should be taken from tailing seepage or mine discharge and the parameters that must be analyzed are Fe, Mn, alkalinity, pH and acidity (Hedin, et al., 1994). The composition of samples can change considerable in different seasons meaning that samples must be collected in all seasons if it is expected to operate the selected passive treatment system during different seasons (Hedin, et al., 1994). Unfortunately the Mozambican legislation doesn't have legislation concerning Fe and Mn from mining wastewater effluent and it makes design of passive methods complicated for Moatize, but to overcome this situation parameter from EPA can be used.

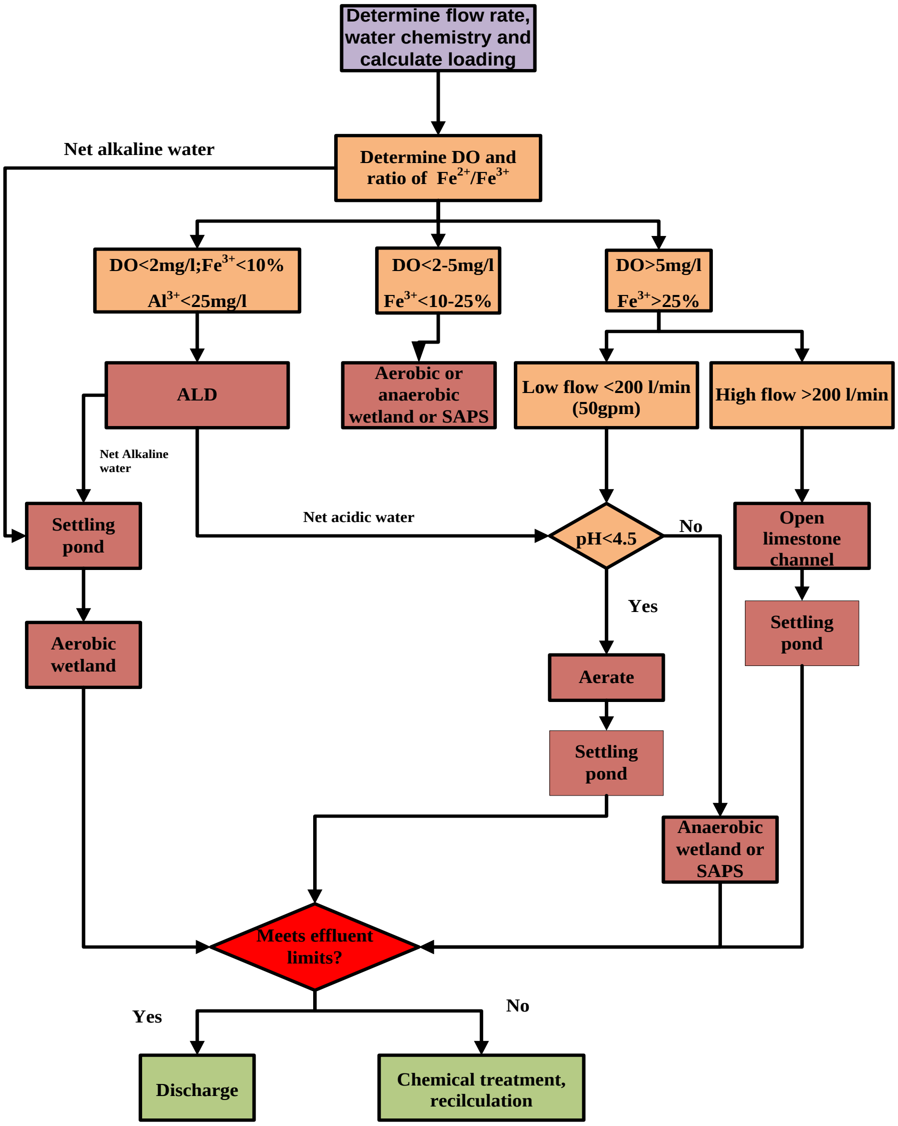

Figure 19: Flowchart for selection of passive treatment methods for AMD (Ford, 2003).

5.2 Summary of treatment methods

The summary of active treatments that were discussed in this report are presented in table 10 with advantages and disadvantages of each method. This table can be used to have a rough idea about which active treatment must be used for a certain AMD and what could be the efficiency of the selected method.

Table 10: Summary of Active treatment systems

Treatment method	Advantages	Disadvantages	Efficiency removal	Suitable to remove
Aeration	Low operation costs; release CO_2 from mine water; Increase DO.	Not effective for water with low Fe^{2+}.	80-100% Fe oxidation (Kirby, et al., 2009).	Fe^{2+} and Mn
HDS	Generation of small sludge volume; automatic systems; high water recover; low lime cost, scalling control; treatment of high AMD flow; sludge recycle.	Sludge generation, limited sulfate removal	About 99% of Fe,Al,Mn,Zn,Cu and about 85% of SO_4^{2-} (Kuyucak, et al., 1999)	Fe^{2+},Fe^{3+}, Al,Cu,Zn and Pb, SO_4^{2-}
Limestone/lime neutralization	Application of inexpensive alkali and reuse of sludge produced during the process; sludge recycle.	Sludge generation	About 99.8% of Al and Mn and about 60% of SO_4^{2-} (Geldenhuys, et al., 2003)	Fe and Al
Membrane process	High quality of treated water(drinking water quality); high water recovery.	Scaling, fouling, pre- treatment and post-treatment needed; brine and sludge production, short membrane life.	About 99% of Ca^{2+}, Mg^{2+} and SO_4^{2-} (Magdziorz & Sewerynsky, 2000).	Brackish and saline mine water.

The summary of passive treatments that were discussed in this report are presented in table 11 with advantages and disadvantages of each method. This table can be used to have a rough idea about which passive treatment must be used to treat certain AMD and what could be the efficiency of the selected method.

Table 11: Summary of Passive treatments

Treatment method	Advantages	Disadvantages	Efficiency removal	Suitable to remove
Aerobic wetlands	Low operating and maintenance costs; No power consumption; Last for many years.	Cannot treat high acidic water efficiently (best for pH>5.5).	Between 60-75% of Fe (Hedin, et al., 1994).	Acid water with Fe, Mn and SS.
Anaerobic wetlands		Coating (Al;Fe^{3+}) in limestone surface; Need large area and high retention time to remove Mn.	Between 60-75% of Fe (Hedin, et al., 1994).	Acid water with low DO, Al, Fe^{3+} and SS.
ALDs		Best for Low DO,Al and Fe^{3+} to avoid armoring Pre-treatment.	About 62% of acidity (INAP, 2013)	Acid water with low content of Al and Fe^{3+}.
Vertical flow systems (SAPS)		Metal flocs accumulation and degradation of organic layer; Pre-treatment for water with high Fe^{3+} and SS.	40-91% of acidity;60-90% of Fe;35% of Al (Demchak, et al., 2001).	Acid water with high metal content (Fe, Al, Zn, Cu).

Table 12 shows typical characteristic of AMD influent necessary to have successful treatment.

Table 12: Influent characteristic of AMD to have successful treatment (Taylor, et al., 2005).

Treatment method	Acidity range (mg $CaCO_3$/l)	Acidity load (kg $CaCO_3$/d)	Q (l/s)	DO (mg/l)	pH	Maximum pH attainable
Passive treatment						
Aerobic wetland	< 500	≤1	Maximum permissible resident time (e.g 1-5 days).	Ambient	> 6	Not available
Anaerobic wetland	< 500	1	Maximum permissible resident time (e.g 1-5 days).	Near surface is is ambient and < 1 mg/l in subsurface	> 2.5	6-8
ALD	< 500	< 150	< 20	< 1	> 2	6-8
SAPS	< 300	< 100	< 10	< 1-3	> 2.5	6-8
Active treatment						
All	1-10,000	1-50,000	No limit	------	No limit	14

5.4 Characteristic of mine water in Moatize

Mine water characteristics and flow rate are very important to design a treatment system for AMD. Unfortunately this information was not given to the author of this work by the mining companies operating in Moatize. To have an idea about what is happen in Moatize some estimation were done to determine flow rate and mine water characteristic of an old coal mine of Moatize was used. It is important to let it clear that this information is not realistic and to have real scenario of what is going on in Moatize it is necessary to have data from mining companies operating there. Mine water parameters from an old mine of Moatize are presented in table 13 and in this table there is no information about Al, Mn and flow rate.

Table 13: Mine water from Moatize (Denconsult, 1998).

Water parameter	Units	Values
TDS	mg/l	750
Alkalinity	mg/l	365
SO_4^-	mg/l	230
Fe	mg/l	4
Mn	mg/l	No data
Al	mg/l	No data
pH	---	5.9
Flow	l/s	No data

In coal mines the majority of acidity comes from dissolved iron, manganese and aluminum at low pH. These metals can react with water producing ions H^+, decreasing thus the pH. The equations 15 or 16 are quite used to estimate acidity of coal mine water.

Using the equations above the equations to determine acidity of acid drainage is following:

$$Acid_{calc} = \left[50(\frac{2}{56}Fe^{2+} + \frac{3}{56}Fe^{3+} + \frac{3}{27}Al^{3+} + \frac{2}{55}Mn^{2+} + 1000*(10^{-pH}) \right] (15)$$

All metal concentration are in mg/l and 50 is the equivalent weight of $CaCO_3$ which changes mg/l of acidity to mg/l as $CaCO_3$. This equation can be simplified to:

$$Acid_{calc} = \left[1.79Fe^{2+} + 2.68Fe^{3+} + 5.56Al^{3+} + 1.82Mn^{2+} + 50{,}000*(10^{-pH}) \right] (16)$$

To estimate acidity of Moatize mine water based on values from table 13 it was assumed that the total dissolved Fe is mainly constituted by Fe^{2+} and Al,Mn and Fe^{3+} will be set to zero due to no information.

$$Acid_{calc} = \left[1.79 * 4 + 50{,}000 * 10^{-5.9}\right] = 7.22 mg..CaCO_3 / l$$

The acidity value calculated for Moatize is very low.

To estimate flow rate from mining effluent of Vale Moçambique and Rio Tinto in Moatize it was necessary to use ratio supplied by world bank (table 14) for surface coal mine and coal production of each company.

Table 14: Parameters to estimate waste generated in open pit coal mining (World bank , 1998).

Type of waste generated	Tone of waste generated per 1000 tons of coal produced
Liquid effluents	1.2
Solid waste	10
Dust	0.06

The total coal production for Vale is 11Mt/year and for Rio Tinto is 10Mt/year (see table 1).

Assuming that the density of mine water is the same of water (1000kg/m^3) it is possible to estimate effluent mine flow rate for both companies using equation 17.

$$Q = \frac{m}{\rho} \quad (17)$$

Where: Q- is volumetric flow rate; m- is mass flow rate and ρ is the density.

The mass flow rate and the volumetric flow rate for Vale Moçambique is:

$$m = 11*10^6 \frac{ton..of..coal}{year} * 1.2 \frac{ton..of..waste}{1000..ton..of..coal} = 13200 \frac{ton..of..waste}{year}$$

$$Q = \frac{13200*10^3 \frac{kg}{year}}{1000 \frac{kg}{m^3}} = 36.20 \frac{m^3}{d} = 25 \frac{l}{\min} = 0.42 \frac{l}{s}$$

The coal production of Vale Moçambique and Rio Tinto are almost the same and it means that it can be considered that they will produce almost the same amount of mine effluent. It is important to remember that the estimated flow rate is only for process water. There is no enough information to estimate flow rate of pits from each mining company. But water from pits need treatment also.
The load acidity can be calculated by multiplying the flow rate with acidity:

$$Load..acidity = 0.42 \frac{l}{s} * 7.22 \frac{mg}{l} = 3.032 \frac{mg..CaCO_3}{s} = 0.265 \frac{kg..CaCO_3}{d}$$

The estimated acidity and load acidity are very low. Net alkalinity is the difference between alkalinity and acidity (365 -7.22=358 mg/l), it means that this water is net alkalinity because the difference is positive. If the difference was negative it would be net acidity water.

6. Discussion

The main adverse environmental impacts of coal mining activities in Moatize are generation of AMD from tailing, pits, coarse waste and overburden. The transport of sediments to the rivers is also other problem. The rivers that can be affected by Rio Tinto mining are Zambezi, Reuben and creeks of Nhacomba and Nharenga. The rivers that can be affected by Vale Moçambique are Moatize and Muarazi which are inside the mining section of this company, Zambezi, Revuboe, Nhacomba and Nharenga which are outside of mining concession area. Zambezi is a big river with very high flow (about 1595 m^3/s in Tete) and probably the impact of AMD will not affect significantly this river. Revuboe River which is one of the main tributary of Zambezi is a seasonal river with average flow rate of 85 m^3/s and Moatize River which pass through mining section of Vale Moçambique is one of its tributary. The AMD can reach Revuboe through Moatize River and can reach Zambeze River through Revuboe. Muarazi river is a tributary of Zambezi river and it pass through mining concession area of Vale Moçambique.It means that pollution from mining activities can reach Zambezi river through Muarazi. The impact of AMD in Moatize will be more severe in the tributaries because they have small flow and because they are close to the mining sections. AMD can be transported to the rivers by runoff if there is no any measure to prevent it.

If surface water and ground water will be contaminated it will affect the people of Moatize because most of household (more than 60%) use water from rivers and wells (figure 20). Only 11% of household are connected to the public network water distribution. Moatize village is located very close to the concession area of Vale Moçambique and this village can be affected due to the source of water used by the population.

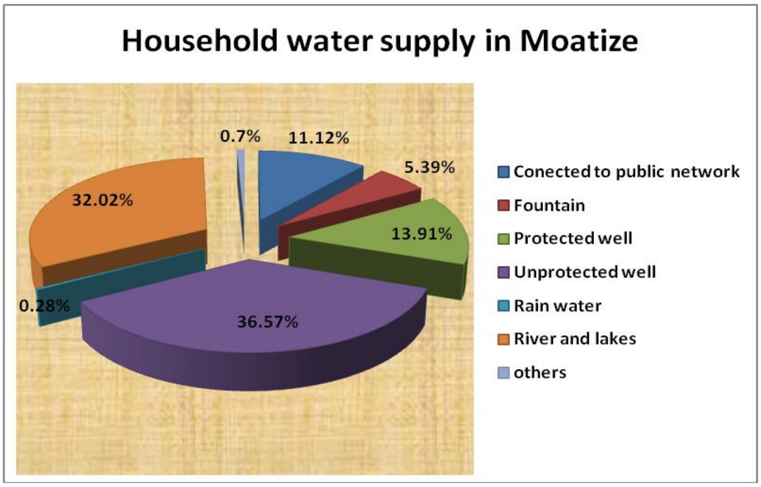

Figure 20: Water distribution in household in Moatize (INE, 2012).

As said before fishering and agriculture represents source of food for the people living in Moatize. Contamination of rivers represent a great risk for health of these people.

Some active and passive treatment methods of AMD were discussed throughout the report in order to have a general picture of what has been done in other parties of the world by other coal mining companies. Only the basics methods were described but in reality there are variations of those basic methods which are used around the world. In general the active treatments are suitable for places with no land availability and for mine in operation because they need operators to control the process. They can remove efficiently pollutants from AMD but they have high investment cost, high maintenance and operation costs. The passive treatments in general are suitable for closed mine because they need less maintenance and they operate naturally. They need big space and high retention time to operate efficiently. Most of passive method use limestone as neutralization agent. It is difficult to suggest a treatment method for coal mining companies without information about mine water quality, flow rate and description of the place (topography, land availability etc.).

Most of information about coal mining operating in Moatize presented in this report was obtained from environmental assessment reports of Vale and Rio Tinto and this information can be different from what is happening inside the mining companies now, because these reports were made before the mining companies started with operation. The information about the characteristic of mine water in Moatize presented in table 13 is from an old coal mine company which was operating in Moatize and it means that it is not true that the mine water characteristic in Moatize now is the same as presented in table 13, but due to lack of data the information from table 13 was used. The estimated flow rate for Vale and Moatize are based on ratio provided by World Bank for coal surface mining which means that it is not realistic. The estimated acidity and load acidity are not real because they were estimated based on information from table 13 and flow rate.

Based on calculation of acidity 7.22 mg$CaCO_3$/l, load acidity 0.265 kg $CaCO_3$/d and flow rate 0.42 l/s it is possible to compare with values from table 12 which gives condition of influent AMD to have a successful treatment. After comparing it can be conclude that aerobic wetland could be suitable to treat this mine water from old coal mine in Moatize. Figure 19 cannot be used now due to lack of information (e.g: dissolved oxygen).

Active treatment can also be used to treat this mine water but it is difficult to say which method can be used without data of manganese, aluminum, and dissolved oxygen. But as Mozambique is a country rich in natural resource it is possible to use limestone-lime neutralization for Moatize because Mozambique has huge reserve of limestone with high quality. The average annual production of limestone in Mozambique between 2002 and 2006 was about 1,011,000 ton/year (Selemane, Tomás, 2009). It means that the mining companies can use limestone produced in Mozambique to treat their mining water. To save transportation cost of limestone it is suggested to take limestone from Chire and Maringue deposits because they are located close to Tete province (Moatize).

Limestone in Mozambique has been produced and used in construction industries (e.g: cement industry). The limestone and dolomite limestone occurring in the southern part of Mozambique (Cheringoma and Jofane) are very pure (Cumbe, 2007). The deposits occurring in Chire and Maringue-Canxixe they are known to be pure with high quality (Cumbe, 2007). The limestone in Mozambique can be found also in Maputo (Magude, Sabie and Salamanga), Gaza (Massingir and Mpulanguene), Inhambane (Inharime, Homoíne-Morrumbene, Vilankulos and Jofane), Manica,Sofala and Inhambane (in the Save river basin), Sofala (Buzi and Cheringama), Nampula(Nacala) and Cabo Delgado (Mocimboa da praia and Pemba) (Cumbe, 2007).

7. Conclusion

Along the report different issues were described and analyzed. The objectives were established and also the problem was described. The Moatize area was described and also the two mega mining companies operating there were analyzed with some limitation due to lack of information. The impacts of coal mine in water resources in Moatize were presented. Active treatment methods such as aeration, neutralization and membrane process were discussed; also passive treatments such as aerobic and anaerobic wetlands, ALD, SAPS were analyzed.
The main conclusions that can be taken from this work are:

- Contamination from coal mine in Moatize can reach Zambezi River through its tributary Revuboe and Muarazi. Moatize river pass through mining section in Vale Moçambique and it can transport pollutants to Revuboe River. Reuben River and creeks of Nhacomba and Nharenga can also suffer because they are inside the concession area of Vale and Rio Tinto. In general impact of AMD in Zambezi River will not be significant because it has big flow rate, but in small tributaries the impact could be significant.

- More than 60% of household in Moatize use water from unprotected wells and rivers. If ground water and surface water be contaminated by AMD the quality of drinking water will also be bad and people in Moatize can suffer. People from Moatize use water from the river for agriculture and fishing which means that if water resources in Moatize be contaminated people living there will suffer to survive.

- There were not enough data to decide which treatment method can be applied for Moatize, but based on data from an old mine from Moatize presented in table 13, acidity, load acidity and flow rate were estimated and from these estimation it is possible to conclude that aerobic wetland could be used to treat mine water of this old mine in Moatize.

- Mozambique has large reserves of limestone with high quality and since there is no enough information to decide which active treatment could be used and to save cost of transport of limestone to Moatize, lime-limestone neutralization method can be used to treat AMD of coal mine in Moatize. The limestone could be taken in Chire and Maringue-Canxixe because these reserves are close to Tete province (Moatize).

- In general the advantages of active treatment are: high removal efficiency, can treat AMD with different characteristics and with high flow, they can be controlled automatically, they occupy small space, but they have high costs and they generate sludge. The advantages of passive treatment are: low costs, they last for many years and they don’t use power, but they need large areas and high retention time to operate efficiently.

- In general it is possible to conclude that active treatments are more suitable for mines that are in operations and passive treatments are suitable for closed mines.

8. Future work and recommendation

There are too many things that should be done to improve this work, but the first steps are:

- It is necessary to promote meetings with mining companies operating in Moatize to explain them the advantages of this work in order to have access to the coal mines for data collection;
- It is necessary to collect data (flow rate, mine water chemistry characteristics) to have really scenario of which treatment can be applied for each coal mine company;
- It is necessary to perform laboratory tests of rocks from Moatize to determine potential risk of AMD generation in Moatize;
- To build a mine wastewater pilot plant to test different treatment methods;
- Assessment of applicability of treatment methods for selected mine waters.

9. Bibliography

Ashton, P., Love, D., Mahachi, H. & Dirks, P., 2001. *An Overview of the Impact of Mining and Mineral Processing Operations on Water Resources and Water Quality in the Zambezi,Limpopo and Olifants Catchments in Southern Africa,* Pretoria: University of Zimbabwe.

Assembleia da República de Moçambique, 1997. *Lei do ambiente número 20/97,* Maputo: Imprensa Nacional.

Assembleia da República de Moçambique, 2002. *Lei número 14/2002: Lei de minas,* Maputo: Imprensa Nacional.

Assembleia da República de Moçambique, 2004. *Decreto número 18/2004 de 2 de Junho,* Maputo: Imprensa Nacional.

Cumbe, Â. N. F., 2007. *O património geológico de de Moçambique: Proposta de metodologia de intervenção, caracterização e avaliação,* Braga: Universidade do Minho .

Demchak, J., Morrow, T. & Skousen, J., 2001. Treatment of acid mine drainage by four vertical flow wetlands in Pennsylvania. *Clarion University.*

Denconsult, 1998. Water consumption and effluent from urban and rural area,manufacturing and services,industries and mining industry. *Zambezi river autority, SADC.*

Dharmappa, H., Sivakumar, M. & Singh, R., 2002. *Wastewater characteristics,management and reuse in mining and minerals processing industries.* Vol. I ed. s.l.:Oxford,UK.

Dharmappa, H., Wingrove, K., Sivakumar, M. & Singh, R., 1999. Wastewater and storwater minimisation in a coal mine. *Cleaner production,* p. 24.

Ford, K., 2003. Passive treatment systems for acid mine drainage. *U.S. Bureau of land management papers.*

Geldenhuys, A., J.P, M., Beer, M. & Hlabela, P., 2003. An integrated limestone/lime process for parcial sulphate removal. *The South african institute of mining and metallurgy,* p. 349.

Global, AICEP Portugal, 2010. *Moçambique Dossier de Mercado,* Maputo: Portugal Global.

Golder Associates Africa, 2010. *External audit of coal reserves for Moatize coal project,* Sandton: Golder Associates.

Hatton, W. & Fardell, A., 2011. New descoveries of coal in Mozambique-Development of the coal resource estimation methodology for International Resource Reporting Standards. *Coal Geology.*

Hedin, R. S., Narin, R. W. & Kleinmann, R. L. P., 1994. Passive treatment of coal mine drainage. *Boreau of mines.*

INAP, 2013. *The global acid rock drainage guide,* s.l.: International network for acid prevention (INAP).

INE, 2012. *Estatistica do distrito de Moatize,* Maputo: Instituto nacional de estatistica.

Jennings, S., Neuman, D. & Blicker, P., 2008. *Acid mine drainage and effect on fish health and ecology.* Review ed. Alaska: Reclamation research group.

Jessen, G. & Silva, H., 2008. Gestão hidrológica da albufeira de Cahora Bassa em períodos críticos. *Congresso Luso Moçambicano de Engenharia.*

José, D. S. & Sampaio, C. H., 2011. Estado da arte da mineiração em Moçambique: Caso carvão de Moatize, Tete. *Universidade Federal do Rio Grande do Sul-RS, Brasil.*

JSPL Mozambique Minerals, LDA, 2011. *Relatório de estudo de impacto ambiental da concessão mineira 1218L,* Maputo: s.n.

Kirby, C., Dennis, A. & Kahler, A., 2009. Aeration to degas CO2, increase pH and increase iron oxidation rates for efficient treatment of net alkiline mine drainage. *Elsivier,* Issue Applied geochestry.

Kuyucak, N., 2006. *Selecting suitable methods for treating mining effluent,* Ontario, Canada: Golder Associates.

Kuyucak, N., Lindvall, M., Serrano, J. & Oliva, A., 1999. Implementation of high density sludge "HDS"treatment process at the Boliden Apirsa mine. *International mining water association,* Issue Mine, water and environment.

Magdziorz, A. & Sewerynsky, J., 2000. The use of mambrane technique in mineralized water treatment for drinking and domestic purposes at Pakoj coal mine district under liquidation. *Central mining institute, Department of water protection.*

Riversdale Moçambique Limitada, 2009. *Título mineiro da área de Benga: Projecto de carvão de Benga,* Maputo: Riversdale.

Rosenfeld, D., 2012. *The coal mining sector in Mozambique: A simple model for predicting government revenue,* Maputo: Instituto de estudos sociais e económicos.

Selemane, Tomás, 2009. *Alguns desafios na industria extractive em Moçambique,* Maputo: Centro de integridade pública.

Silvas, F. P. C., 2010. *Biotecnologia aplicada a drenagem ácida de minas,* São Paulo: Escola Politécnica da Universidade de São Paulo.

Southern Waters , 2011. *Environmental flow assessment report (Final report). ESHIA for the Riversdale Coal barging project phase 2, Zambezi river, Mozambique,* Cape Town: ERM.

Stiftung, B., 2012. *Mozambique country report,* Maputo: BTI.

Taylor, J., Pape, S. & Murphy, N., 2005. A summary of active and passive treatment technologies for acid and metalliferous drainage (AMD). *Earth system,* Issue Environmental-water-sustainability.

Trumm, D., 2010. Selection of active and passive treatment system for AMD-flow chart for New Zealand conditions. *New Zealand journal of geology and geophysics,* pp. 53,2,195-210.

Vale Moçambique, 2010. *Estudo de impacto ambiental do complexo industrial de Moatize e sua expansão. Relatório-volume II-Caracrerizaçao da situação de referência,* Maputo: Aerecom.

Water affairs and Forestry, 2008. *Best practice guidelines A5: water manegement for surface mines,* Pretoria: Department of water affairs and forestry.

World bank , 1998. *Pollution prevention and abatement handbook-Toward cleaner production,* Washington,DC: The world bank group.

Zipper, C., Skousen, J. & Jage, C., 2011. Passive treatment of acid mine drainage. *Virginia Tech,* Issue Reclamation guidelines for surface mined land.

10. Appendixes

Table A1: Design criteria for passive treatment of AMD (INAP, 2013).

Treatment method	Design criteria	Depth (cm)
Aerobic wetland	10 g/(m^2*d) of Fe and 1 of Mn g/(m^2*d) for legal compliance. 20 g/(m^2*d) of Fe and 2 of Mn g/(m^2*d) for other propose. 36 g/(m^2*d) of acidity for other propose.	Water depth 10 – 30
Anaerobic wetland	Mixer of limestone and organic matter 50 – 100 cm 3.5 g/(m^2*d) of acidity for legal compliance. 7 g/(m^2*d) of acidity for other propose.	Water depth 10 – 30 Organic matter layer 30 – 60 Limestone layer 15 – 30
Anoxic limestone drain (ALD)	Retention time (t) =15 h $M = \underbrace{\left(\frac{Q*\rho*t}{V}\right)}_{\text{Limestone volume to reach designed t}} + \underbrace{\left(\frac{Q*C*T}{x}\right)}_{\text{Limestone volume expected to dissolve over T}}$ M- Mass of limestone to build ALD; ρ- density of limestone; V- volume of limestone bulk void (expressed in % of total volume); Q-Flow rate of influent; C- alkalinity generation rate (mg $CaCO_3$/l); T- design lifetime; x- content of $CaCO_3$ in limestone (it is recommended to be greater than 90%).	
Vertical flow system (SAPS)	First cell generates 40-60 g/(m^2*d) of alkalinity and next cell are expected to generate 15-20 g/(m^2*d).	Water depth 100 – 200 Organic matter layer 15 – 60 Limestone layer 60 - 100