01 December 2014

Designing a treatment system for the underground effluent at Loulo Gold mine (Mali, West Africa)

Msc Thesis Report

Author	**:**	Hilaire B Diarra	
Student nbr	**:**	4237536	
Supervisor (s)	**:**	Mike Buxton	Associate Professor Resource Engineering, TuDelft
		Charles Wells	Group Sustainability Manager, Randgold Resources Ltd
		Graham Trusler	Chief Executive Officer, Digby Wells Environmental
		Jennifer Molwantwa	Research Manager, Water Research Commission (South Africa)
Address	**:**	Section for Resource Engineering Department of Applied Earth Sciences Delft University of Technology P.O. Box 5028 The Netherlands	
Telephone	**:**	(31) 15 2781328 (secretary)	
Fax	**:**	(31) 15 2781189	

Abstract

Water monitoring and analysis results have shown that the current underground water discharge into the adjacent Faleme river is substandard, indicating that the existing settling ponds are not suitable to bring the effluent into compliance with the Malian discharge limits

prior to discharge. Since the identification of the problem, the mine has undertaken a number of studies to find the best possible solution to the discharge quality issue.

This study puts all the different studies into perspectives and uses the available data to assess the impact of the effluent on the receiving environment and to develop a constructed wetland which is believed to be a more adequate treatment solution than the existing settling ponds. The study is divided into three main parts.

The first part assesses the impact of the mine effluent on the Faleme river by characterizing the discharge water quality since mining commenced (i.e. from 2010) up to date; then by evaluating the current ecological status of the Faleme river and finally by attempting to draw conclusions as to the potential sources of the issues identified in the Faleme with the mine discharge quality and other activities in and along the river (e.g. artisanal mining activities, agriculture, and others). Even though the quality of the mine discharge is substandard, the current issues associated with the Faleme river ecosystem are caused by the artisanal mining activities and aggregate mining by the clandestine sand miners.

The second part of the report deals with the designs of a thickening system to remove the solids from the effluent prior to entering a constructed wetland which design also is proposed to remove the nitrate from the effluent. A 10 m diameter thickener was designed assuming a 160m3/h maximum flow rate, a 5%m solid concentration in the feed and a 2m/h critical rise to achieve a settling rate of 20 t0 30 m/h. the overflow of the thickener will enter a subsurface horizontal flow type wetland with an inlet, macrophyte zone and an outlet. Due to the complex nature of the processes in the wetland and the difficulty in modelling it, a number of design options was proposed to be trial tested. Since the final wetland should be at least 100 m wide and 300m long, the proposed pilot scale size is 10m x 30m. *Cyperus papyrus* and *Typha* will be tested as the plants to be used.

If the uncertainties around the design of the wetland can be reduced and a model developed through the pilot scale test, this can be used in other mines in Mali and even in other countries with similar climatic conditions and similar problems.

Acknowledgement

Sincere thanks go to my hierarchy in Randgold Resources Ltd (Haladou M Manirou, Rodney Quick and Charles Wells) to have allowed me to pursue a Master degree. Thanks to Randgold Resources Ltd to have funded this study. I would like to thank also Dr Mike Buxton, M. Graham Trusler, Dr. Jennifer Molwantwa & Charles Wells for reviewing the report and providing valuable inputs.

Special thanks go to Mrs. Jikste van der Laan for her constant assistance all along my studies at Delft (registration, visa and accommodation arrangement). Prof Hans de Ruiter has always been available to help the EGEC student – thank you.

Contents

Nomenclature

CW	Constructed Wetland
DnS	Downstream
DWA	Digby Wells and Associates
DWE	Digby Wells Environmental
EMS	Environmental Management System
EPT	Ephemeroptera (Mayflies), Plecoptera (Stoneflies) and Trichoptera (Caddisflies)
ET	Evapotranspiration
FAO	Food and Agriculture Organisation
FAST	Faculté des Sciences et Techniques
FL1	Faleme Downstream of Loulo Operation
FL2	Faleme Upstream of Loulo Operation
FWS	Free Water Surface
GK	Gounkoto
GK1	Faleme Downstream of Gounkoto Operation
GK2	Faleme Upstream of Gounkoto Operation
GR1	In the lower reaches of the Garra Dam adjacent to the Loulo camp
GR2	At the Garra River bridge downstream of the local orpailleurs (artisanal miners)
HECRAS	Hydrologic Engineering Centers River Analysis System
HF	Horizontal subsurface Flow
HSSF	Horizontal Subsurface Flow
ICP-OES	Inductively Coupled Plasma Optical Emission Spectrophotometry
ICP-MS	Inductively Coupled Plasma Mass spectrophotometry
IFC	International Finance Corporation
IHAI	Intermediate Habitat Assessment Integrity

ISO	International Organization for Standardization
MEC	Midpoint Effect Concentration
OMVS	Organisation pour la Mise en Valeur du Fleuve Sénégal
PC-UP	Immediately Upstream of the discharge area into the Falémé River
PC-DWN	Immediately Downstream of the discharge area into the Falémé River
PEC	Probable Effect Concentration
PSD	Particle Size Distribution
P&C	Patterson &Cooke
SASS5	South African Scoring System (SASS), Version 5
SSF	Subsurface Flow
TEC	Threshold Effect Concentration
UpS	Upstream
USEPA	United States Environmental Protection Agency
VF	Vertical subsurface Flow

List of Tables

List of Figures

3 Introduction

Loulo Gold Mine is a Randgold Resources Ltd subsidiary and has been in operation since June 2005. The Mine is located in the Western part of Mali, 350 kilometres west of Bamako and 220 kilometres south of Kayes and is adjacent to the Faleme River which forms the border between Mali and Senegal. The river originates in Guinea, approximately 250km upstream of the study area and joins another large river, the Senegal river 270 km downstream of the mine, whereafter it flows 590 km before entering the Atlantic Ocean as the Senegal River. The river is managed by a Basin Management Authority (OMVS – Organisation for utilizing the Senegal River) with the Governments of Guinea, Mali, Senegal and Mauritania having input. The river is also a vital lifeline to communities living along it and is the only regional water supply in the area during drought conditions. Managing the effect of the mine on this vital water resource is thus essential. The tributary streams of the Faleme River that flow in close proximity to the mine include the Gara and Dande. The other likely receptors of the stream water include a few villages (communities), whose sole source of drinking water is groundwater, but utilize the stream water for other domestic and agricultural uses. See below a map showing the location of the Loulo mine.

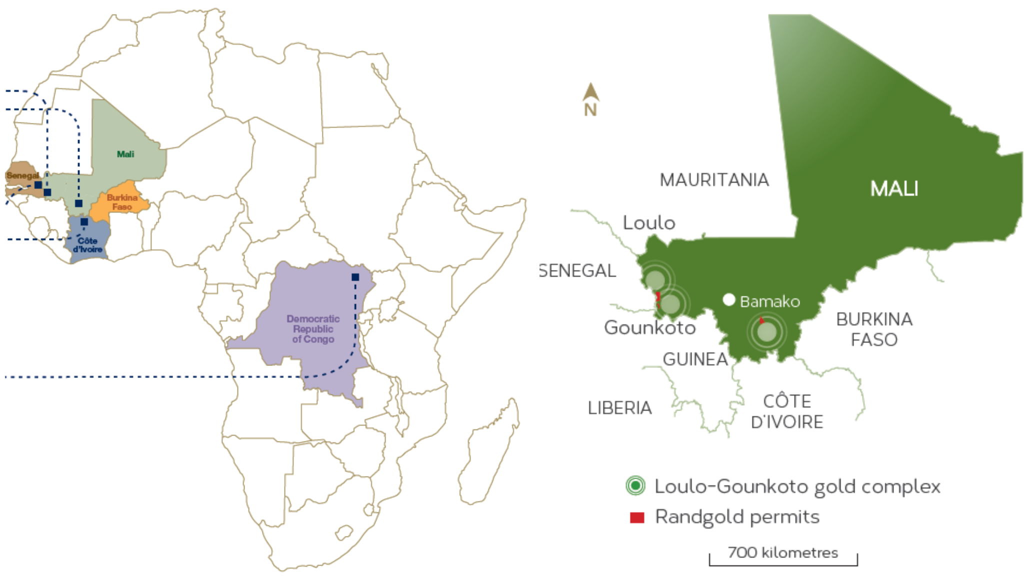


Figure 1. Location map (Source: RRL annual report 2012/2013)

Loulo currently consists of two underground operations (opencast operations stopped at the beginning of 2013) – Yalea and Gara. Although dewatering is taking at both operations, this report will focus on the gara underground dewatering. This thesis characterizes the ecological health of the main receptor, i.e. the Faleme river adjacent to the Loulo mine to understand the existing/potential impact of the substandard mine discharge on it and then develops a feasible treatment solution to bring the mine effluent into compliance with the country water discharge limits. A number of expert advice has been seeked in the past as to the most effective way of treating the effluent prior to discharge. The last two consultations were in January 2011 and in October 2013 when Digby Wells Environmental undertook a site visit to evaluate the issues and to recommend measures. Proposed measures were to settle the solids in a mechanical settler and construct a wetland/reedbeds to deal with the nutrient rich effluent.

3.1. Motivation

The Gara underground project started in 2010 and will be in operation until 2024. Dewatering of the mine has been taking place since the beginning of the mine and the current infrastructures in place to improve the quality of the water before discharge have proven to be inadequate causing substandard effluent to be discharged into the adjacent Faleme river. Looking at the sensitivity of the Faleme river in terms ownership (the faleme is an international river) and use by the downstream communities, it was of paramount importance to determine if the discharge was impacted on the river and to design a solution to bring the effluent into compliance with the acceptable Malian water discharge limit and IFC discharge guidelines in order to preserve the river ecosystem and to preserve the mine image vis-à-vis of its stakeholders. The findings of this study could help resolve the long standing issue related with finding a feasible cost effective technology for the treatment of mine water effluent in the country and in other developing countries where the cost of the sophisticated water treatment system make their implementation impossible, consequently putting the environment at risk. The findings could be adapted to other mines of the Randgold Resources Ltd as well.

Figure 2 below shows the Loulo gold mine and the discharge point and route of the Gara underground effluent towards the faleme.

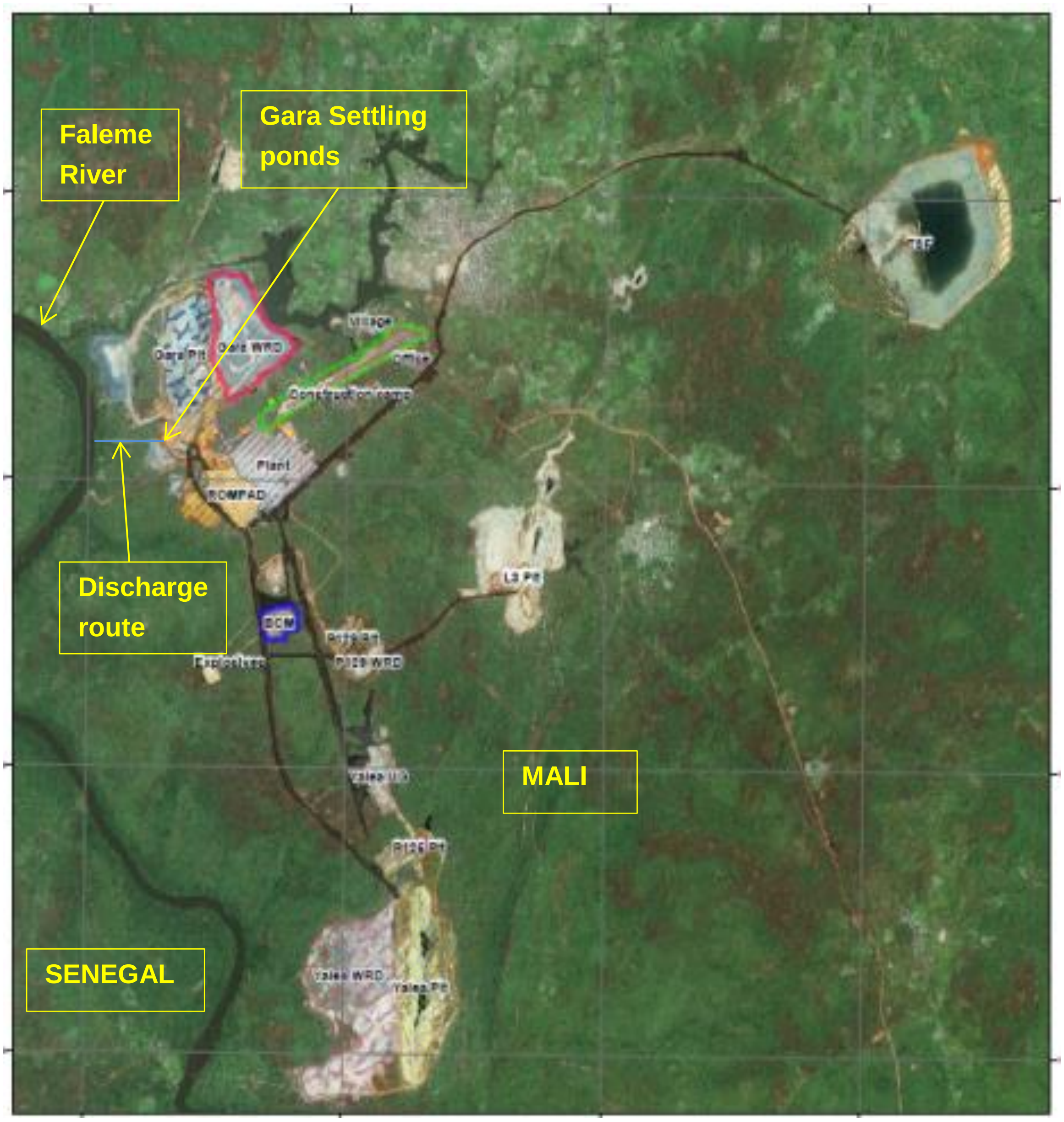


Figure 2. Loulo gold mine with the location of the Gara underground discharge point (source: 2012 satellite image of Loulo gold mine modified in arcGIS 10.1)

3.2. Research Questions

It is evident from the above that the substandard mine effluent has been discharged for a while and may have resulted in a possible environmental damage which could, if it is proven to occur, have an impact on the company image and reputation and on the people using the resources of the water not to mention the high cost that would be involved for the remediation. Continuing to discharge substandard water into the river is a legal noncompliance that may result in lawsuit from the regulatory bodies (OMVS and Mali Government) and potentially fines.

It is therefore of paramount importance to answer the following question –

- Has/Is the mine effluent caused/causing any impact on the receiving aquatic environment (Faleme river)? If yes, to what extent? If no, what are the risks?

Independently of the first question, two second questions are to be answered as it is a legal requirement to treat substandard effluent before discharge –

- Which type of settling will work on the gara effluent? Passive or dynamic? With flocculant or without flocculant?

- Which type of wetland will work better considering the site specific parameters?

3.3. Aim and Objectives

This study aims at characterizing the impact of the Gara mine effluent into a river body and developing an integrated cost effective solution to treat the effluent before discharge. The findings will contribute at developing the mine water treatment technologies industry in a developing country such as Mali and for Randgold Resources Ltd. There are two objectives as described below:

The determination of the impact of the gara effluent discharge on the Faleme river ecosystems based on:

- The Malian regulatory framework;
- The characteristics of the mine effluent discharge
- The characteristics of other non-mining related activities along the river
- The current ecological health status of the Faleme river upstream, downstream and at the mine discharge area.

The design of integrated and adapted cost effective physical settling infrastructure and wetland to treat the mine effluent, based on:

- The characteristics of the mine effluent discharge;
- The site specific parameters such as climate, soil, vegetation, and land availability

Figure 3 shows the research objectives (left) and questions (right)

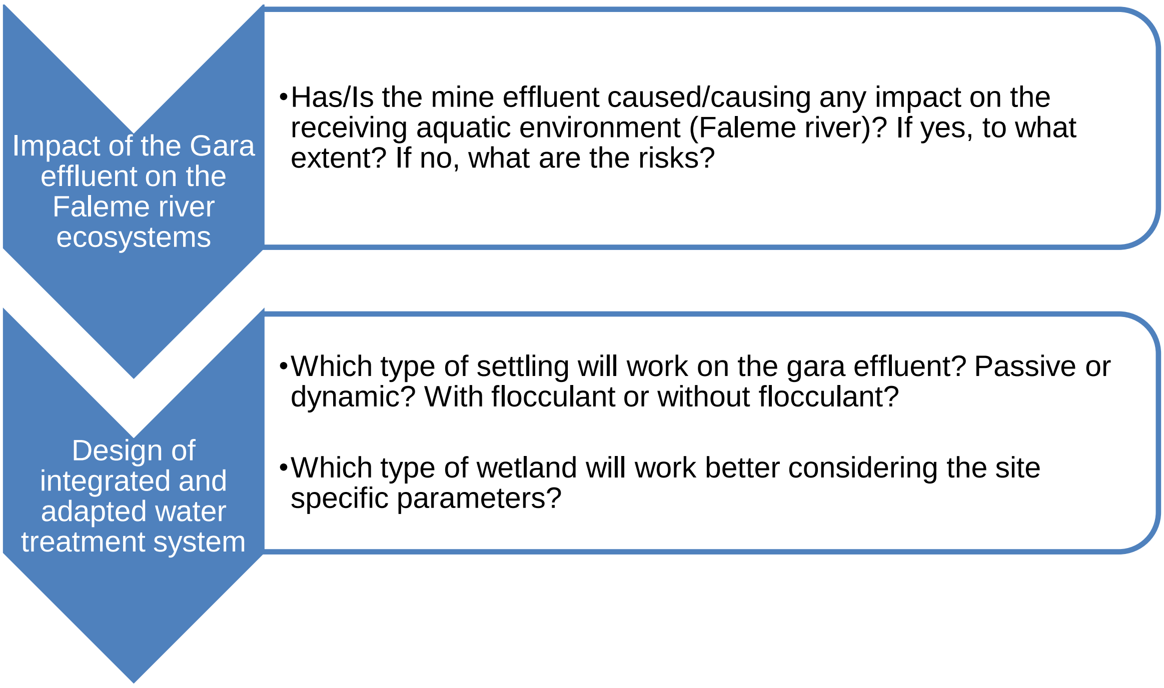


Figure 3. Objectives (left) that answer the research questions (right)

3.4. Methodology and the structure of the report

Figure 4 summarizes the methodology used to achieve each objective and to answer the research questions. First, the available monitoring data will be used to characterize (flow and quality) the gara discharge and an assessment will be undertaken to evaluate the ecological health of the receiving aquatic system (Faleme) to establish any link between the discharge quality and the health thereof; second, a literature review will be undertaken to describe the state of the constructed wetlands in the water treatment industry and to review the most critical parameters for a design in order to propose some design options specific to our study; and third the designs of the treatment system will be proposed. Results will be presented and discussed and recommendations made for the treatment of the gara effluent and the way forward.

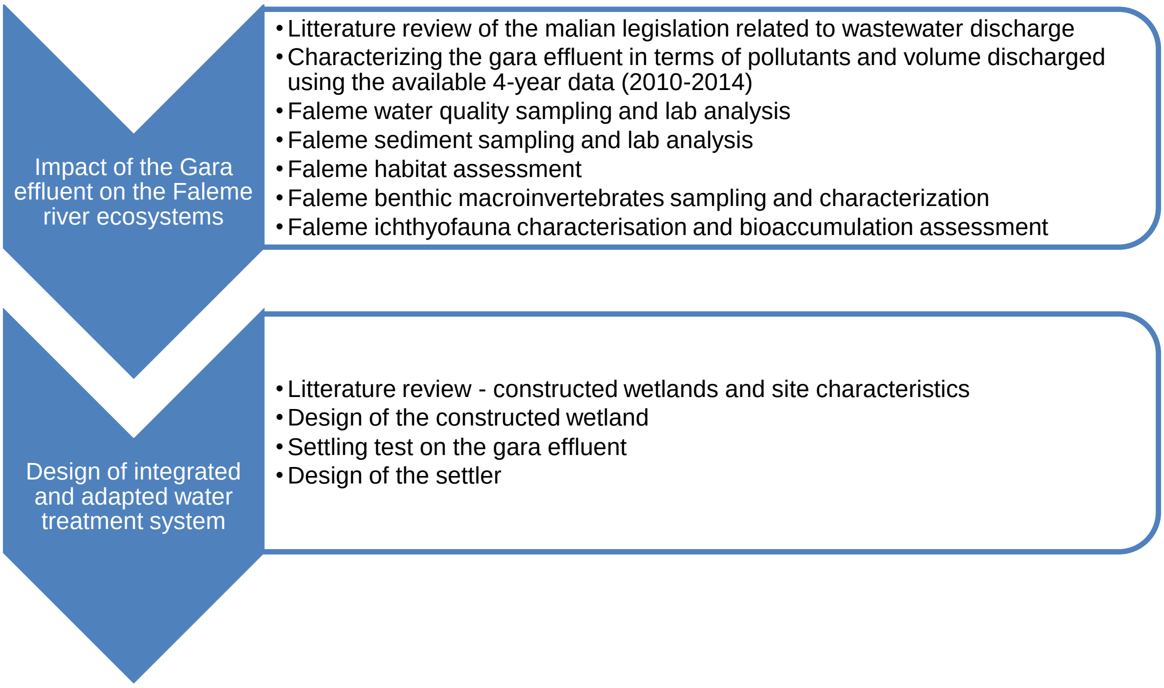


Figure 4. Methodology

The report will consist of three parts. Part 1 will consist of describing the site in terms of climate, geology and the mining; part 2 will consist of reviewing the legal requirements related to wastewater discharge and evaluating the impact the mine discharge has had so far on the Faleme river, part 3 will cover the design of the treatment options and part 4 will deal with the discussions, conclusions and the recommendations.

3.5. Research Scope

This research will lead to the development of conceptual designs for the treatment of the mine effluent that eventually may need to be tested and fine-tuned through a pilot scale field experiment before a large scale implementation. **Table 1** tabulates the aspects included in this research and those excluded. The study did not evaluate the impact of the volume of the discharge on the state of the faleme river as it was assumed to have negligible effect compared to the quality of the discharge. A detailed assessment of the other activities (e..g. artisanal mining activities etc.) along the Faleme and in its catchment to determine the other potential sources of pollutions was not undertaken even though there is a broad knowledge and mention thereof. A literature review on the different wastewater technologies was not needed as experts recommended the construction of a thickener to remove solids and the constructed wetland to remove the nitrate and heavy metals. This report determines the design requirements to achieve the final water objective. Unfortunately due to time constraint and the complex nature of water treatment systems – the research stop short of providing a fully tested concept to be directly used. The report includes aspects related to the quality impact of the discharge and its impact on the faleme river ecosystem that is the habitats, ichthyofauna, the sediments and the water quality. The sizing of the settler is limited to technical tests data, analyses and recommendations provided by Patterson and Cooke. The study focuses on the design requirements of a subsurface flow constructed wetland type.

Table 1. Scope of the research

	Included	**Excluded**
Impact of the gara effluent on the Faleme ecosystem	Effluent quality monitoring data over 4 years and during the survey Aquatic assessment results of the Faleme adjacent to site Limited or broad information on the artisanal mining activities	**Quantity impact** **Detailed assessment of the non-mining activities and potential impact**
Design of the constructed wetlands	The sub surface flow wetland system Conceptual models to be tested based on literature research	**Literature on water treatment technologies in use in the mining industry** **Rationales behind the selection of a wetland to remove nitrate** **Testing of the design parameters**
Design of the settler	Results of the settling testwork Sizing results of the settler	**Rationales behind the selection of a thickener to remove the solids**

4 Background information

4.1. Regional Climate

The climate at Loulo is strongly influenced by the northward and southward movement of the Inter Tropical Convergence Zone (ITCZ), which creates distinctive wet and dry seasons. The site falls within the Sahelian transition zone between the Sahara Desert in the North and the tropical climate in the South. The low altitude of the site and the absence of any intervening mountains mean that the humidity is directly conveyed to the area by the wind. Climate data was obtained from the Kéniéba weather station (12.85°N, 11.20°W; 132 m above mean sea level) located 35km south of Loulo Mine and from data collected on site.

4.1.1. Temperature

Western Mali is extremely hot for most of the year. The average maximum temperature varies from 30.6ºC in August to 40.4ºC in April. The average minimum temperature varies from 15.8º in December to 27.1º in May. **Figure 5** below indicates the monthly average temperatures taken over a 31 year period from the Kéniéba weather station.

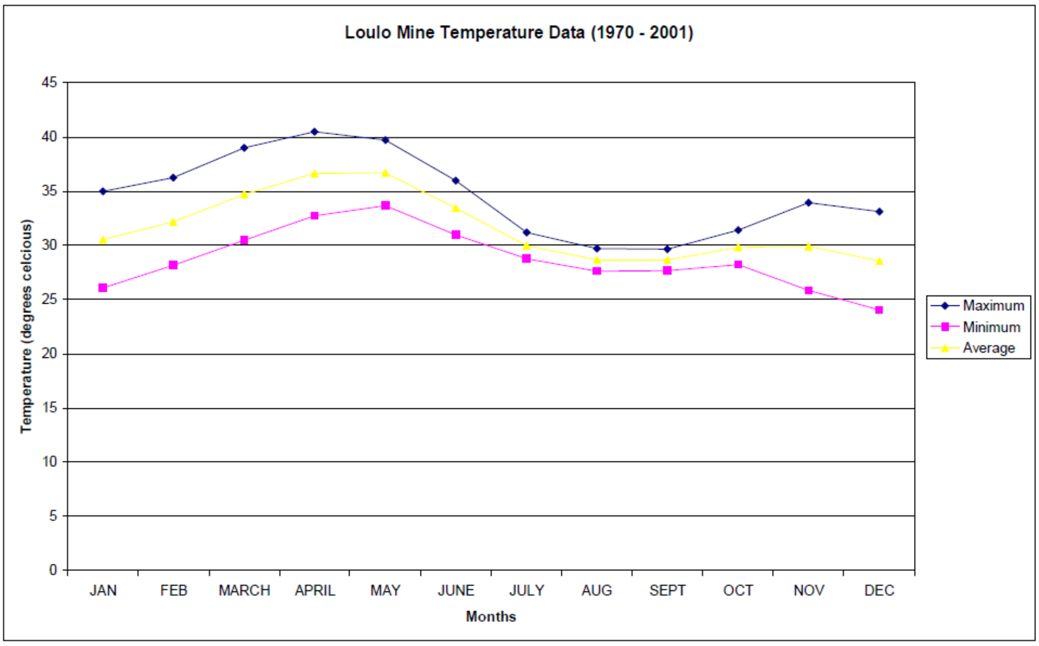


Figure 5. Average monthly temperatures (Source: DWA, 2007)

4.1.2. Rainfall and Evaporation

Rainfall data was obtained from the Kéniéba weather station for the period 1969 to 2005. The results captured indicate that there is a distinctive rainy season from May to October with little or no rainfall from December to April (Figure 6). The highest rainfall levels (above 400mm) were recorded during the month of August in the years 1969, 1973, 1981, 1982, 1999 and 2000. During the time period 1969 to 2005 the months of December, January and February; negligible or no rainfall was recorded.

Evaporation data was obtained from the Kéniéba weather station for the 1970 to 1996 period. The trend for evaporation was opposite to rainfall with higher evaporation over the dry, sunny months of November to May where evaporation exceeded rainfall and lower evaporation for the overcast and rainy season from June to October where rainfall exceeded evaporation (Figure 7). During this period, February 1976 showed highest total evaporation (331.5 mm) and August 1971 showed lowest total evaporation (49 mm).

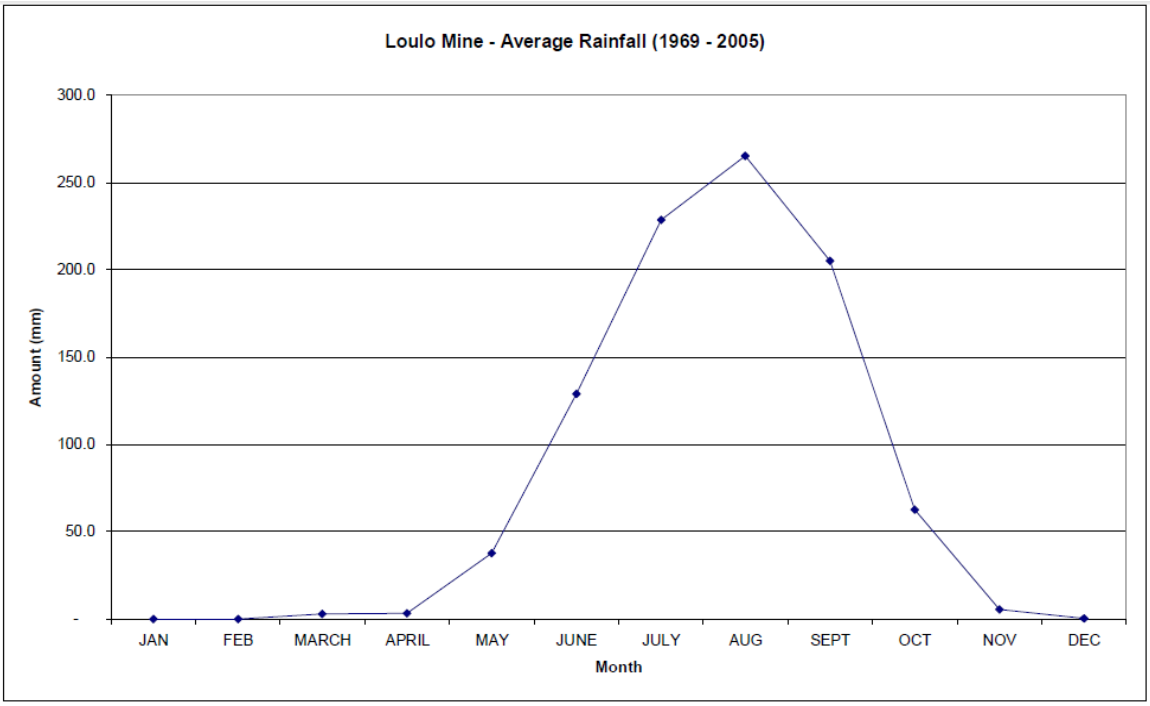


Figure 6. Average monthly rainfalls (Source: DWA, 2007)

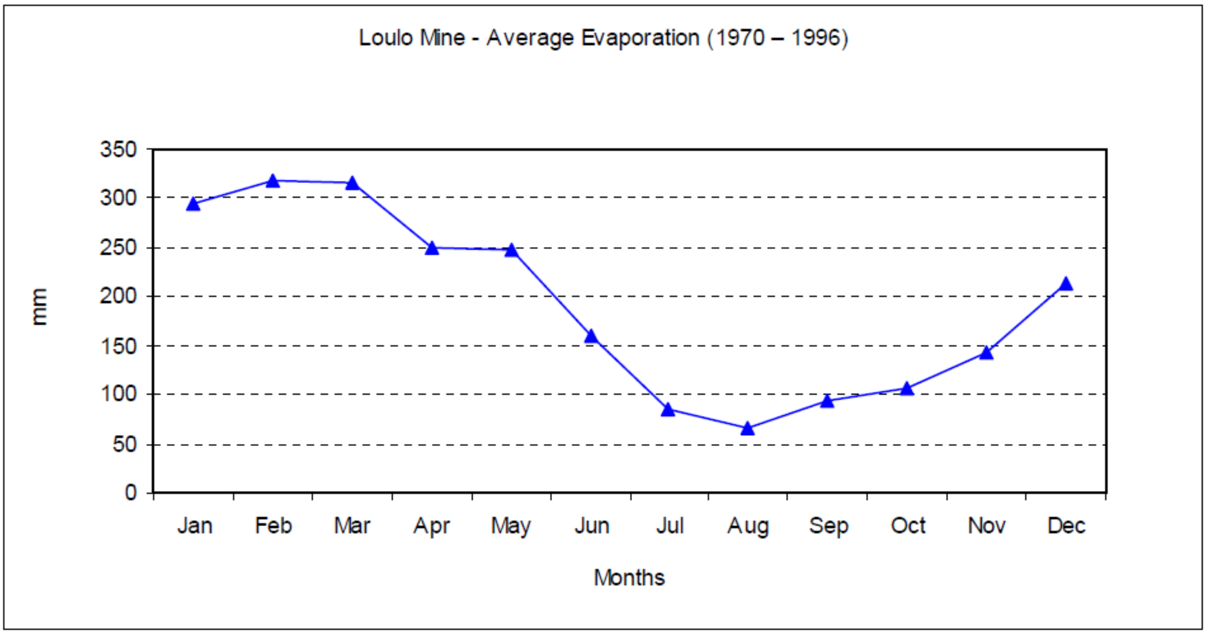


Figure 7. Average monthly evaporation (Source: DWA, 2007)

4.1.3. Wind and sunlight hours

The north and southward movement of the intertropical convergence zone is a prime determinant of the wind direction at the site. Wind speed and direction data was obtained from the Kéniéba weather station for the 1970 to 1996 period (Figure 8). The general wind direction changes according to the seasonal shifts of the intertropical front. During the dry season the intertropical front is located to the south and the dominant wind is north to east (Harmattan). In the rainy season the front is located to the north of Mali and the dominant wind is the north to west (Monsoon). The Harmattan is responsible for carrying large amounts of fine dust from the Sahara over large parts of Northern Africa. For a few months of the year, this has a large impact on activities by reducing visibility. This generally clears up after the first rains.

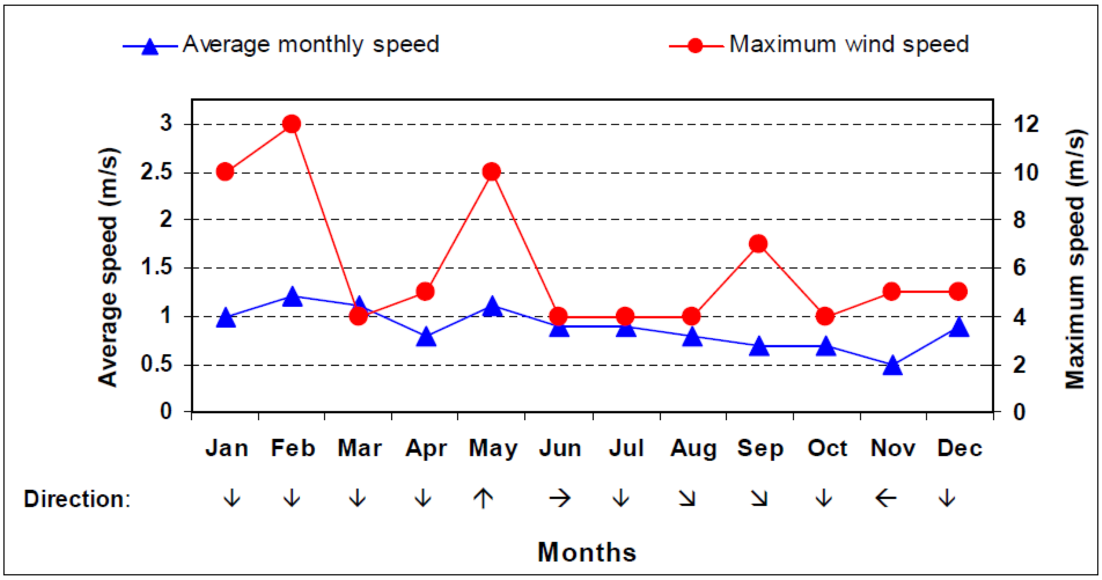


Figure 8. Average and maximum wind speed and direction (Source: DWA, 2007)

There are not many cloudy days at Loulo giving a high number of sunlight hours throughout the year. The monthly averages have been obtained from cumulative monthly totals for the 1970 to 1996 period from the Kéniéba weather station and are indicated in Figure 9.

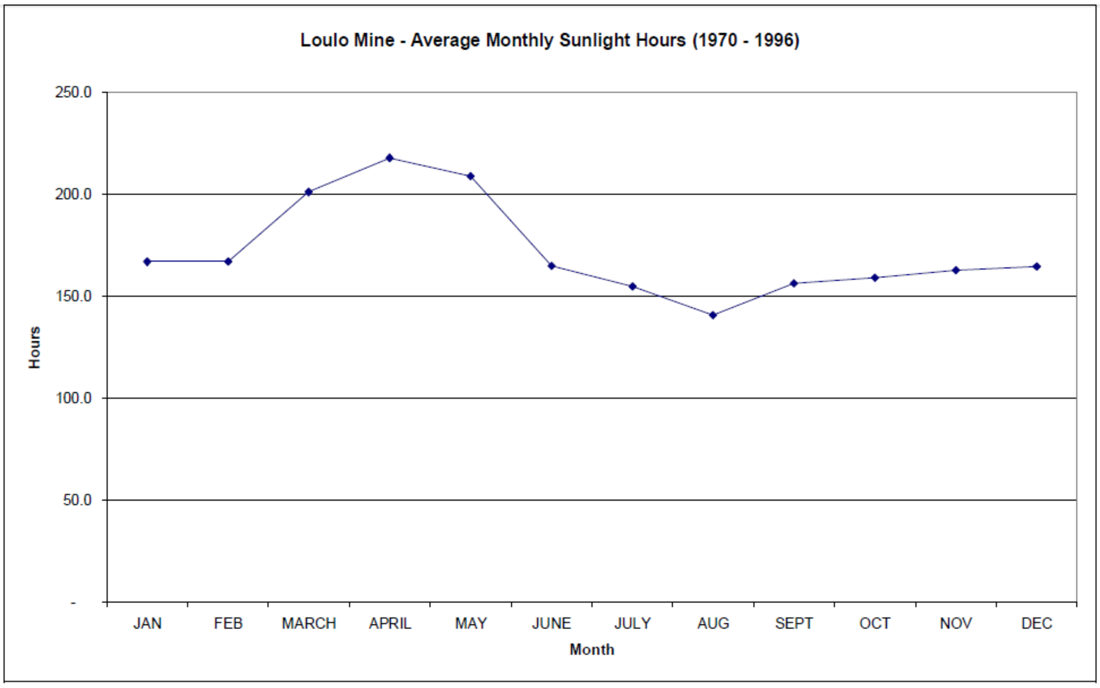


Figure 9. Average monthly sunlight (Source: DWA, 2007)

4.2. Geology and Mining

4.2.1. Petrography

The regional geological setting is well described in the environmental baseline report done in 2007 by Digby Wells Environmental. Figure 10 gives a geological map of the region. The area is located within the Kéniéba inlier of Lower Proterozoic (2.1 Ga) Birimian metasedimentary-volcanic sequences. The stratigraphic sequences of the inlier include from west to east the volcanic and sedimentary units of the Kenieba Formation, the continental shelf sedimentary sequences of the Saboussire Formation and the shallow to deep marine sedimentary units of the Kofi formation. These formations have been subjected to a series of deformation events of which the principle one is characterized by a N-NE trending schistosity with associated structures. The most prominent of these is the Senegal – Malian shear zone, a major first-order lineament trending N15°, which can be traced for over 200 km in Mali and Senegal and forms the contact between Upper and Lower Proterozoic sequences in the vicinity of the Sadiola deposit. The geology of the Kéniéba Inlier is also characterized by a series of syn and post tectonic granitoid to dioritic intrusives associated with the major structural zones.

The current geological model for the area of study involved the juxta positioning of the various formations as a result of generation of a series of accretionary wedges related to the development of back-arc, arc, shelf and basin successions generated by low angle subducting tectonic plates. Crustal melting relating to this collision produced a whole suite of evolving extrusive and intrusive bodies and the generation of hydrothermal gold and sulphide-bearing fluids.

The Senegal – Mali shear marks a major break in the geology from shelf carbonates with the Falémé ironstone unit in the west to the sedimentary sequences of the Kofi formation in the east. East of the Senegal – Mali shear the sediments of the Kofi formation are characterized by the following: limestone's and shallow shelf sandstones followed by cyclical succession of greywacke with intercalated mudstone, quartzite, marl and limestone which progressively evolve eastward into a classic turbiditic sequence (see Figure 11 below). This sequence is transacted by three major N-NE orientated structures referred to as the (1) Sakola shear zone, (2) Yalea shear zone and the (3) Senegal – Mali shear zone. These major lineaments have been subjected to major strike slip movement with associated antithetic structures and often resulted in the repetition of the stratigraphy. There is a coincidence of major gold targets and regional soil anomalies associated with these major shear zones and their antithetic structures.

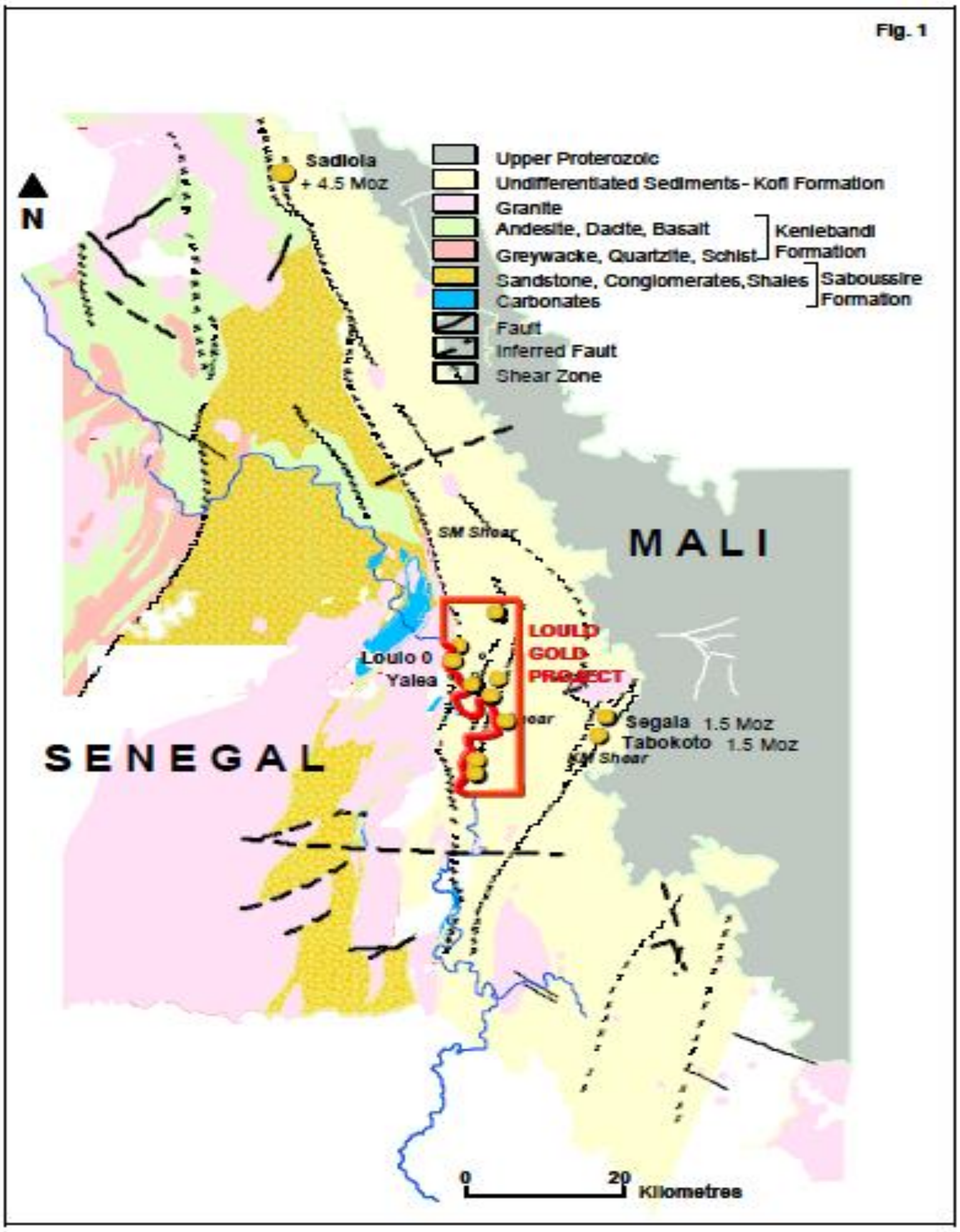


Figure 10. Geological Map of the Kenieba window (source: DWA, 2007)

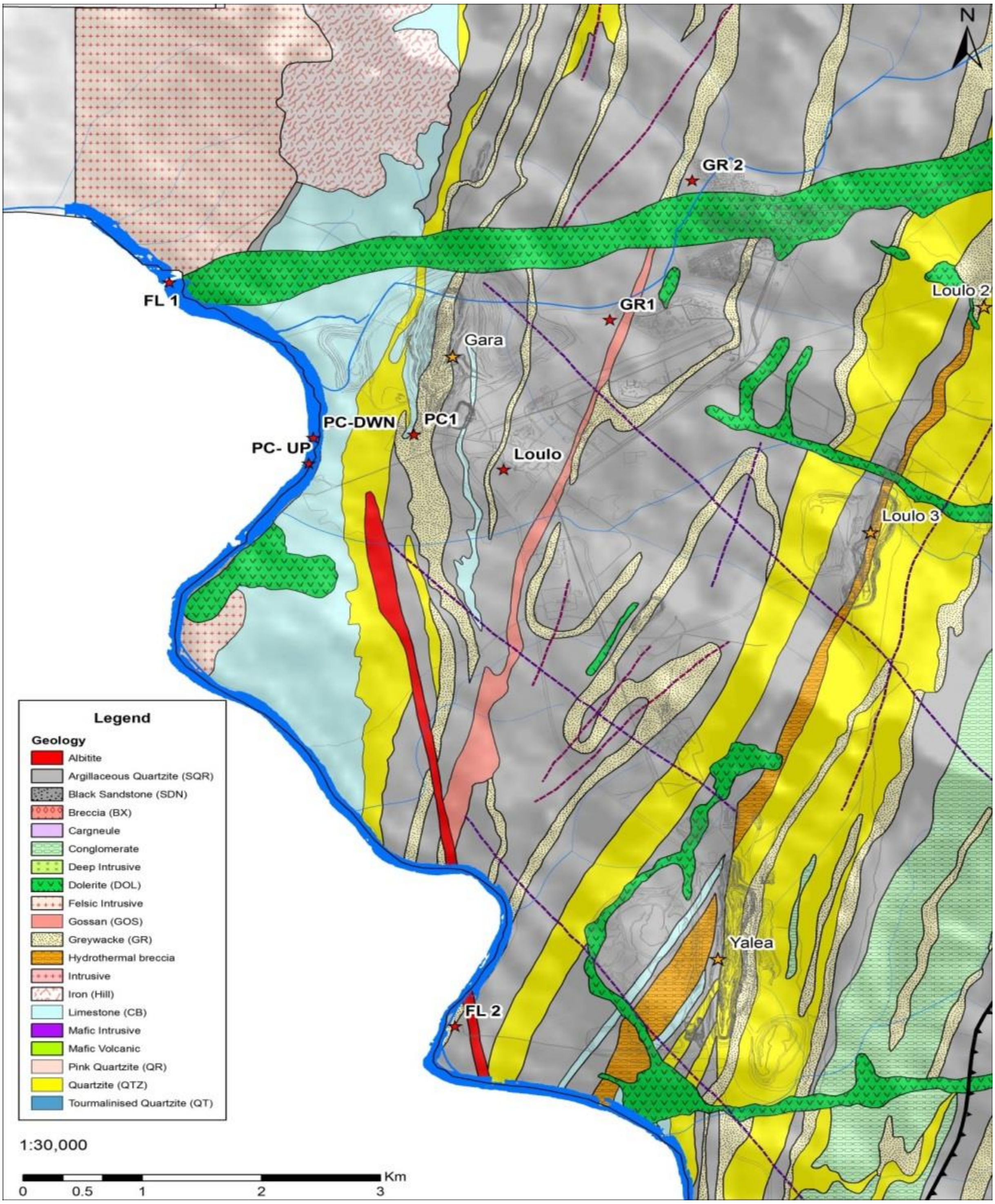


Figure 11. Geology in the study area (unpublished map from Joe holiday, 2014)

4.2.2. Mineralogy

Lawrence et al. (2013) described the mineralization of the Gara ore, our area of concern – Figure 11 below shows the detailed Gara geology – he described that Gara forms a carbonate-quartz-sulphide vein stockwork deposit. The Gara stockwork contains high carbonate concentrations (60-70 vol.% of the veins). This is an atypical characteristic for vein-hosted orogenic gold deposits, where carbonate concentrations are usually ≤5 to 15 vol.%. Mineralised veins are composed of Fe-Mg bearing carbonates (ankerites), while carbonate constituents of the barren veins are mainly composed of calcite. Quartz is the second major component of the Gara veins. Two separate styles of quartz generation are observed. A broad milky quartz generation exists as a cogenetic phase with ankerite or calcite, while a late grey quartz generation can be seen sealing brecciated ankerite veins (reactivation phase; Figure 12. c). Sulphides mainly occupy 5-30 vol.% of the veins (see Figure 13) and are situated in both carbonate and quartz vein material. Gangue minerals include albite and minor chlorite. The most common accessory minerals are rutile and apatite. Rutile exists as acicular, blocky and skeletal grains (20-80 μm) dispersed within quartzcarbonate vein material. Apatite increases in abundance in carbonate-dominated veins and contain micro-inclusions (<10 μm) of scheelite and monazite. In terms of sulphide phases, Gara contains a fairly simple ore petrogenetic history with pyrite occurring as the principal sulphide mineral (95-99% of total sulphides) and the only gold-bearing sulphide phase. Chalcopyrite is the main accessory sulphide, occurring as a trace phase (<5%). Two generations of chalcopyrite are observed: an early phase forming contemporaneously with pyrite (chalcopyrite-I); and a later, more dominant, phase post-dating pyrite formation (chalcopyrite-II). Other accessory sulphides, in order of decreasing abundance, include: pyrrhotite, gersdorffite, pentlandite and arsenopyrite. No Sb, Pb or Zn-bearing sulphides are observed at Gara. The Gara mineralised veins also contain common rare earth minerals with similar concentration levels to chalcopyrite (monazite and xenotime coexist with pyrite). Other accessory minerals include scheelite (a common ore phase at Loulo).

Pyrite is host to a range of trace Fe-Ni-As sulphides. Pyrrhotite and gersdorffite are the most common phases.

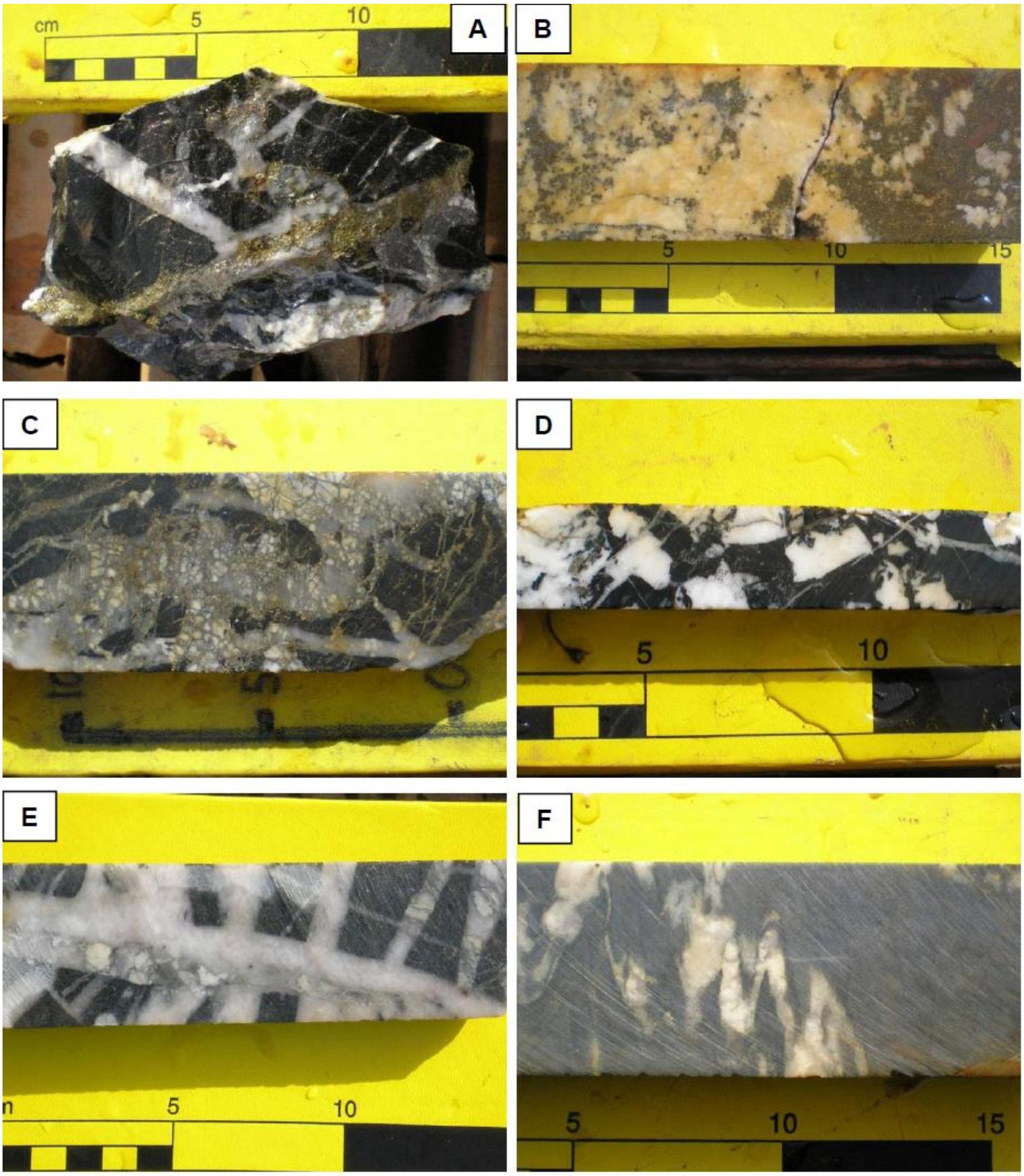


Figure 12. Grab and drill core samples of the Gara vein stockwork. The photographs illustrate the composition of the veins and the range of vein morphologies that occur in the tourmalinite host. A) A pit sample from a high-grade zone showing the presence of ankerite-pyrite veins. B) A sulphide-rich ankerite vein associated with high-high grade (90.3 g/t), showing clearly the link between gold concentrations and carbonate-pyrite abundance. Limonite alteration (brown material on the right of the image) occurs after pyrite (LOCP124, 552 m). C) Sigmoidal mineralised vein showing reactivation and brecciation of an early carbonate vein (white material) by later dull grey quartz, with both vein phases associated with sulphide generation (LOCP97, 347 m). D) A strongly brecciated carbonate vein with the vein structure no longer present (LOWDH23, 441 m). E) Straight barren (0.11 g/t) milky quartz veins (minor carbonate). The low-grade can be attributed to the lack of the vein carbonate and the low number of veinsets (2 vein directions, perpendicular to each other)

(LOCP49, 180.6m). F) A folded barren calcite vein (LOCP81, 676.55m). Folded veins usually occur within the weakly-tourmalinised quartz-wacke (note the lighter colour of the host rock compared to A to D) and pre-date mineralisation (D1 to D2 origin) (Source: Lawrence, 2013).

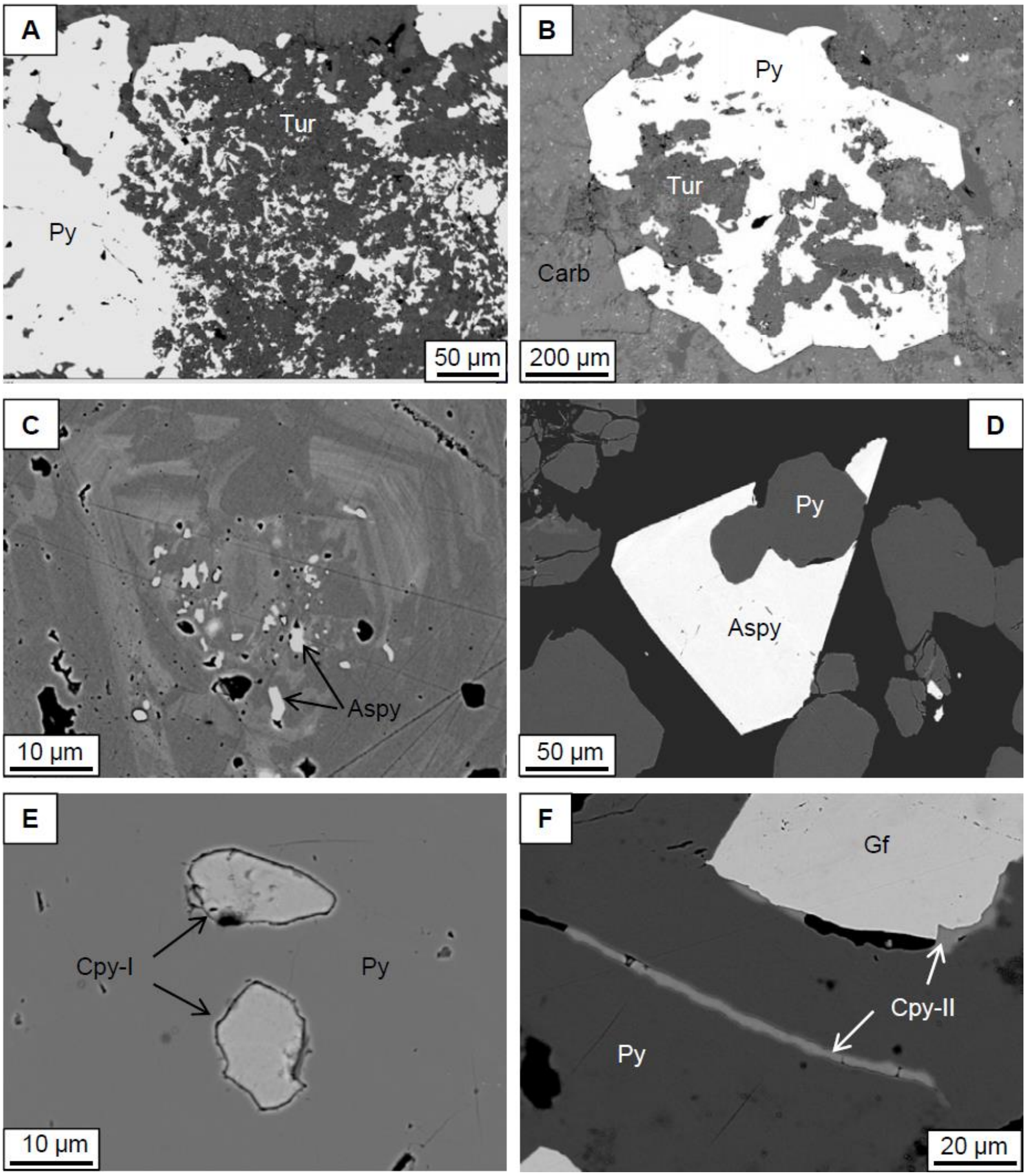


Figure 13. Back-scattered electron (BSE) images of the major and minor sulphide phases present at Gara. A) Highly altered pyrites replaced by late stage tourmaline (discussed in chapter 5) (LOCP117, 338 4) B) V it l d b t li (LOCP117 338 4) C) Z d it t l 10 µm 20 µm 338.4 m). Vuggy pyrite replaced by tourmaline LOCP117, 338.4 m). Zoned pyrite crystal showing lighter zones of As-Ni bearing pyrite. Small inclusions of arsenopyrite are associated with these As-Ni bearing zones (LOCP124, 557.6 m). D) Euhedral arsenopyrite intergrowth with

pyrite (LOCP59, 535.4 m). E) Anhedral chalcopyrite-I inclusions situated within the core of a pyrite crystal (LOWDH23, 438.05 m). F) Late chalcopyrite-II sealing fractures within pyrite or located along pyritegersdorffite contacts (LOWDH23, 438.05 m). Abbreviations- Carb = carbonate; Tur = tourmaline; Py= pyrite; Aspy = arsenopyrite; Cpy = chalcopyrite; Gf = gersdorffite. (Source: Lawrence, 2013)

4.2.3. Mining

The Loulo Underground mine uses conventional drill and blast to extract the ore from the stopes and to develop the underground workings. The mining consists of drilling blastholes, charging them up with the explosives (Rioflex, ANFO or emulsion), blasting, washing down the broken rock, scaling, supporting, mucking and transporting the ore to crusher and then to surface while waste is used to backfill open voids underground. Other activities that happen concomitantly to the mining are the geological drilling (deep probing holes) and dewatering. Total decline metres developed to the south bottom is 3414m and vertical distance developed is 420m (survey department, 2014). Monthly averages of 181 tons of rioflex and 35 tons of ANFO (ammonium nitrate and fuel oil, diesel) are used in Gara (2012-2013 explosive record).

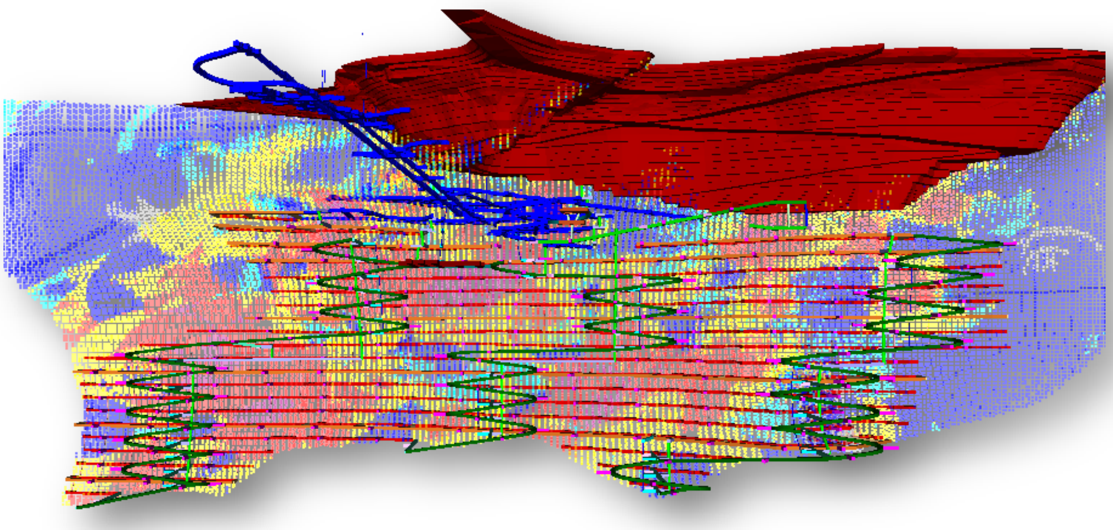


Figure 14. Gara underground layout showing the portal from the gara pit into undergrounds through spirals declines (Source: gara ore reserve statement report, Dec 2012)

4.2.4. Dewatering

The dewatering in the underground is such that all waters (clean or dirty) are drained to lowest points on every level and pump to the underground pumping station sump where it is mixed and pumped into the surface settling ponds – this makes dewatering the main pollutants pathway in the event of any pollution. Below is a figure showing the dewatering layout from underground to surface dams.

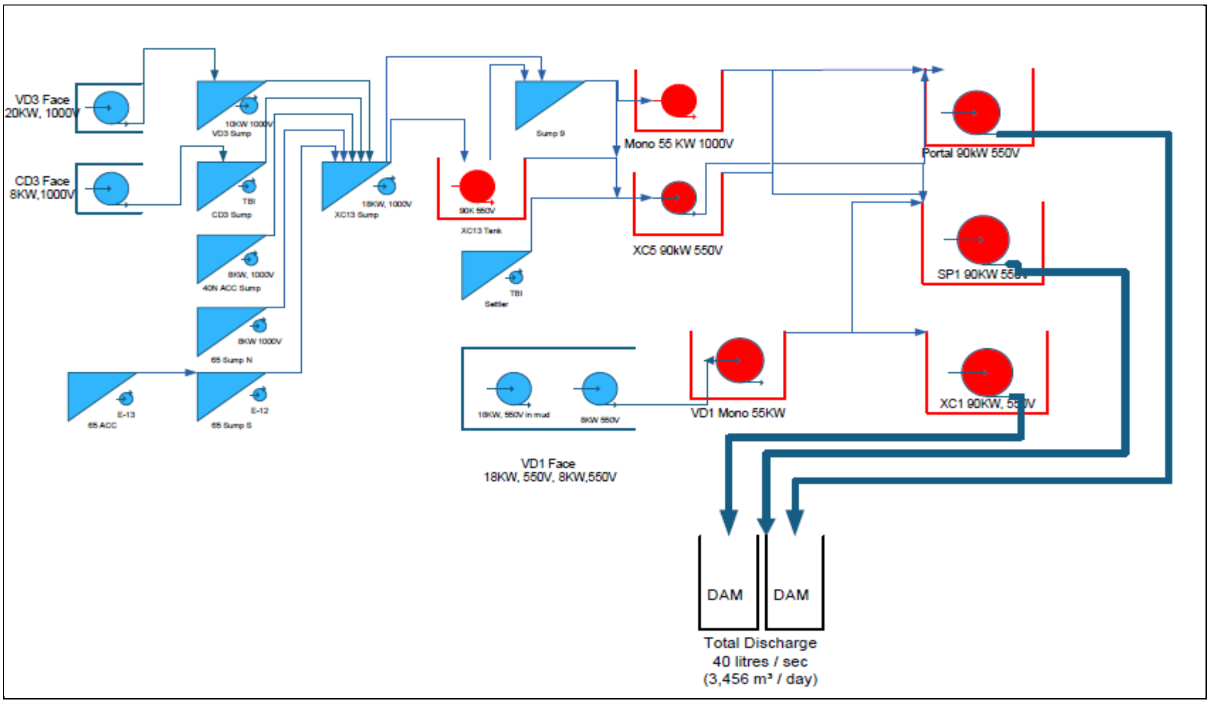


Figure 15. Underground water reticulation

Potential pollutants sources

The potential contaminants to expect in the discharge from the underground workings include chemical elements from explosives used, from the ore and to a lesser extent from the host rock, hydrocarbons and the emissions from the fleet, and sediments from the drilling and blasting activities. Release mechanisms into the effluent include emissions and spills from the fleet (including drilling rigs), washing explosives materials not fully detonated or spills during chargeup, and dust particles generated during drilling. Below are the different pollutants, their sources and exacerbating factors.

5 Regulatory framework

5.1. Mining code

The mining in Mali is regulated by the mine code (Law no. 2012-015/AN of 27 February 2012) which states in his article no. 142 that all owner of a mining permit must comply with the Malian legal and regulatory requirements related to the Environment.

5.2. Convention

The convention (1993) between the mine shareholders and the Government also says in its article 20 (refer to art. 20 hereafter) that the mine must:

- Art. 20.c. – At any time comply with the legal requirement related to hazardous waste, Natural resources and the protection of the environment.
- Art.20.f. – establish a treatment system for its wastewaters (the discharge guidelines are defined in the document MN-03-02/002:2006)

5.3. Water code

In Mali, the law that covers water related issues is the water code (Law no.02-006/AN of 31 January 2002) and its implementation decree No. 04-183/P-RM of 11 June 2004. It describes all the requirements related to water resource protection on the Malian territory – of interest to us are the articles 14, 16 and 60 that stipulate that it is forbidden to discharge pollutants into water courses which could threaten public, aquatic and flora health – anyone whose activity can cause pollution of the water course should take the necessary measures to prevent it. Polluters must pay for the cleanup costs.

5.4. Pollution and Nuissance prevention Laws

Seeing above and the other legal requirements such as those related to pollution and nuisance (Law no. 01-020/AN of 30 May 2011) and those related to the required measures for the management of wastewaters in Mali (Decree no. 01-395/PRM of 06 September 2001) – the mine must ensure the underground mining effluents comply with the acceptable discharge limits before discharging it into the Faleme river which is under the regime of the water charter (OMVS – Organisation for utilizing the Senegal River). OMVS has no guideline for the discharge water quality which leaves us with the Malian and the International Finance Corporation (IFC) guidelines to comply this. Below is a table showing the different standards and guidelines used in this study.

Table 2. Water quality standards and guidelines

Guidelines	Drinking water	Effluent discharge	Malian Discharge Standards
	WHO Drinking water guidelines (Gorchev & Ozolins 2008)	**IFC EHS Mining guidelines** (IFC 2007)	
Al	0.2	-	≤1
As (soluble)	0.01		-
As (total)	0.01	0.1	≤ 0.05
BOD	50	50	≤50
Cd	0.003	0.05	≤ 0.02
Cl	250		≤ 1200.0
COD	250	150	≤150
EC (uS/cm)	-	-	≤2500
Cr 3			2
Cr (hexavalent)	-		≤ 0.2
Cr (total)	0.05	0.1	
Cu	2	0.3	≤ 0.1
CN (free)	0.07	0.1	-≤0.5
CN (total)	0.07	1	≤ 1
CN WAD	-	0.5	-

Guidelines	Drinking water	Effluent discharge	Malian Discharge Standards
	WHO Drinking water guidelines (Gorchev & Ozolins 2008)	**IFC EHS Mining guidelines** (IFC 2007)	
Faecal Coliform	0	-	≤12000
Escherichia coli	0	-	-
Total Coliforms	0	-	≤ 20000
Fe	0.3	2	≤ 2
F	1.5	-	≤ 6
Hg	0.006	0.002	≤ 0.005
Ni	0.07	0.5	≤ 2.0
Mn	0.4	-	≤ 2
PO4	-	-	≤ 10
NO3	50	-	≤ 30
NO2	3	-	
Oil andgrease	-	10	-≤5
Pb	0.01	0.2	≤ 0.2
pH	6.5-9.5	6-9	6.5-9.5
Phenols	200	0.5	≤ 0.5
Se	0.01	0.1	-
Sn			10
Na	200	-	-
SO4	250	-	≤ 1000
S			1
Sulphite			1
TDS	1000		≤ 1000
Temp Increase	-	< 3	-
Temp. Total			≤40
Total Hardness	-	-	
TSS	-	50	≤ 30
Turbidity (NTU)	5	-	-
Zn	-	0.5	-≤0.5
Ag	-	-	≤ 0.01
V	-	-	≤ 1.0
B	0.5	-	≤ 1.0
Dissolved oxygen			> 6
Chlorine			≤0.2
Ammonia			≤15
Animal and veg. fat			≤20
Aromatic solvent			≤0.2

The elements of concerns, against the above table, in the discharge have been described below in the section on the characterization of the underground effluent.

6 Characterization of the Underground Effluent

6.1. Flow volume

6.1.1. Historical data

The records available cover three years (January 2011 to January 2014) of recording using ultrasonic flowmeters (Innova-Sonic model 205 thermal energy) on the discharge lines.

Although there were instances where the flow volume was read over 24-hour period, most of the times the flow data were read irregularly (48-hour, 72-hour and sometimes monthly cycles) making it difficult to evaluate the peak and low flow 24-hour discharge volumes and instantaneous variations. The data was averaged over the number of days accumulated between two subsequent readings – this was found to provide a fair representation of the reality which will allow the design of a treatment system capable of handling the expected volumes and taking into account the fluctuations in volume. Also any value below 100 m^3 was removed from the data set. In total a data set of 754 out of 844 values was used. The Statistical description of the data is shown below in Table 3 together with a bar graph showing the monthly volumes (see Figure 16) –

Table 3. Descriptive statistics of the data set (value in m^3)

Minimum	102
Maximum	9538
Mean	1671
Median	1486
First Quartile	533
Second Quartile	1485.6
Third Quartile	2364.3
Fourth Quartile	9538

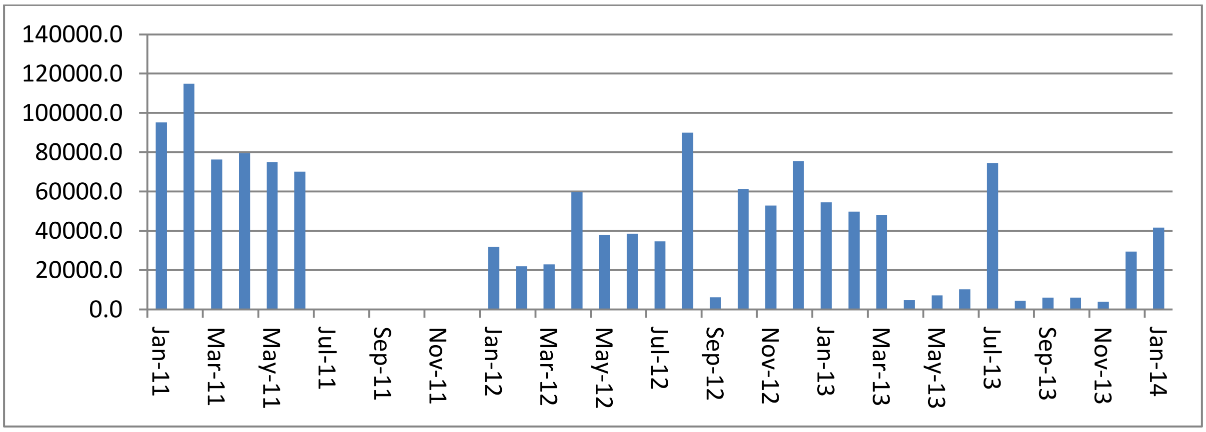


Figure 16. Monthly flow data from January 2011 to January 2014 (source: water monitoring database of Loulo Gold mine)

The maximum daily flow data analysis returned 9,538 m^3 as the highest daily flow and was recorded in April 2012; the minimum and the average daily volumes were 102 m^3 and 1,671 m^3 respectively.

6.1.2. Future Flow prediction

Methodology

A geohydrological investigation was undertaken in 2012 around the gara underground areas to determine the volume of water inflow underground life of mine. Digby Wells Environmental was appointed to assist. The author participated in all data collection and interpretation of the results. The scope of work has been conducted through several tasks as defined in the final report submitted by Digby Wells, and included the following:

- Assessment of available geological and hydrogeological data;
- Ground geophysical survey around the pit and underground areas;
- Extended drilling of candidate dewatering holes in the perimeter;
- Refinement of the conceptual groundwater flow model;
- Construction and calibration of a numerical flow model; and
- Determination of the required dewatering rates and number of dewatering boreholes to ensure workable conditions at Gara underground.

The aquifers in the vicinity of Gara were studied based on recent drilling and pre-existing boreholes, in conjunction with the structural geology established at Gara. A total of 12 boreholes were sited and drilled at Gara. Details of all drilled boreholes are presented in Appendix A. The figure below indicates the position of the different boreholes

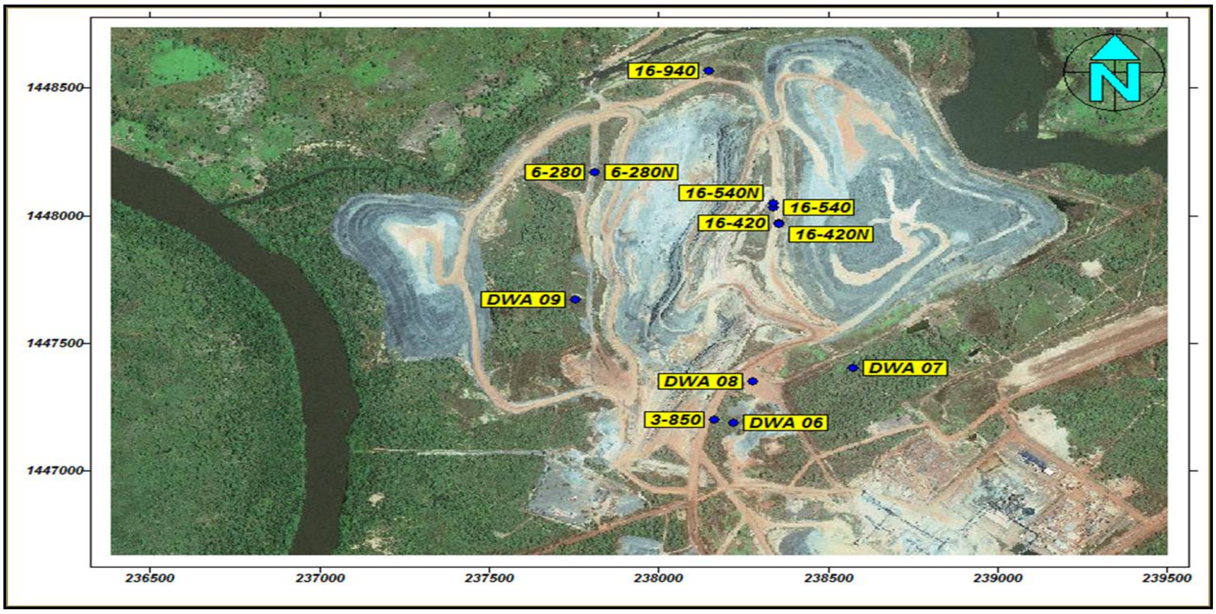


Figure 17. Boreholes locality map (Source: DWA, 2012)

Previous conceptual hydrogeological models of Gara aquifer system suggested is a two-aquifer system, consisting of a fractured aquifer overlain by a weathered aquifer, where groundwater flow mimics surface topography (DWA, 2007). It is evident that gold mineralisation in Gara was structurally controlled. The geomorphology of the local drainage system is highly controlled by the fault architecture. Surface water flowed through and eroded open fractures in exposed damage zones (zone of subsidiary structures surrounding a fault).

The fractured aquifer consists of a rock matrix and a fracture network. In rocks with low primary porosity (in the rock matrix), groundwater flow only occurs in the secondary porosity provided by fracture networks and dissolution associated with fault zones. Within a typical fractured aquifer the secondary porosity, i.e. fracture network, dominates the groundwater flow, while the primary porosity, i.e. rock matrix, dominates groundwater storage. Based on the current drilling and reassessment of historic geological and hydrogeological data, the groundwater system cannot only be described in terms of an elevation or stratigraphic units, as traditional aquifers are, but instead by the relationship with the fault (and the nature of the fault architecture). The fault damage zones and fracture networks in Gara study are so large and interconnected, that they allow substantial groundwater systems to be hosted in a system almost entirely controlled by secondary (fracture) permeability. However, some of the fault zones form an impermeable barrier caused by the breccia re-cementation and gouge development. Breccia zones demonstrate additional strength (resistance to erosion when fractures are cemented). This effectively fuses cracks and heals fractures which creates barrier for fluid flow.

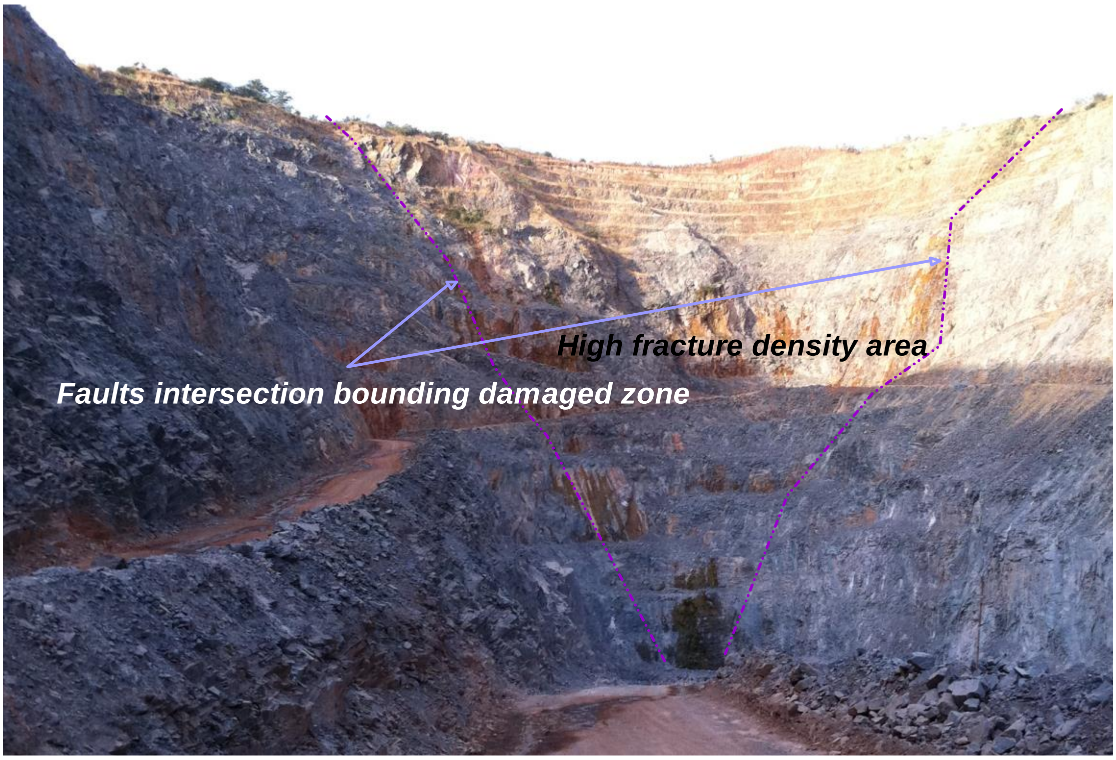


Figure 18. Damage zone with fault intersection - north wall of Gara pit (Source: DWA, 2012)

The fractured aquifer system around the pit is highly compartmentalised by faulting both laterally and vertically, as depicted by the sudden change in hydraulic head over short distances. A steep change in groundwater level occurs between boreholes 16-420N and 16-540N. Groundwater levels changes from 84mamsl, at borehole 16-520N, to 19mamsl at borehole 16-420N. These boreholes which are just 75m apart have a collar elevation difference of 1m. A SE structure, SSE of Gara pit, also seems to act as a flow barrier. The groundwater head drops to 15m below mean sea level SSE of Gara pit. Intersection of any given fracture will only allow drainage of the rock matrix immediately adjacent to the fracture. To achieve reasonable dewatering in the current decline, it was recommended that the decline shear zone has to be depressurized. DWA06 and DWA08 were perfect candidate boreholes for depressurization Gara decline shear zone. They might significantly reduce the underground water ingress, and hence underground dewatering requirement in this area.

The rock matrix west of Gara pit has a very low drainable porosity. All water is transmitted in fractures (the main fracture zone and interconnected microfractures). Main fracture zone north and west of Gara pit, typically yield 1.3 to 2 L/s, sufficient to sustain flow in boreholes. The multi-layered SQR beneath the limestone west of Gara pit is intersected by a dolerite sill. Potential recharge to the aquifers beneath is partially blocked by the dolerite sill.

Groundwater flow in shallow aquifers, controlled to some extent by relic structures, is much more homogenous than flow beneath. There are no discrete highly transmissive fracture zones. The fracture zones and matrix have both been completely weathered.

Compartmentalisation is much less important than in the deeper fractured aquifer. There is also low lateral seepage from these aquifers to the pit walls. Isotope studies concluded that the Falémé River has little or no contribution to Gara underground inflows. A steady state groundwater flow model for the study area was constructed to simulate current hydrogeological conditions at Gara study area. These conditions serve as starting heads for the transient simulations of groundwater flow. Visual MODFLOW 2010.1, a MODFLOW based modelling software package, was used for the simulations. MODFLOW and Visual MODFLOW are internationally recognised modelling packages that have been proven to be capable of simulating these types of groundwater flow and contaminant transport assessments to a high level of accuracy. The simulation model is based on three-dimensional groundwater flow equation.

A model, no matter how sophisticated, will never describe the investigated groundwater system without deviation of model simulations from the actual physical process (Spitz, 1996). The list of assumptions made can be found in the full report (DWA, 2012). The model covers an area of 10.7 km x 9.7 km. The model is a finite difference model. The individual cell sizes vary from 25 m x 25 m, within the vicinity of the Gara pit and underground, to a maximum of 100 m x 100 m in the outer extremes of the model area where less accuracy is required and dewatering impacts are expected not to be as pronounced.

The numerical model design incorporates river/aquifer interaction features to enable representation of both baseflow and recharge from the streams to the groundwater. The Falémé River, Gara River and the creek in the southern boundary were represented using the River (RIV) package, where river bed elevation, river stage and conductance of the riverbed were specified. Groundwater does not flow across the Gara pit, thus the pit area was represented internally with no flow boundaries. The area covered by the no flow boundaries in the pit area was progressively reduced from layer 1 through to layer 4. Drain boundaries set at the pit walls, in areas where groundwater seeps into the Gara pit. The decline actuals were incorporated into the model as drain cells, to simulate steady state groundwater flow condition at the end 2011. A regional recharge value calibrated from 2007 model 1.5E-6 m/d was used as recharge to the model.

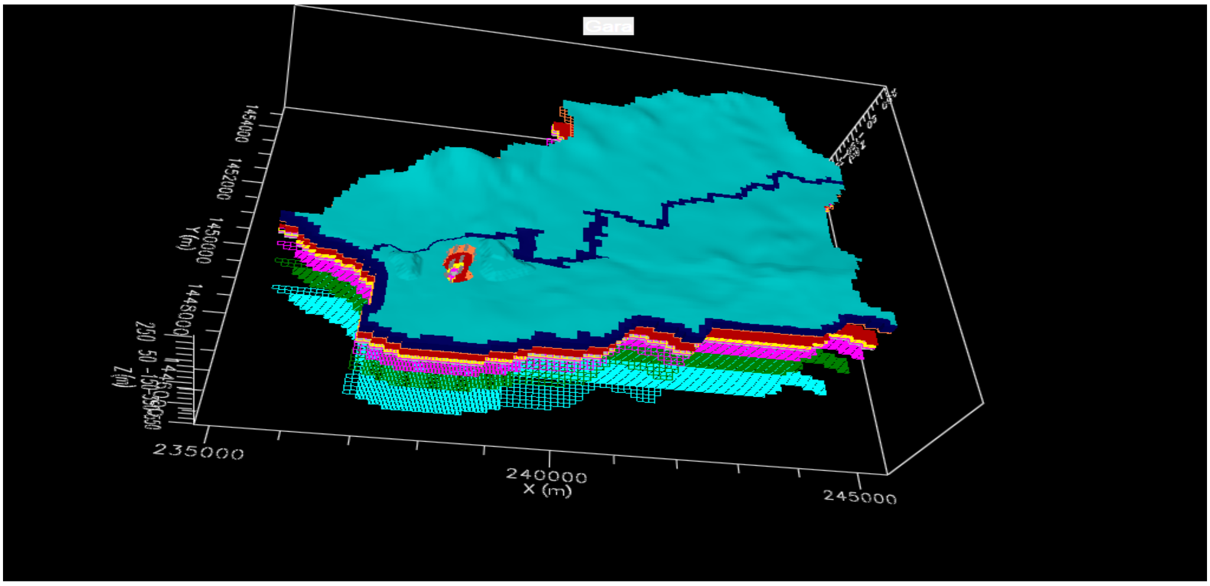


Figure 19. Model setup (not all layers are shown) (Source: DWA, 2012)

The observed heads were used as calibration criteria. The inflow rate into the modelled decline was compared to the average observed discharge rate from the Gara underground. Steady state calibration of the model was accomplished once the flow and head criteria were showed a reasonable resemblance to the observed values.

The predictive model produced time-variant dewatering requirements for the Gara pit, and underground monthly developments from 40 Level to 285 Level, between January 2012 and December 2014. The mine plan from January 2015 onwards is not detailed.

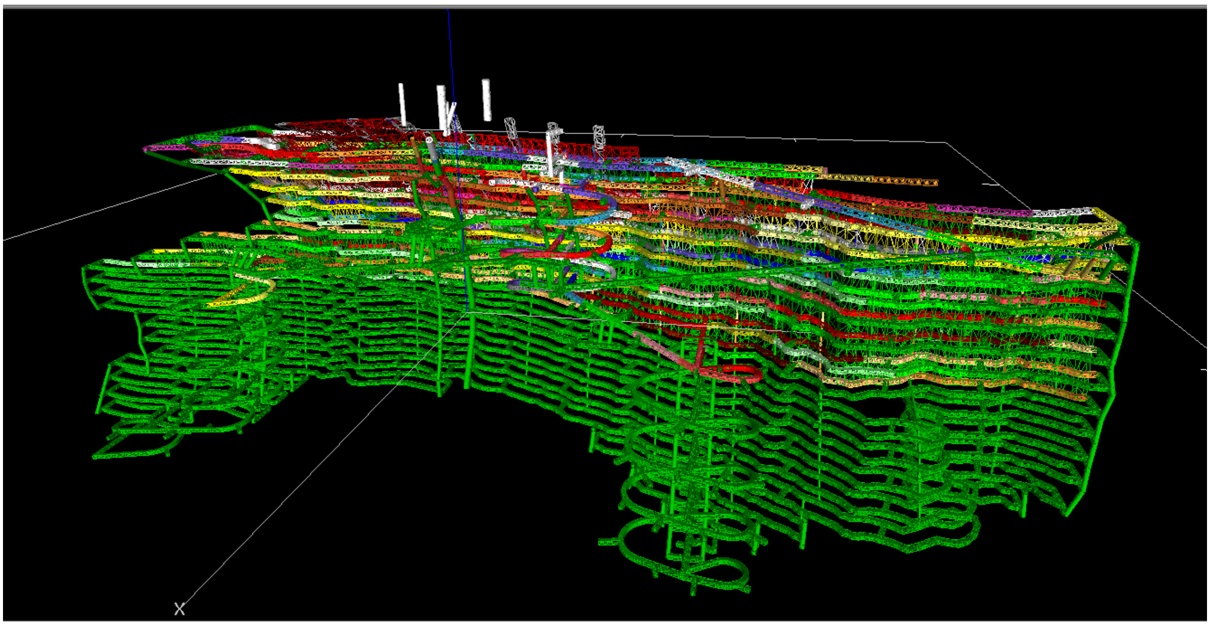


Figure 20. Gara Underground mine plan (rotated 110̊ clockwise to show decline) (Source: Loulo Gold mine, 2012)

Results

The predicted inflows increase with increasing depth below surface. This is due to increases in the groundwater flow gradients and the flux area contributing to ingress into the underground workings) as new levels are being developed. The model predicted a total underground inflow of 3600m³/d for March 2012. A maximum inflow of 6100m³/d is expected in November 2012. The cumulative effect of the unknown details of the mine plan after 2015 is depicted by an unusual rise in total influx from January 2015. However, the predicted maximum inflow of 17000m³/d in January 2015 is not expected to occur. The findings of the model are summarized below:

- The groundwater model is more sensitive to the storage of the aquifer (than the recharge and transmissivity). Increase in confined and unconfined storage may increase the dewatering requirement by up to 55%. The actual storage coefficient will be evaluated after aquifer tests.
- Groundwater inflow into the actual decline is expected to drop from a maximum of 820m³/d in January 2012 to a minimum of 600m³/d in October 2012, after which it will range below 620m³/d till the end of mining.
- Groundwater inflow into developments in 40 Level is predicted to drop down to 34m³/d by October 2012. A maximum inflow, 300m³/d, into producing stopes of 40 Level is expected to occur in March 2012. Little or no seepage is expected into any 40 level developments from November 2012 onwards.
- A maximum inflow of 1300 m³/d into 65 Level is expected to occur in March 2012. 65 Level inflows are expected to decrease to 12.6m³/d by the end of 2014.
- Inflow into 85 Level is predicted to rise to a maximum of 1760.8m³/d in October 2012, then decrease to 560m³/d at by the end of 2014.
- Groundwater inflow into 110 Level is significantly less than the other levels. 110 Level inflows are not expected to rise above 500m³/d during mining. A maximum of 420m³/d is predicted to occur in October 2012.
- Inflow into 135 Level is expected to be below 500m³/d in 2012. 135 Level inflows are predicted to rise to 1020m³/d in June 2013, after which it decreases to 780m³/d at the end of 2014.
- An average inflow 560m³/d is predicted for the first three years of mining at 160 Level, during which a maximum inflow of 748.1m³/d is expected to occur in April 2012.
- Groundwater inflow rates between 1000m³/d and 1200m³/d are predicted in 185 Level from November 2012 to January 2014. Higher inflows are expected from January 2015 as more areas in 185 Level are mined.
- A maximum inflow of 460m³/d into 210 Level is predicted between 2012 and 2014. Higher inflows in should be expected from January 2014 onwards.

- The predicted inflows from 235 Level to 285 Level range below 500m³/d, till the end of 2014. Major developments in these levels are scheduled to occur after 2014. These will result to elevated inflows, and dewatering requirements.
- The model predicts decreasing groundwater inflow into Gara pit as the underground mine develops. As more levels are mined, the groundwater gradient towards the open pit walls are reduced, thus the reduction of inflow. The pit inflows are expected to drop to 430m³/d by the end of 2014, and even less from 2015 onwards. It should however be noted that during the rainy season, pit dewatering requirements are expected to increase. Sump pumping will be suitable to handle rainfall events.
- There are seven candidate dewatering boreholes at the Gara pit. They include: DWA06, DWA08, DWA09, 3-850, 6-280N, 16-540N, and 16-940N. The maximum borehole depth for these boreholes is 200mbgl. This correlates to fractured systems extending to 110 Level.
- Maximum pumping at a rate of 6100m³/d is required during the first three years of mining to ensure workable conditions underground. During this time, Gara pit dewatering requirement would decrease to 430m³/d.
- The progress of underground mining will reduce the pressure in the pit walls, reducing inflow into the pit as the underground mine advances. The two sumps in Gara pit can effectively handle pit inflows. If however inflows into the pit are to be reduced by any perimeter borehole, 16-540N should be used to reduce in-pit dewatering requirement by 40%. 16-940N can also be used in conjunction with 16-540N, the cumulative effect will reduce inflows through the north wall damaged zone.

Data calibration

Steady state calibration of the model was accomplished once the head criteria showed a reasonable resemblance to the observed values. The calculated versus observed groundwater levels are depicted in Figure 21. The steady state water balance is shown in Figure 22. As depicted in Figure 21 the calculated groundwater levels plot close to the 45 degree line which represents the perfect fit between calculated and observed values. Eight of the thirteen calculated groundwater levels fall within the 95% confidence interval, while the five plot within the 95% interval. The 95% confidence interval show the range of calculated values for each observed value with 95% confidence that the simulation results will be acceptable for a given observed value. The 95% interval is the interval where 95% of the total number of data points is expected to occur.

The maximum residual (difference between calculated and observed groundwater level) is 11.63m as calculated for borehole DWA06. The minimum residual is -0.172m at borehole BH12. The absolute mean residual is calculated to be 4 m, indicating that on average the calculated groundwater levels are 2.7m above the levels measured in the field.

An inflow rate of 2,199.5m³/d, comparable to the average discharge rate of 2,528m³/d, was simulated as steady state groundwater inflow rate into the modelled decline.

The hydraulic conductivity zones used to achieve calibration are depicted in Table 4 and Figure 22.

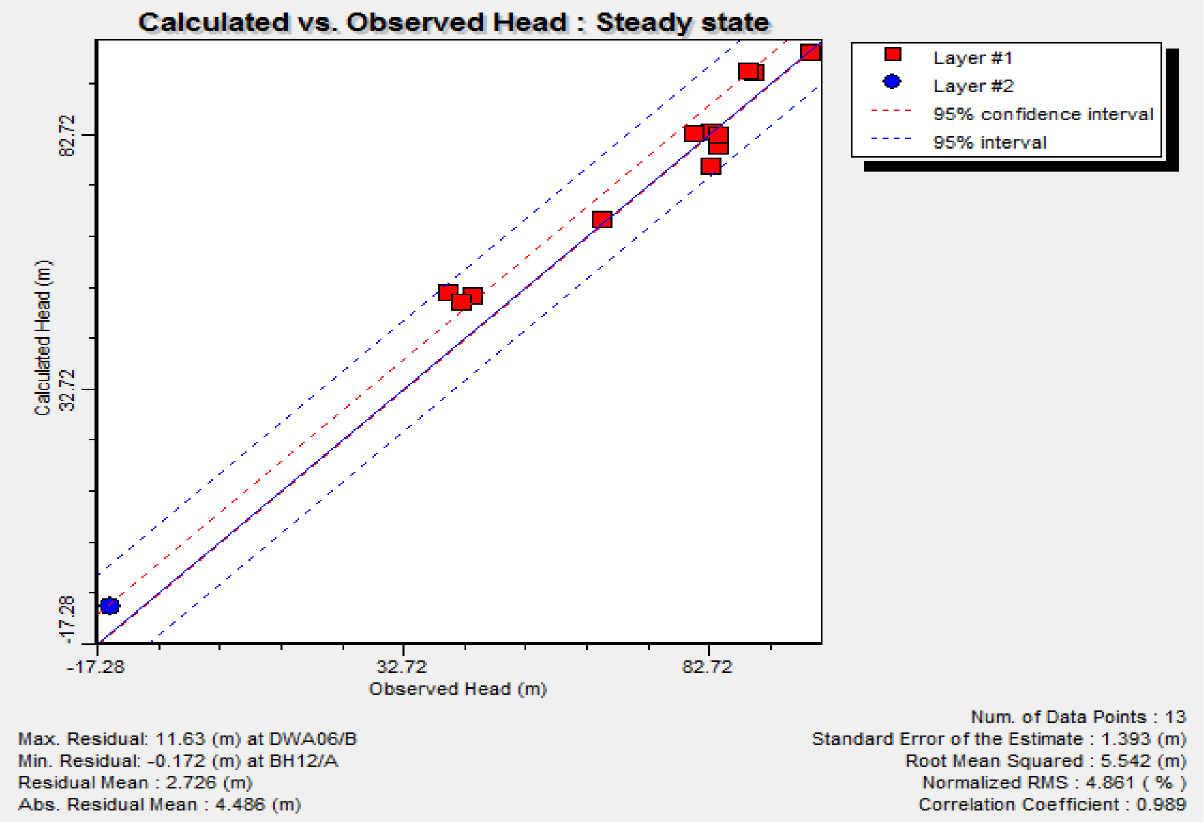


Figure 21. Calculated vs. observed groundwater levels

Table 4. Steady state calibrated hydraulic conductivity (K) values

Zone	Khx(m/d)	Kv(m/d)
Layer 1 matrix	3.92E-03	3.92E-05
Layer 2 matrix	9.00E-04	9.00E-05
Layer 3 matrix	2.00E-04	2.00E-05
Layer 4 matrix	5.00E-04	5.00E-05
Layer 5 matrix	3.30E-04	3.30E-05
Layer 6 to 25 matrix	4.80E-04	4.80E-05
NNE trending fault	2.50E+00	2.50E-01
NE trending fault	1.50E+00	1.50E-01
NW trending fault	1.00E-04	1.00E-05
EW trending fault	5.00E-02	5.00E-03
DTM Structure north of pit	5.00E-01	5.00E-02
Dolerite NW of pit	1.00E-04	1.00E-05

Zone	Khx(m/d)	Kv(m/d)
Dolerite SW of pit	1.00E-05	1.00E-06

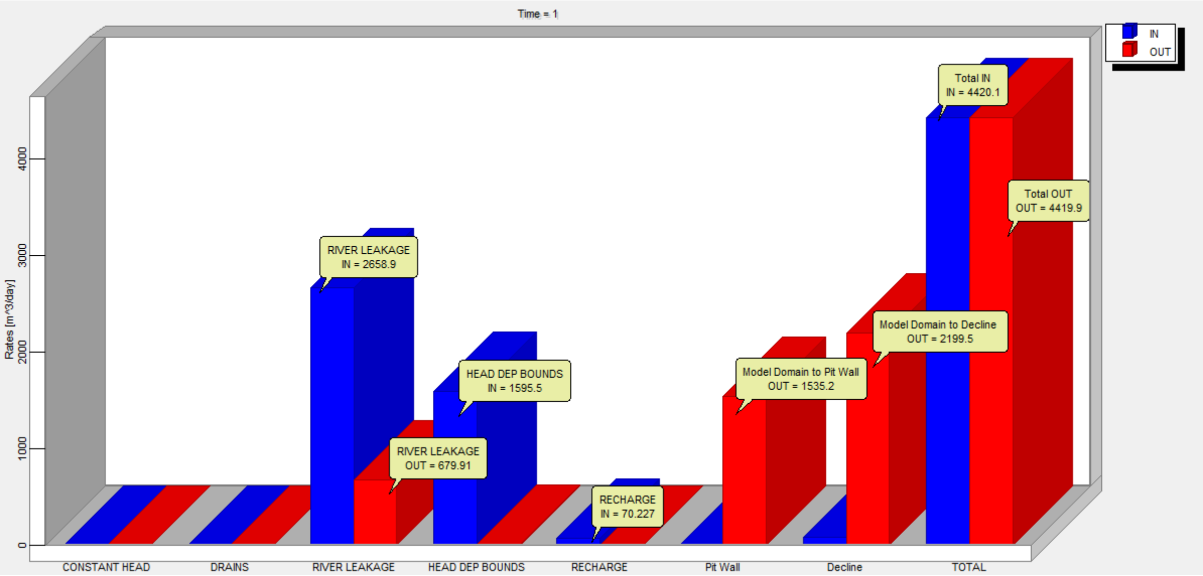


Figure 22. Steady state water balance

6.1.3. Conclusion

Historical data averaged over time returned 1671m3/day and the predictive model over the life of mine indicated an average flow of 2528 m3/day.

6.2. Water quality

Discharge quality data has been generated monthly over 4 years (2010 - 2014) – water sampling has followed standard sampling procedures and analyses were done at the SGS Laboratory in Ghana (an ISO 17025 certified lab). The results are shown in Appendix B. chemical elements of concerns include nitrate (NO_3), total suspended solids (TSS), and to a lesser extent heavy metals (Aluminium, Iron, and traces of copper, Arsenic, cadmium etc). Below is a series of graphs showing the elements of concerns compared to the Malian water discharge quality limit (see Table 2).

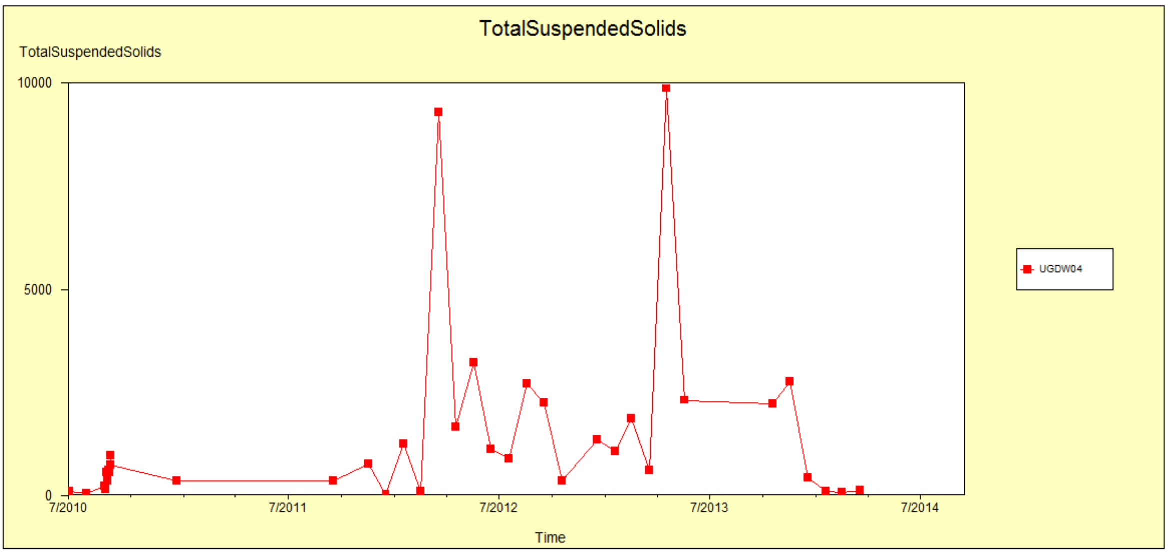


Figure 23. Variations of total suspended solids (TSS) in the final discharge

As shown above the maximum suspended solids (TSS) value recorded was 9870 mg/l in May 2013 and a minimum value of 18 mg/l in January 2012. Average value recorded from 2010 to 2014 is 1435.7 mg/l (largely above the accepted limit as indicated in Appendix B).

A grab sample of solids in the surface settling pond was analyzed in 2012 in South Africa and in 2014 at the laboratory of the University of Sciences and Techniques (FAST) in Bamako to determine its metal content (results are summarized in Table 5). Arsenic (As) and Manganese (Mn) were determined to be elevated compared to limits established by McDonald in 2000. The Gara ore being relatively Arsenic (As) depleted (Lawrence et al., 2013), that being locked up in pyrite (<1 wt.% As), the 64-78 mg/kg (vs. 33 mg/Kg as guideline) determined in the settling ponds maybe due to localised arseno pyrite zones which hasn't been picked up in previous petrography work. Another analysis done by Patterson and Cooke on sediment in the effluent indicated no particular issue in the solids. The high Manganese (Mn) levels (2050 mg/Kg vs. 1100 mg/Kg guideline) are likely sourced from the Kofi limestones, which are common along the Senegal-Mali Shear Zone. The effluent sediments are classified as toxic according to McDonald et al. (2000).

Table 5. Effluents Solids analyses results for heavy metals

	Mn -(ppm)	Cr – (ppm)	V (ppm)	Ba (ppm)	As (ppm)	Mo (ppm)	Nb (ppm)	Zr (ppm)	Sr (ppm)	Rb (ppm)	Cl (ppm)	Au (ppm)	Zn (ppm)	Cu (ppm)
2012 Survey	2050	55			64									
Sample 1 (FAST, 2014)	462		226	498	72	7	6	90	129	36	526	< 20	79	< 15
Sample 2	501		197	414	78	8	6	93	122	23	< 70	< 20	60	< 15

	Mn -(ppm)	Cr – (ppm)	V (ppm)	Ba (ppm)	As (ppm)	Mo (ppm)	Nb (ppm)	Zr (ppm)	Sr (ppm)	Rb (ppm)	Cl (ppm)	Au (ppm)	Zn (ppm)	Cu (ppm)
(FAST, 2014)														
Aquatic ecosystem integrity survey, 2014	170	35			74								38	22
Guideline (McDonald, 2000)	1100	111			33									149

As shown below, the maximum value recorded was 51.3 mg/l (May 2013) and the last aluminum value was at 4.79 mg/l which is above the Malian discharge limit of 1mg/l.

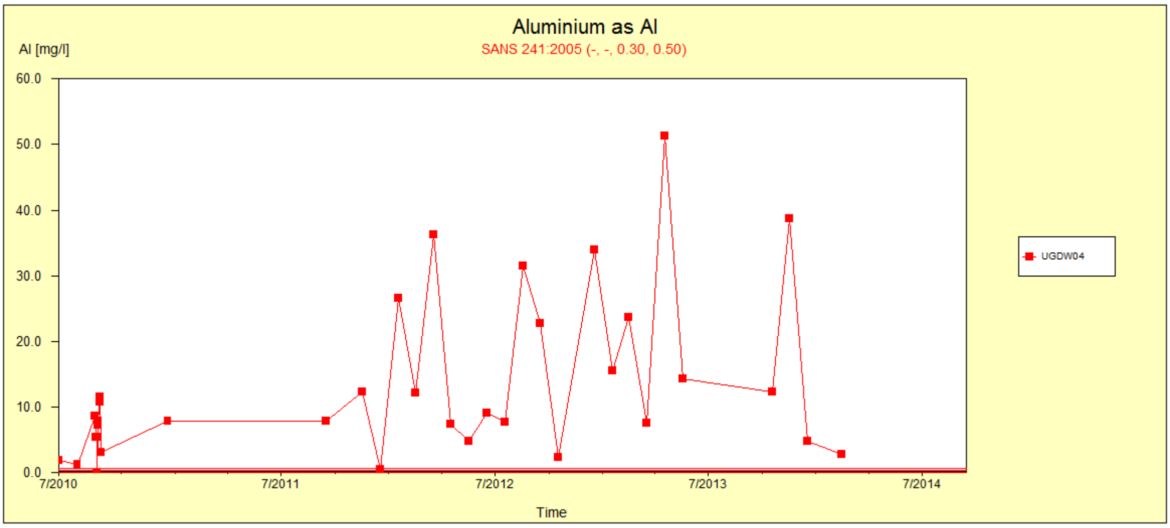


Figure 24. Variations of Aluminium (Al) in the final discharge

Iron level is fluctuating around an average of 19.8 mg/l with a maximum of 110 mg/l recorded on May 2013 - the limit is 2 mg/l – see graph below.

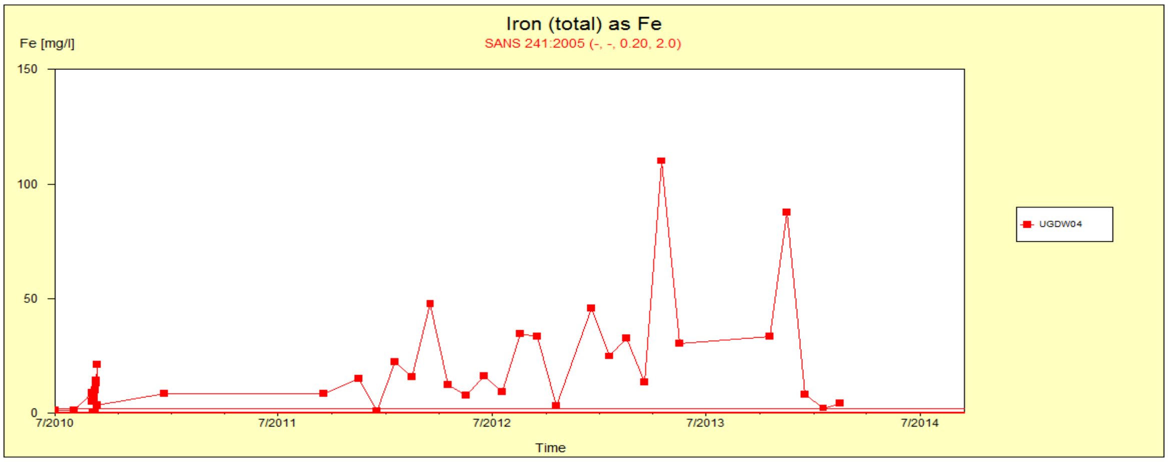


Figure 25. Variations of total Iron (Fe-Total) in the final discharge

Nitrate average value since 2010 is 159.2 mg/l – vs. a limit of 30 mg/l. the variation is shown in the graph below

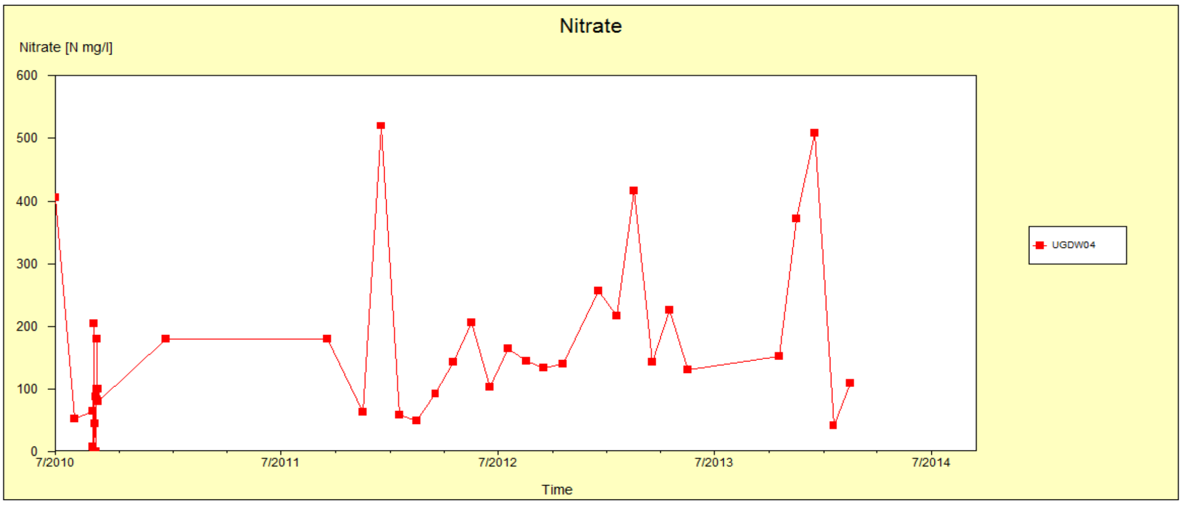


Figure 26. Variations of Nitrate (NO_3) in the final discharge

Human health impacts is the norm used for nitrate standard determination in the South African Drinking Water Standard and Target water quality guideline for domestic use, which is set at 6 mg/L as N (equivalent to 26.6 mg/l as NO_3). The reason for this is that Nitrate readily converts in the gastrointestinal tract to nitrite as a result of bacterial reduction. Nitrite, upon absorption, combines with haemoglobin, the oxygen carrying red blood pigment, to form methaemaglobin, rendering the blood incapable of carrying oxygen – a disease known as methemoglobinanemia. Arterial blood with elevated methaemaglobin levels has a characteristic chocolate-brown colour as compared to normal bright red oxygen containing arterial blood. Values between 6 and 20mg/L as N could lead to methaemaglobinanemia in infants, while values above 20mg/L will cause methaemaglobinanemia in children, and mucus membrane irritations in adults. Signs and symptoms of methemoglobinanemia (methaemaglobin >1%) include shortness of breath, cyanosis, mental status changes, headache, fatigue, exercise intolerance, dizziness and loss of consciousness. Severe methemoglobinanemia (methaemaglobin >50%) patients have dysrhythmias, seizures, coma and death. Metabolically, nitrates may also react with amines and amides, commonly found in food such as meat to form nitrosamines, which are known carcinogens (cancer causing agents), and which can lead to especially stomach cancer (SABS, 1996).

Sulfate level is below the guideline of 1000 mg/l but has increased since 2010. The levels should continue to be monitored as it is possible that they may increase over time as the mine working ages and continue to access new areas exposing new faces to oxidation. A graph below shows the variation of sulfate levels.

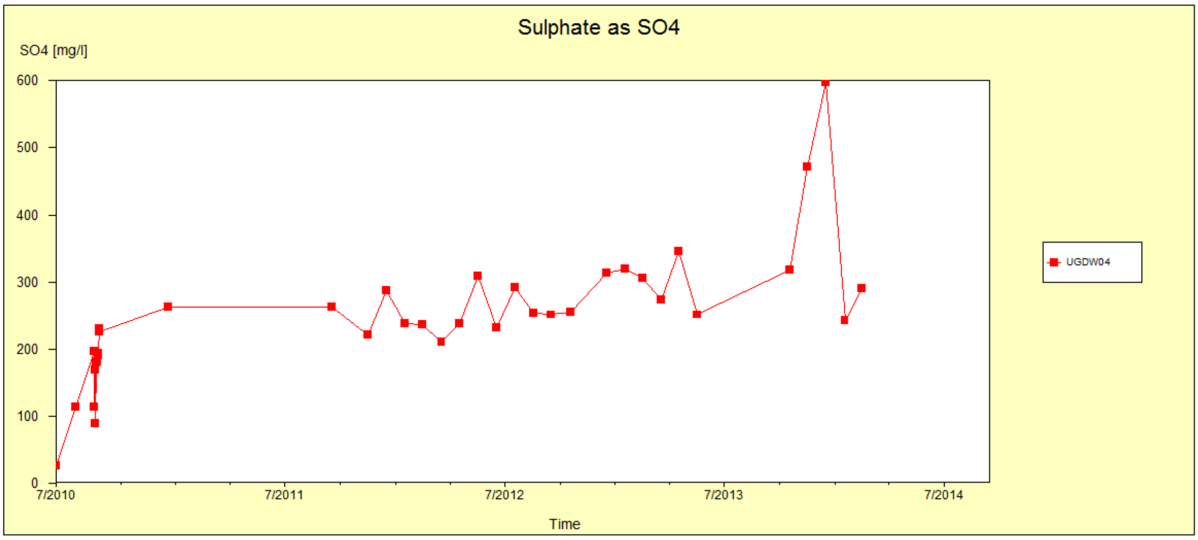


Figure 27. Variations of Sulfate (SO4) in the final discharge

.

The Summary quality data of water being discharged from the underground before (Table 6) and after (Table 7) current treatment is shown below:

Table 6. Quality data of the discharge before settling (2010-2014)

	unit	Max	Min	Average	limits
Aluminium	mg/l	162	0.04	18.8	1
Nitrate	mg/l	428	2.02	134.7	30
Suspended Solids	mg/l	17000	0.01	2130	30
Sulphate	mg/l	369	20	228.5	1000
Iron	mg/l	242	0.7	27.6	2

Table 7. Quality data of the discharge after existing settlers

	unit	Max	Min	Average	limits
Aluminium	mg/l	51.3	0.41	13.4	1
Nitrate	mg/l	520	49.2	159.2	30
Suspended Solids	mg/l	9870	18	1435.7	30
Sulphate	mg/l	471	26	248.1	1000
Iron	mg/l	110	0.8	19.4	2

From what precedes, it is evident the quality of water being discharged into the adjacent river is substandard (compared to the Malian discharge standards) and requires improvement of the current treatment system prior to discharge as per the water code –

The next section evaluates the current health state of the Faleme river ecosystem to determine any impact related to the past discharge of this substandard mine effluent.

7 Faleme River Ecosystem Assessment

7.1. Information on the Faleme

The river originates in Guinea, approximately 250km upstream of the study area and joins another large river, the Senegal river 270 km downstream of the mine, whereafter it flows 590 km before entering the Atlantic Ocean as the Senegal River. The river is managed by a Basin Management Authority (OMVS – Organisation for utilizing the Senegal River) with the Governments of Guinea, Mali, Senegal and Mauritania having input. The river is also a vital lifeline to communities living along it and is the only regional water supply in the area during drought conditions. The Falémé River forms the Mali border with Senegal, and has the westward flowing Garra River as a tributary; these two rivers converge approximately 1.5 km north of the mine site. Other rivers in the Loulo region include the Loulo Kaba River. The catchment areas for the Falémé River, Garra River and the Loulo Kaba River are 17 100 km^2, 561 km^2 and 32 km^2 respectively. (DWA, 2009).

Previous studies have analyzed the 41-year flow record in the Falémé River to determine the Average, Minimum and Maximum monthly flow rates. There are two catchments identified namely the Falémé and Gara catchments. By proportioning the flow according to the catchment ratios, corresponding data was estimated for the Gara River as summarised in Table 8.

Table 8. Summary of water quantity of the two catchments (Source: DWA, 2009)

Month	Monthly Flow Rate (m3/s)			
	Falémé Catchment		Gara Catchment	
	Sept	Annual	Sept	Annual

Min	69.1	20.7	2.2	0.7
Mean	515	110	16.2	3.5
Max	1 250	223	39.4	7.0

Note: September has the highest flow rates per annum.

The lowest annual flow for Falémé River was 20.7 m^3/s compared to the Gara River which is 0.7 m^3/s. Gara River is a perennial river which is tributary to the Falémé River. The surrounding villages of Djidian-Kenieba (DK), Loulo, Baboto and Sakola use the available surface and groundwater (Falémé River and Gara Dam). Water collected by the villages is used for personal drinking water, clothes washing, drinking water for cattle and crop irrigation (Digby Wells, 2009).

7.2. Methodologies

A study was carried out in July 2014 to evaluate the health of the Faleme river ecosystem. The assessment consisted of chemical analysis of water (effluent and rievers water), metal analysis of sediments and fish tissue and the assessment of the state of the local fish and macroinvertebrates communities and habitat. Areas have been sampled also in the Faleme at Gounkoto area (upstream of the study area) and at artisanal mining sites to help in the interpretation of the results. Below are a table and a figure showing the different sampling points.

Table 9. Sampling points and description (Modified from DWA, 2012)

Site	Description	Water	Sediment	Fish Tissue
FL1	Falémé River downstream of Loulo operation (weir)	√	√	√
FL2	Falémé River upstream of operation	√	√	√
GR1	In the lower reaches of the Garra Dam adjacent to the Loulo camp	√	√	√
GR2	At the Garra River bridge downstream of the local orpailleurs (artisanal miners)	√	√	√
GK1	Falémé River downstream of Gounkoto operation	√	√	
GK2	Falémé River upstream of Gounkoto operation	√	√	
PC1	Surface settlers (referred to as Settling ponds)	√	√	
PC-UP	Immediately Upstream of the discharge area into the Falémé River	√	√	
PC-DWN	Immediately Downstream of the discharge area into the Falémé River	√	√	

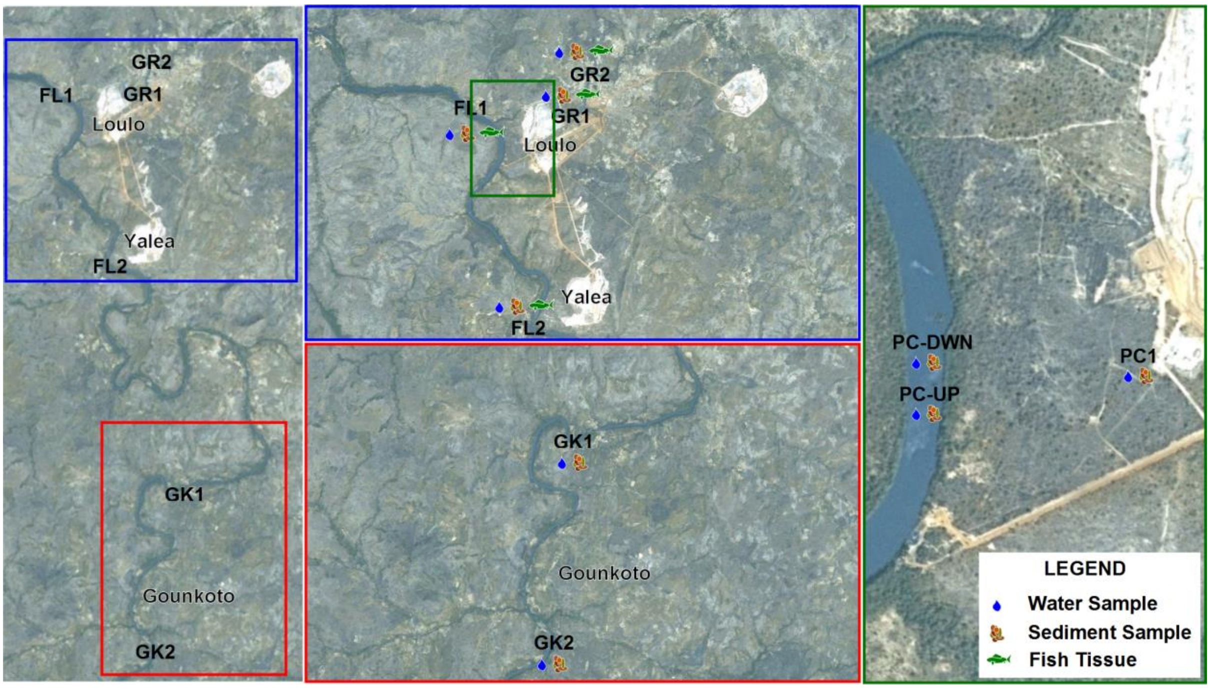


Figure 28. Arial map showing the sampling points (Source: DWA, 2012)

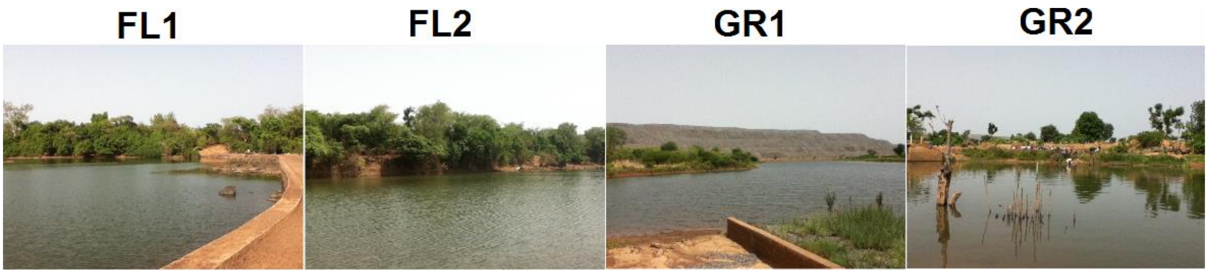


Figure 29. Photography of the sampling points at Faleme and Garra (Source: modified from DWA, 2012)

7.2.1. Habitat assessment

The habitat integrity of a river refers to the maintenance of a balanced composition of physico-chemical and habitat characteristics on a temporal and spatial scale that are comparable to the characteristics of natural habitats of the region (Kleynhans 1996). Methodologies developed for the Rapid Bioassessment Protocols for use in Streams and Wadeable Rivers (USEPA, 2006) for low gradient systems were primarily applied for the assessment of the habitat. This was assessed and characterized according to section D of the "Procedure for Rapid Determination of Resource Directed Measures for River Ecosystems, 1999". It should be noted that the Intermediate Habitat Assessment Integrity (IHAI) was based on regions assessed in the current studies and therefore may only constitute the assessment of conditions within a 50 km length of the potentially effected water courses. The table below shows the scoring system.

Table 10. Description of IHAS scores with the respective percentage category (McMillan, 1998)

IHAS Score (%)	Description
>75	Very Good
65 – 74	Good
55 – 64	Fair/Adequate
< 55	Poor

7.2.2. Water quality

Water quality analysis was completed for the project utilising a calibrated water quality meter (EXTECH, DO700). In addition to this, laboratory analysis of water was completed. The analysis involved the determination of metal content as well as the concentrations of macronutrients such as nitrate, nitrite and phosphate. The analysis involved the use of spectrophotometry applying techniques used in Inductively Coupled Plasma Mass spectrophotometry (ICP-MS) as well as ICP- Optical Emission Spectrophotometry (ICP-OES). The laboratory testing of water was be completed by SGS in Bamako, Mali. The water quality data during the study was validated using the quality data generated over 4 years for the Falémé river and then compared to the water quality guidelines for aquatic ecosystems as described by the Department of Water Affairs for South Africa (1996). Where guidelines were not prescribed for selected constituents, the guidelines described for domestic use were considered since this is believed to be the top use of the Faleme by the riverine communities.

7.2.3. Sediment

Sediment samples were collected using a plastic spoon where the top 2/3 cm of the sediment surface was utilized. Sediment samples were then placed into plastic bottles and analysed according to USEPA 2006 guidelines with ICP-MS. The following indices were applied according to Pheiffer *et al*. (2014): the Enrichment Factor (E_f) which provides an indication of enrichment of individual elements emanating from anthropogenic sources; the Geo-accumulation index (I_{geo}) which provides an indication of pollution potential of specific elements; the Pollution Load Index (PLI) which indicates the effect of a mixture of metals; and the Sediment Quality Index. MacDonald *et al.* (2000a) determined the toxicity levels of sediments based on a combination of a number of sediment quality guideline studies in the United States (comprising a total of 17 data sets). Sediments can be placed into one of three classes, based on the level of selected constituents in the sediments. These guidelines were determined for Cadmium, Chromium, Copper, Lead, Mercury, Nickel and Zinc (MacDonald *et al.*, 2000a). In addition to categories described by (MacDonald *et al.*, 2000a), sediment contaminant concentrations obtained during the study were also evaluated against other guidelines and authors, these references are shown in table below.

Table 11. Defined thresholds for metal concentrations in sediments (DWA, 2012)

Analyte	mg/kg dry weight (ppm)			Reference
	EC[1]	MEC[2]	PEC[3]	
Antimony as Sb	2.0	13.5	25.0	Long & Morgan, 1991
Arsenic as As	.79	9.79-33	33	MacDonald et al., 2000a
Barium as Ba	100.0	500.0	3000.0	I.P.C.S., 1990
Cadmium as Cd	.99	0.99-4.98	4.98	MacDonald et al., 2000a
Chromium as Cr	3.4	43.4-111	111	MacDonald et al., 2000a
Cobalt as Co	9.73	13.83	37.1	Masoud et al. (2005)
Copper as Cu	1.6	31.6-149	49	MacDonald et al., 2000a
Lead as Pb	5.8	35.8-128	128	MacDonald et al., 2000a
Manganese as Mn	460.0	780.0	1,100.0	Persuad et al., 1993
Mercury as Hg	0.18	0.18-1.06	1.06	MacDonald et al., 2000a
Nickel as Ni	22.7	22.7-48.6	48.6	MacDonald et al., 2000a
Silver as Ag	1.6	1.9	2.2	MacDonald & MacFarlane, 1999
Zinc as Zn	121	121-459	459	MacDonald et al., 2000a

7.2.4. Aquatic benthic macroinvertebrates

Aquatic macroinvertebrate assemblages are good indicators of localised conditions because many benthic macroinvertebrates have sedentary characteristics with relatively long lives (±1 year) (Barbour et al., 1999). Macroinvertebrates are useful for their ability to integrate pollution effects over time, their detectable response to environmental impacts as well as the easy field sampling techniques involved in their collection. Benthic macroinvertebrate assemblages are made up of species that constitute a broad range of trophic levels and pollution tolerances, thus providing strong information for interpreting cumulative effects (Barbour et al., 1999). The assessment and monitoring of benthic macroinvertebrate communities forms an integral part of the monitoring of the health of an aquatic ecosystem. The sampling protocols of the kick and sweep methodology of the South African Scoring System (SASS, version 5) (Dickens and Graham, 2002) was used for the current assessment. Identification of organisms was then made per family level and the number of individuals was recorded (Thirion et al., 1995; Dickens and Graham, 2002; Gerber and Gabriel, 2002). Both qualitative and quantitative assessments were undertaken. The qualitative analysis followed the United States Environmental Protection Agency's (USEPA) Ephemeroptera (Mayflies), Plecoptera (Stoneflies) and Trichoptera (Caddisflies) (EPT) Taxa Richness Metric. The EPT taxa are considered to be sensitive to pollution and therefore provide information on the state and extent of pollution at a site (Barbour *et al.,* 1996). The results of this assessment provide baseline data for future rapid bio-assessment protocols. The level of impairment at a site was then determined though the characterization of the

[1] Threshold Effect Concentration (TEC)

[2] Midpoint Effect Concentration (MEC)

[3] Probable Effect Concentration (PEC)

EPT taxa, where a high EPT taxa richness would indicate no or low impairment levels and a low EPT taxa richness indicating high impairment levels. The quantitative analysis included the calculation of the following macroinvertebrate indices: the Margalef's Measure of Richness Index (1961), the Shannon-Wiener's Diversity Index (1963), and the Pielou's Evenness Index (1986).

7.2.5. Fish

The use of fish to determine levels of ecological disturbance has many advantages over other bio-assessment techniques (Zhou *et al*., 2008). This is because fish are long lived and populations respond to environmental modification. They are continuously exposed to aquatic conditions, are often migratory, and fulfil higher niches in the aquatic food web. Therefore fish assemblages can provide an effective indication of the degree of modification in the aquatic environment. A variety of techniques was used to sample the available fish species within the project area. These sampling methods included cast nets, fyke nets, gill nets and *electro-fishing* depending on site characteristics. Fish community structures and diversity was determined at each site, this information is investigated as to determine dominant species. The information and specific characteristics on dominant and present fish species, in conjunction with macroinvertebrates data then allowed for the analysis of the current state of the aquatic ecosystem. Muscle tissue samples were removed from the fish species sampled from the Falémé River and frozen. In the laboratory, an inductive coupled plasma mass spectrometry (ICP-MS) was used for metal screening for prepared whole body tissues.

7.3. Results

7.3.1. General Description of the Faleme

The Falémé River is located within the Senegal–Gambia freshwater ecoregion. The river systems associated with this ecoregion experience "pronounced flooding during the wet season" (Thieme, 2014). Due to the scale of the flooding within the ecoregion large floodplains are created resulting in the creation of extensive feeding and breeding grounds for ichthyofauna, with flooding conditions often being responsible for the triggering of migrations. The terrestrial ecology associated with the drainage area of the Falémé River consists of savannah/grasslands within the study focus area with wetter conditions in the southern portion of the river catchment.

The Falémé River's major habitat type, within the study focus area, is described best as "a savannah river system within the middle reaches with a moderate gradient, resulting in large colluvial deposits, moderate entrenchment, scoured and spaced pools with a gentle meandering nature" (Rosgen, 1996). The sinuosity is approximately >1.2 producing stable banks, however, within the study focus area, dolerite dykes are fairly common producing bedrock riffles, large scour pools and at times diverting the path of the river. The general sinuosity and common dykes are illustrated in the figure below (Figure 30).

Large cobble beds often associated with dolerite dykes are also found throughout the study area (Figure 31). These cobble beds are usually dry during the low flow season and inundated during periods of flooding. These cobble beds are likely fish spawning areas and act as high aquatic biodiversity habitats, for this reason they are considered important in the Falémé River system. Based on the importance of these cobble beds for aquatic biodiversity and potential fish spawning grounds a critical habitat assessment would be included in this study. Typical riparian habitat is illustrated in the images below (Figure 32 and Figure 33). The longitudinal profile of the Falémé River is provided in the figure below (Figure 34). It should be noted that this profile is a rough representation of the gradient associated with the sites selected and is based on the height recorded at each sampling site considered in this study. The profile will be used for basic reference purposes only.

Figure 30. Aerial Image of the Falémé River, depicting meandering nature and alluvial deposition (Google Earth)

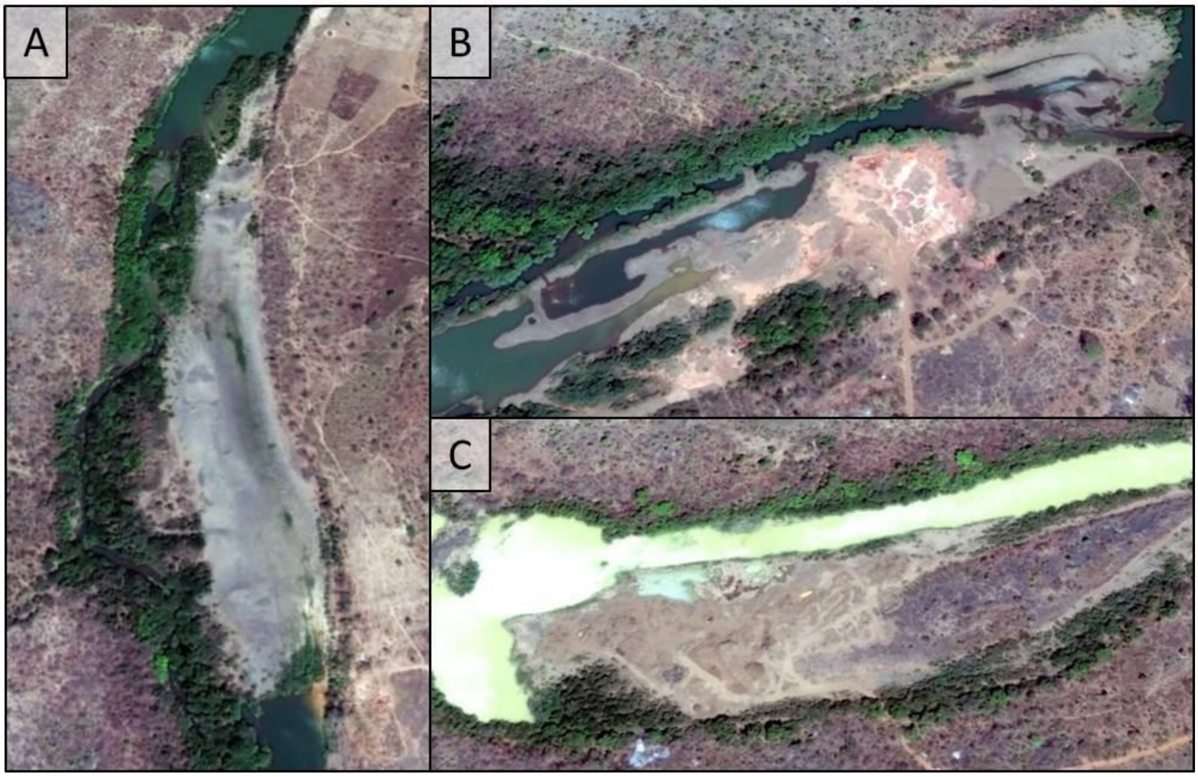


Figure 31. Cobble beds in the Falémé River. A: Natural cobble bed; B: Modified cobble bed; C: Modified cobble bed.

Figure 32. Image of intact riparian habitat (Farandie).

Figure 33. Image of riparian habitat (Cobble Bed)

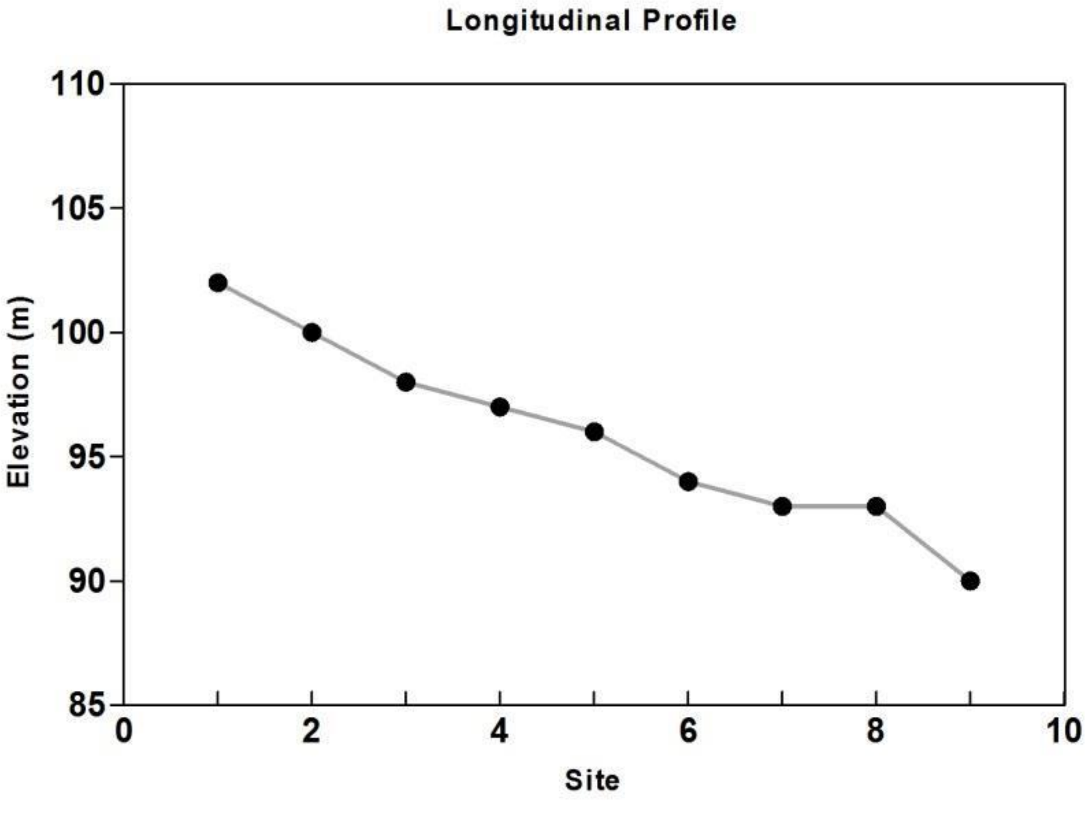


Figure 34. Longitudinal profile of the Falémé River (Google Earth™)

As seen in the above figure the gradient is relatively gentle and therefore geomorphological characteristics should remain relatively constant between sites.

7.3.2. Habitat integrity

The Faleme river habitat was found to be moderately modified or class C with the instream habitat being scoring less than the riparian habitat (62.36 and 76.84 respectively); and the Gara river habiat was found to be largely modified or class D with the instream habitat scoring also less than the riparian one (45.24 and 52.6 respectively). The results are shown in the tables below.

Table 12. IHIA for instream Habitat within the Faleme River (Source: Tate, 2014)

Instream	**Average score**	**Score**
Water abstraction	8	4.48
Flow modification	10	5.2
Bed modification	15	7.8
Channel modification	15	7.8
Water quality	10	5.6
Inundation	5	2
Exotic macrophytes	3	1.08
Exotic fauna	4	1.28
Solid waste disposal	10	2.4
Total Instream	**37.64**	
Category		**62.36**

Table 13. IHIA for Riparian Habitat within the Faleme River (Source: Tate, 2014)

Riparian	**Average score**	**Score**
Indigenous vegetation removal	10	5.2
Exotic vegetation encroachment	5	2.4
Bank erosion	3	1.68
Channel modification	2	0.96
Water abstraction	3	1.56
Inundation	5	2.2
Flow modification	5	2.4
Water quality	13	6.76
Total Riparian	**23.16**	
Category		**76.84**

Table 14. IHIA for instream Habitat within the Gara River (Source: Tate, 2014)

Instream	Average score	Score
Water abstraction	10	5.6
Flow modification	18	9.36
Bed modification	18	9.36
Channel modification	18	9.36
Water quality	18	10.08
Inundation	10	4
Exotic macrophytes	5	1.8
Exotic fauna	5	1.6
Solid waste disposal	15	3.6
Total Instream	**54.76**	
Category		**45.24**

Table 15. IHIA for Riparian Habitat within the Gara River (Source: Tate, 2014)

Riparian	Average score	Score
Indigenous vegetation removal	15	7.8
Exotic vegetation encroachment	5	2.4
Bank erosion	10	5.6
Channel modification	10	4.8
Water abstraction	10	5.2
Inundation	15	6.6
Flow modification	15	7.2
Water quality	15	7.8
Total Riparian	**47.4**	
Category		**52.6**

7.3.3. Water quality

The results of the *in situ* water quality analysis are presented in the table below (Table 16). Water quality guidelines utilized were the DWAF aquatic ecosystems guidelines. The rationality for this is that these guidelines are designed specifically for aquatic biota. Current available guidelines for East, Central and West Africa do not take into consideration sensitive aquatic biota and are based on human needs.

Table 16. Water quality results obtained during the 2014 July survey

Constituent	pH	Temperature (ºC)	Conductivity (µS/cm)	DO (mg/L)	DO saturation (%)	Clarity (cm)
Guideline/Site	**6.5-9**	**10-35**	**<700**	**>5**	**60-120**	**N/A**
GK Upstream	7.3	30	84.0	4.9	70	41
GK Midstream	7.4	31	87.0	4.8	67	47
GK Downstream	7.3	31	93.0	5.2	71	13
Border Bridge	7.5	32	115	3.5	45	22
Downstream Sasanba	7.4	29	73.0	5.4	71	6.0
Cobble Bed	7.4	31	93.0	6.2	85	17
Farandie	7.6	31	100	2.4	31	37
Upstream Gara Discharge	7.8	33	111.0	6.9	80	19
Gara Settling Discharge	8	31	1332	6.5	87	2.0
Downstream Gara Discharge	7.4	29	140.0	5.4	71	18
Faleme Weir	7.5	32	103.0	7.2	105	28
Artisanal Tributary	7.5	29	37.0	4.4	71	6.0
DK Bridge	7.6	33	202.0	3.1	40	30
Gara Dam	7.8	33	182.0	7.3	87	25
Gara Settling Pond	7.8	33	1950	4.5	59	N/A
***Red shading denotes values not within recommended guidelines.**						

Based on results observed in the above table (Table 16), the pH values of the Faleme River range from 7.3 at upstream of gounkoto to 7.8 at the site upstream of the Gara settling pond effluent. The range of pH in the Gara River was found to be relatively small, from 7.5 at the Artisanal Tributary to 7.8 in the Gara Dam. The pH of the Gara settling ponds was found to be basic and was at 8. Temperatures were found to be relatively constant throughout the study and were predominantly measured at approximately to 30 ºC. Conductivity was found to be relatively low in the Faleme River and ranged from 73 µS/cm at the site downstream of the artisanal mining village Sasanba to 115 µS/cm at the Border Bridge site. Conductivity in the Gara River was also found to be relatively low and ranged from 37 µS/cm at the Artisanal Tributary to 202 µS/cm at the DK bridge site. Concentrations of Dissolved Oxygen (DO) in the Faleme River ranged from 2.4 mg/l to 7.2 at the Faleme Weir site. DO levels in the Gara River were found to range from 3.1 at DK Bridge to 7.3 in the Gara Dam.

The results of the chemical analysis of samples from the sites considered in this study are presented in Table 17. Total phosphorus concentrations were found to be exceeding guideline values at several sites including Faleme downstream of Gounkoto, Faleme downstream of artisanal mining areas, Faleme downstream of gara settling pond, and the Gara settling pond. Nitrite values were found to be exceeding recommended guideline values in the Gara effluent. The concentrations of Nitrate were found to be elevated beyond guideline concentrations at Gara settling discharge. Ammonia levels at sites Faleme upstream of Gounkoto, Gara settling discharge, Faleme Weir, Gara Bridge, and the Gara settling pond were found to be elevated. Dissolved arsenic (As) concentrations were found to be exceeding guideline values at Faleme downstream of artisanal mining areas and slightly at the gara effluent settling ponds. Concentrations of Copper (Cu) were found to be below recommended guideline values. Chromium concentrations were found to be above guideline values at Faleme downstream of artisanal mining areas and the Gara settling pond. Concentrations of Cobalt (Co), Cadmium (Cd) and Mercury (Hg) were found to be below guideline values at all sites. However the mercury values were noteworthy at Faleme close to artisanal mining areas. Levels of dissolved Lead (Pb) were found to be above guideline concentrations at Faleme close to artisanal mining areas. The following sites had elevated concentrations of Manganese (Mn) above recommended guideline values; Faleme at Gounkoto, Faleme downstream of artisanal mining areas and the Gara settling pond. Concentrations of Zinc (Zn) were found to be above recommended guideline values at sites upstream of Gounkoto, Faleme at artisanal mining areas as well as the Gara settling ponds. The concentrations of dissolved Aluminium (Al) were found to be exceeding recommended guideline values at all sites with the exception of the Faleme Weir.

Table 17. Chemical analysis of water from the sites considered in the 2014 survey ($mg.l^{-1}$)

Guideline	**6-9**	**< 200**	**<6***	**<6***	**<0.2**	**<0.01**	**<0.1**	**<0.012**	**N/A**	**<0.15**	**<0.006**	**<0.01**	**<0.18**	**<0.002**
Description	**pH***	**SO4**	**NO2**	**NO3**	**NH3**	**As**	**Cu**	**Cr**	**Co**	**Cd**	**Hg**	**Pb**	**Mn**	**Zn**
Upstream GK	7.3	1	<0.05	<0.06	0.22	0.001	0.001	<0.001	<0.001	<0.0001	<0.0001	<0.0005	0.031	0.021
Midstream GK	7.4	2	<0.05	0.52	0.18	0.001	0.001	<0.001	<0.001	<0.0001	<0.0001	<0.0005	0.02	0.009
Downstream GK	7.3	5	<0.05	0.22	0.19	0.002	0.006	0.004	<0.001	<0.0001	<0.0001	0.0008	0.045	0.009
Sasanba DS	7	9	0.11	3.07	0.15	0.24	0.054	0.089	0.058	0.0004	0.003	0.1	1.42	0.083
Farandie	7.6	3	<0.05	0.6	0.12	0.004	0.001	<0.001	<0.001	<0.0001	<0.0001	<0.0005	0.016	0.006
Us settling	7.3	4	0.06	0.92	0.2	0.007	0.004	0.001	0.003	<0.0001	<0.0001	0.0005	0.056	0.006
Gara settling discharge	7.7	94	10.2	96.5	3.59	0.017	0.004	0.008	0.001	<0.0001	<0.0001	<0.0005	0.011	0.007
Ds settling	7.2	4	0.08	0.89	0.14	0.012	0.006	0.004	0.002	<0.0001	<0.0001	0.0012	0.085	0.008
Faleme Weir	7.7	4	<0.05	0.65	0.49	0.003	0.003	<0.001	<0.001	<0.0001	<0.0001	<0.0005	0.01	0.005
Artisanal Area	6.7	27.	0.26	0.7	0.1	0.02	0.012	0.013	0.007	0.0007	0.004	0.0043	0.18	0.021
Artisanal tributary	6.4	8.	0.07	2.96	0.1	0.011	0.009	0.014	0.004	<0.0001	<0.0001	0.0042	0.075	0.028
DK bridge	7.3	4.	<0.05	<0.06	0.41	0.006	0.004	0.005	0.002	<0.0001	<0.0001	0.0014	0.078	0.011
Gara dam	7.6	4.	<0.05	<0.06	0.22	0.004	0.001	0.002	<0.001	<0.0001	<0.0001	0.0005	0.092	0.005
Gara settling pond	7.6	198.	8.9	180.	22.7	0.043	0.017	0.025	0.007	<0.0001	<0.0001	0.0019	0.2	0.038

Guideline	6-9	< 200	<6*	<6*	<0.2	<0.01	<0.1	<0.012	N/A	<0.15	<0.006	<0.01	<0.18	<0.002
* Red Shading denotes constituent exceeding recommend guideline, Yellow shading denotes elevated constituent														

7.3.4. Sediment quality

Sediment samples analyses results are shown below in Table 18.

The majority of elements analysed were found to be below the Threshold Effect Concentrations (TEC). Elements found to be exceeding the Probable Effect Concentrations (PEC) were arsenic (As), chromium (Cr) and mercury (Hg). Levels of As were found to be exceeding the Midpoint Effect Concentrations (MEC) at sites Faleme Downstream of Gounkoto, Faleme & gara at artisanal mining areas, and Gara Bridge. Concentrations of As were found to be exceeding PEC concentrations at Faleme Midstream of Gounkoto, Faleme at artisanal mining areas, Faleme at Gara Settling Discharge, and Gara underground Settling pond. Levels of As were found to be excessively high (above 100 mg.kg-1) at Faleme Midstream of Gounkoto, and Faleme at artisanal mining areas.

Table 18. Chemical analysis of sediment samples collected during the July 2014 survey (mg.kg^{-1})

TEC	9.79	31.6	43.4	9.73	0.99	35.8	460	121	N/A	N/A	0.18
MEC	**9.79-33**	**31.6-149**	**43.4-111**	**11.83**	**0.99-4.98**	**35.8-128**	**780**	**121-459**	**N/A**	**N/A**	**0.18-1.06**
PEC	**>33**	**>149**	**>111**	**>37.1**	**>4.98**	**>128**	**>1100**	**>459**	**N/A**	**N/A**	**>1.06**
Description	**As**	**Cu**	**Cr**	**Co**	**Cd**	**Pb**	**Mn**	**Zn**	**Al**	**Fe**	**Hg**
UPSTREAM GK	4	8.4	37	5	<0.3	4	120	11	4300	14000	<0.06
MIDSTREAM GK	410	62	97	8.5	0.4	8	210	24	2900	35000	0.1
DOWNSTREAM GK	16	8.8	33	3.8	<0.3	3	110	10	3100	13000	<0.06
SASAMBA ARTISINAL STREAM	260	22	38	11	<0.3	10	270	25	4300	24000	1
DS SASAMBA	320	30	89	19	0.4	15	820	19	4600	53000	0.5
FARANDIE	6	11	55	4.2	<0.3	8	54	15	4500	14000	<0.06
US SETTLING	67	18	42	7.4	<0.3	6	250	25	4600	20000	0.2
GARA SETTLING DISCHARGE	74	22	35	6.9	<0.3	3	170	38	5700	17000	<0.06
DS SETTLING	54	21	54	7.6	<0.3	5	210	20	4700	21000	0.2
WEIR FALEME	6	14	240	9.2	<0.3	9	140	16	4100	54000	<0.06
ARTISINAL AREA	28	10	23	3.7	<0.3	3	77	7.1	2800	13000	7.5
ARTISINAL Tributary	8	6.6	14	2.4	<0.3	3	49	10	300	8600	0.1

									0		
DK BRIDGE	7	6.2	19	3.4	<0.3	7	180	9.7	270 0	1100 0	<0.06
GARA DAM	12.	9.7	21.	4.2	<0.3	4.	130.	13.	390 0.	1200 0.	<0.06
GARA UNDERGROUND	42.	20.	16.	5.2	<0.3	2.	160.	31.	390 0.	1000 0.	<0.06

7.3.5. Aquatic Benthic microinvertebrates

The results of the IHAS completed at the various sites are presented in the table below (Table 19).

Table 19. Integrated Habitat Assessment System (IHAS) results for the 2014 survey (Source: Tate, 2014).

Site	Midstream GK	Border Bridge	Farandie	Faleme Weir	DK Bridge
Flow	Moderate	Fast	Slow	Fast	Slow
Clarity (cm)	47	22	37	28	30
Score	64	67	63	69	50
Suitability	Fair	Good	Fair	Good	Poor

A variety of macroinvertebrates were sampled throughout the 2014 survey. The results of the macroinvertebrate survey are presented in Table 20. It should be noted that not all survey sites were included in the invertebrate survey. Only sites with suitable and available “sampleable” invertebrate habitat were selected. The sensitivity ratings are based on the South African Scoring System (Dickens and Graham, 2002). The Average Score Per Taxon (ASPT) is also calculated based on the above biotic index.

Table 20. Macroinvertebrates sampled during the July 2014 survey (Source: Tate, 2014).

Family	Sensitivity	Midstream GK	Border Bridge	Farandie	DK bridge	Faleme Weir
Aeshnidae	8	□	□	1	□	3
Baetidae 1sp.	4	□	□	□	□	□
Baetidae 2 sp	6	□	□	2	□	3
Baetidae >2 sp	8	□	17	□	□	□
Caenidae	6	□	□	4	□	□
Ceratopogonidae	5	1	1	4	3	4

Family	Sensitivity	Midstream GK	Border Bridge	Farandie	DK bridge	Faleme Weir
Chironomidae	2	12	14	22	9	19
Coenagrionidae	4			7	9	23
Corbiculidae	5	1		1	1	
Dytiscidae	5		2			8
Elmidae	8			1		1
Gerridae	5	4				
Gomphidae	6	3		1		1
Gyrinidae	5	2				
Heptageniidae	13	3	1	1		5
Hydracarina	8	21			15	10
Hydropsychidae 2 sp	8					23
Hydropsychidae >2 sp	12		16			
Hydroptilidae	6			7	2	22
Leptoceridae	6	2				
Leptophlebiidae	9		4	4		6
Libellulidae	4	4	4	4	3	2
Oligochaeta	3	4	10	9	8	10
Oligoneuridae	15		2			
Polymitarcyidae	10			6		
Potamonautidae	3		1	1		
Protoneuridae	8	8				
Psychomyiidae	8			1		
Simuliidae	5		4	4		23
Tabanidae	5		1			4
Teloganodidae	12			1		
Thiaridae	3				7	
Veliidae	5		3			
Total Taxa		**12**	**14**	**17**	**10**	**17**

Family	Sensitivity	Midstream GK	Border Bridge	Farandie	DK bridge	Faleme Weir
Total individuals		**65**	**80**	**81**	**54**	**167**
Total Sensitivity Score		**70.0**	**92.0**	**112**	**48.0**	**105**
ASPT		**5.8**	**6.5**	**6.5**	**4.8**	**6.1**
EPT		**2**	**4**	**8**	**5**	**1**

Total macroinvertebrate taxa recorded at the various sites ranged from 10 at the DK Bridge to 17 at Farandie and Faleme Weir. The overall SASS5 scores for the sites ranged from 54 at DK Bridge to 112 at Farandie. The ASPT values ranged from 4.8 at DK Bridge to 6.5 at Border Bridge and Farandie.

The percentage contribution of Ephemeroptera, Plecoptera and Trichoptera (% EPT) at the sites is expressed in Figure 35. Results for the Margalef's diversity index are presented in Figure 36. Shannon's Diversity index results are presented in Figure 37 with Pielou's Evenness index represented in Figure 38.

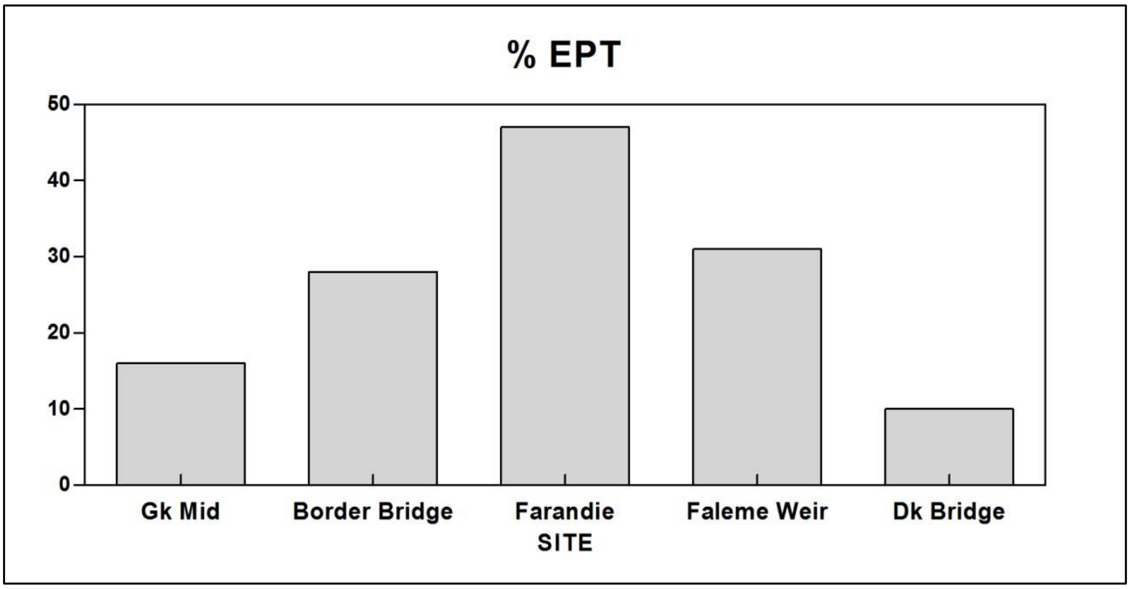


Figure 35. Percentage contribution of EPT at the sites assessed in the 2014 survey (Tate, 2014).

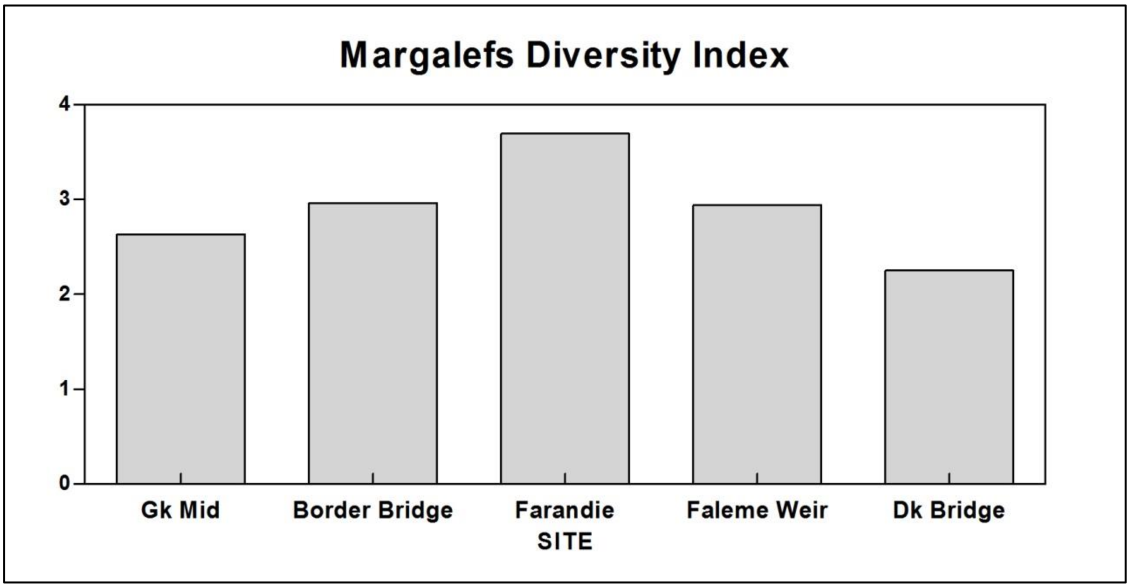


Figure 36. Margalef's Diversity Index results for the July 2014 survey (Tate, 2014).

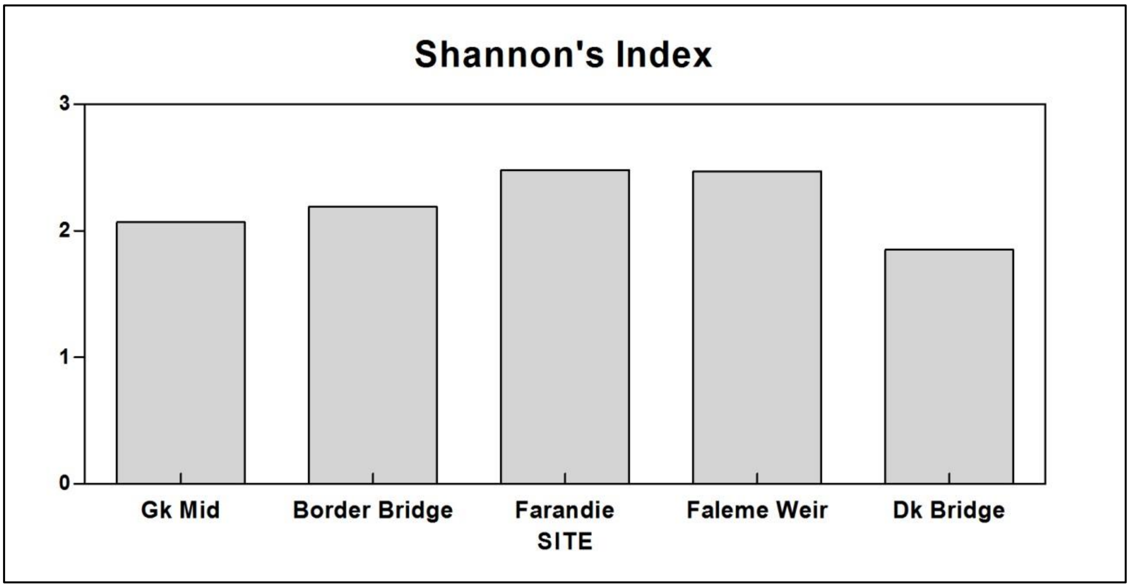


Figure 37. Results of Shannon's Diversity Index during the July 2014 surveys (Tate, 2014).

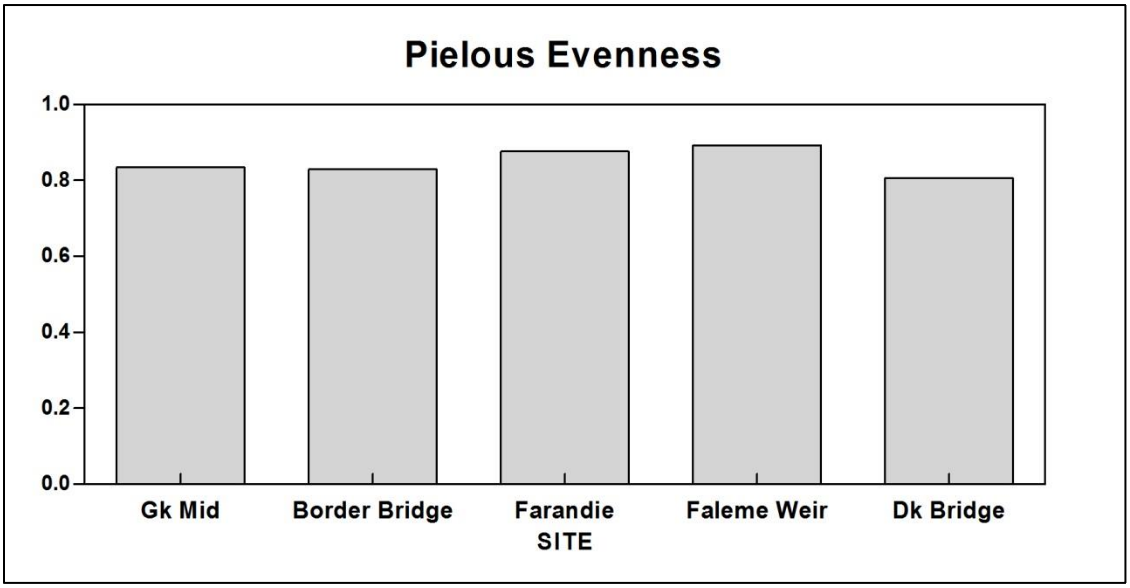


Figure 38. Results of Pielou's Evenness Index during the July 2014 surveys. (Tate, 2014).

7.3.6. Ichthyofauna

The results are summarized in Table 21 below where the various family groups of fish sampled during the 2014 is presented.

33 species of fish were collected representing 12 families, of which 24 fish were identified to species level and the remaining 9 identified to genus level. The different species were collected using various techniques, and as would be expected, were found in their associated meso-habitats. Figure 39 and Figure 40 show examples of fish sampled during the study.

Table 21. Families recorded during the 2014 (Source: Tate, 2014).

Family	No. of species	No. of individuals
Alestidae	7	68
Cichlidae	5	166
Cyprinidae	6	145
Distichodontidae	1	8
Claroteidae	4	44
Clariidae	1	1
Gobiidae	1	4
Malapteruridae	1	1
Mochokidae	3	4

Family	No. of species	No. of individuals
Mormyridae	2	11
Poeciliidae	1	4
Schilbeidae	1	17
Total	**33**	**473**

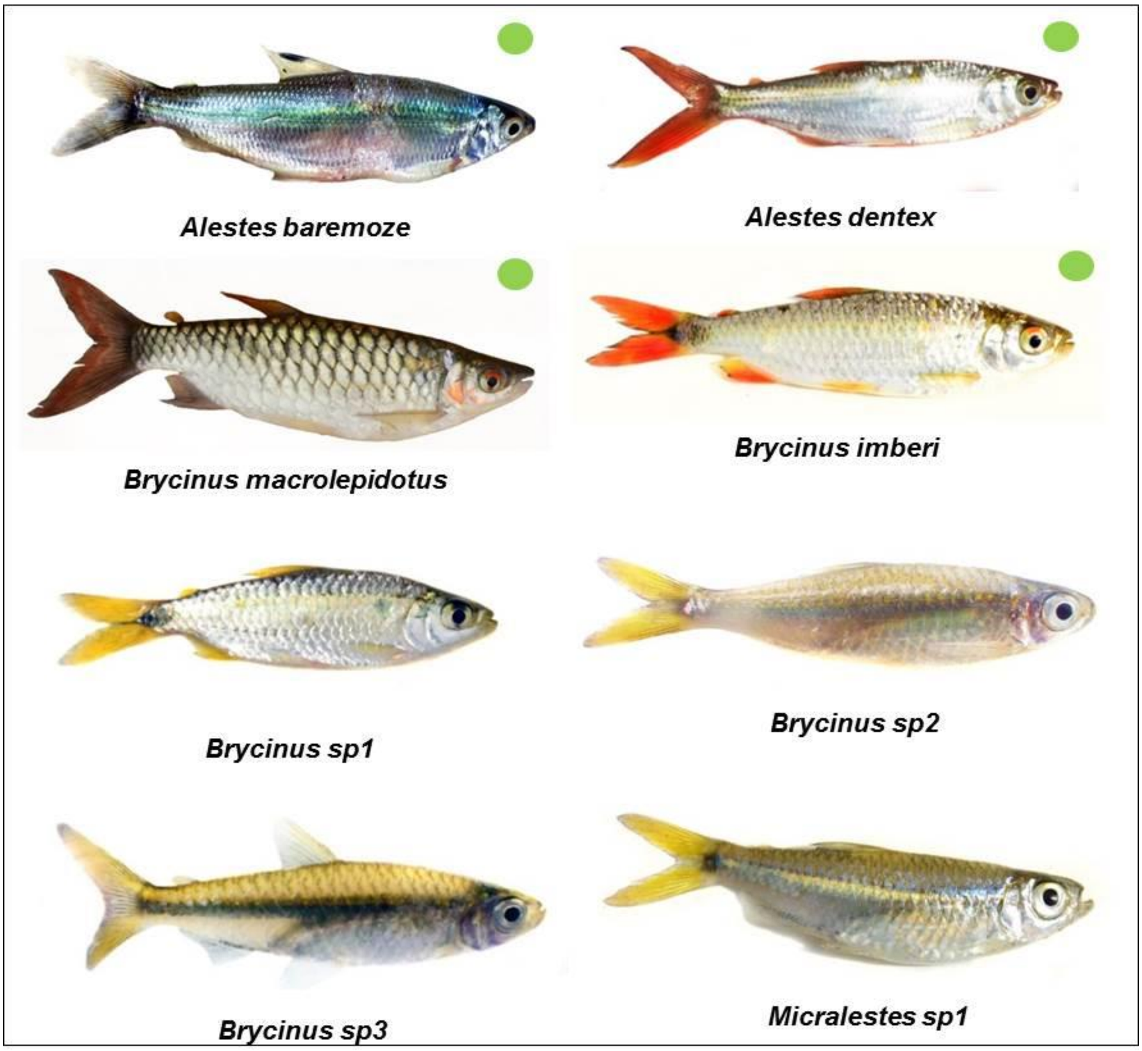


Figure 39. Photographs of fishes from the Alestid family (Source: Tate, 2014)

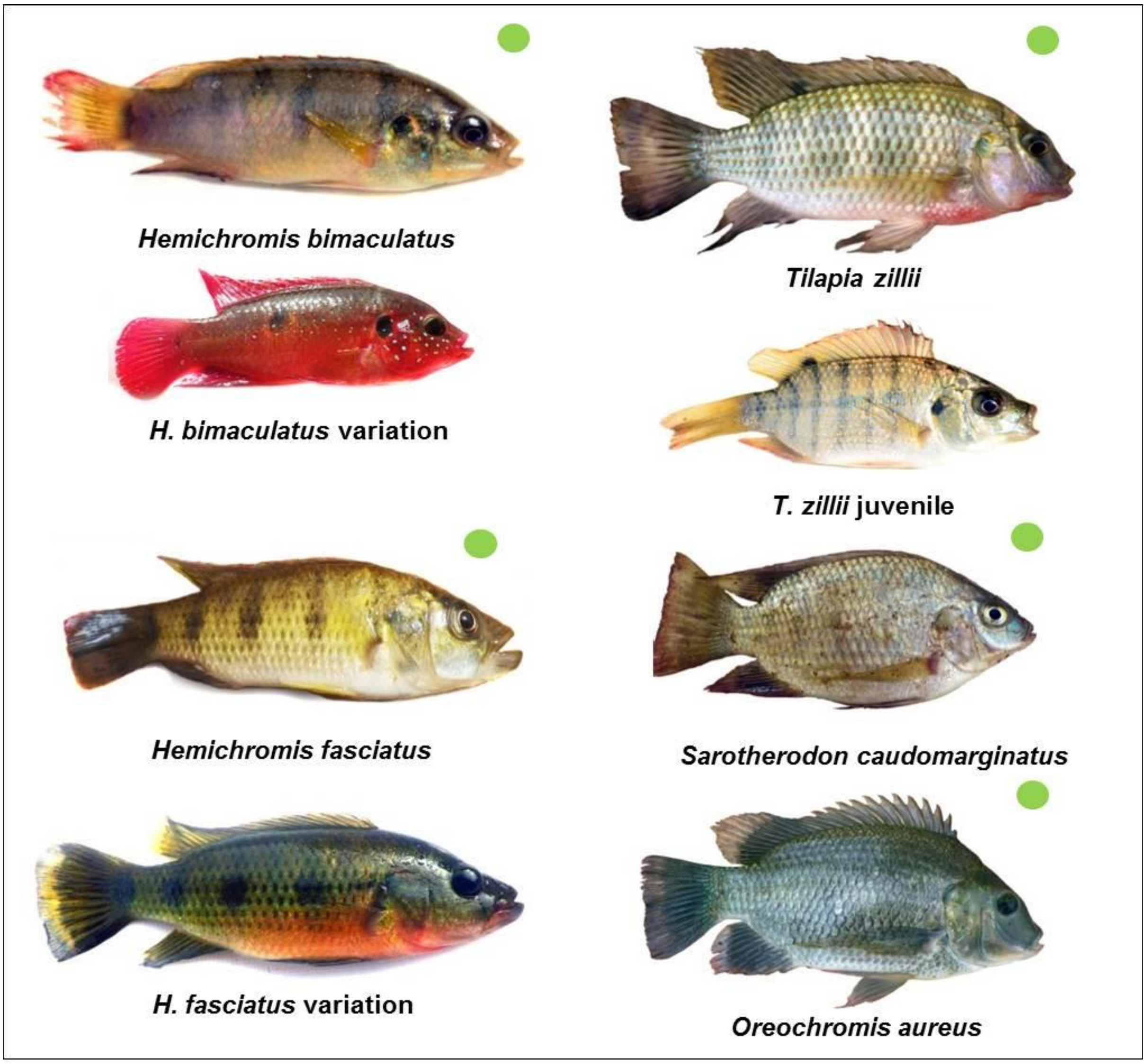
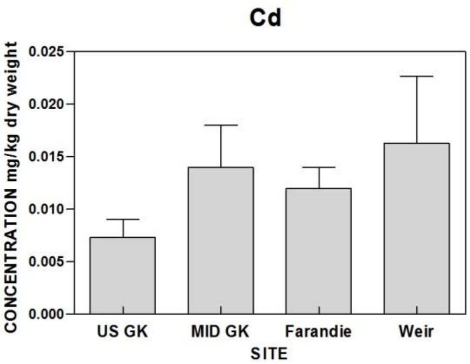
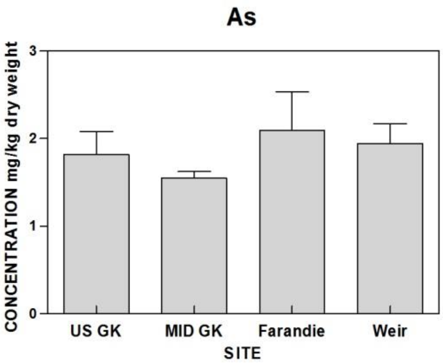


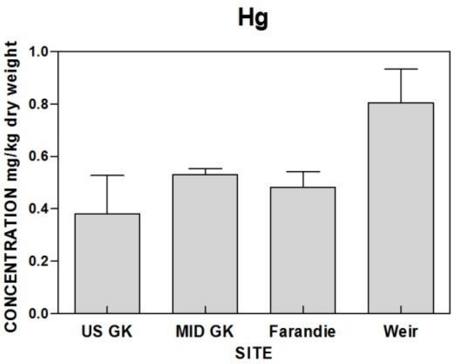
Figure 40. Photographs of fishes from the Cichlid family (Source: Tate, 2014)

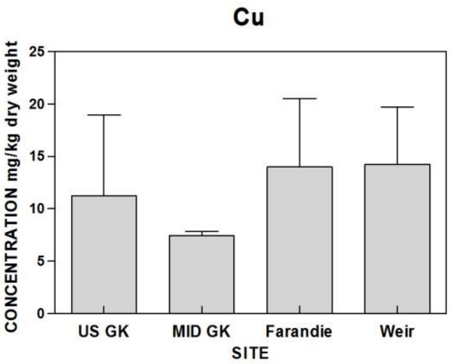
7.3.7. Bioaccumulation

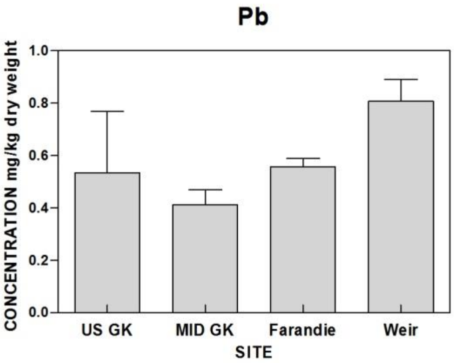
The results of the bioaccumulation of metals within *T. zillii* samples are presented in the figures below (Figure 41, Figure 42, and Figure 43).

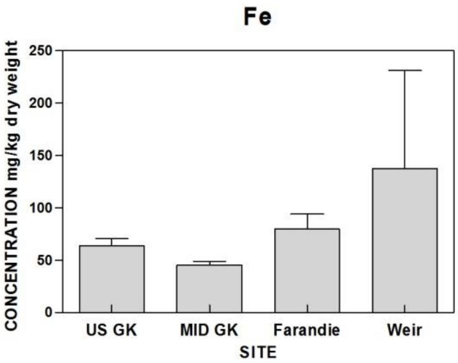

Cd
CONCENTRATION mg/kg dry weight
0.025
0.020
0.015
0.010
0.005
0.000
US GK
MID GK
Farandie
Weir
SITE

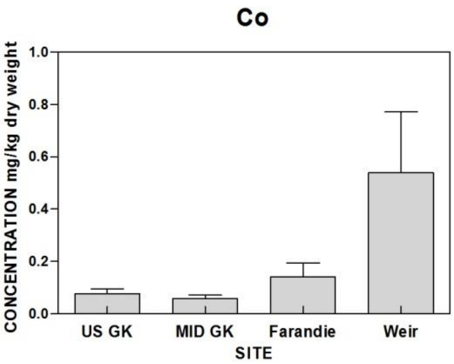

As
CONCENTRATION mg/kg dry weight
3
2
1
0
US GK
MID GK
Farandie
Weir
SITE


Hg
CONCENTRATION mg/kg dry weight
1.0
0.8
0.6
0.4
0.2
0.0
US GK
MID GK
Farandie
Weir
SITE


Cu
CONCENTRATION mg/kg dry weight
25
20
15
10
5
0
US GK
MID GK
Farandie
Weir
SITE


Pb
CONCENTRATION mg/kg dry weight
1.0
0.8
0.6
0.4
0.2
0.0
US GK
MID GK
Farandie
Weir
SITE


Fe
CONCENTRATION mg/kg dry weight
250
200
150
100
50
0
US GK
MID GK
Farandie
Weir
SITE


Co
CONCENTRATION mg/kg dry weight
1.0
0.8
0.6
0.4
0.2
0.0
US GK
MID GK
Farandie
Weir
SITE

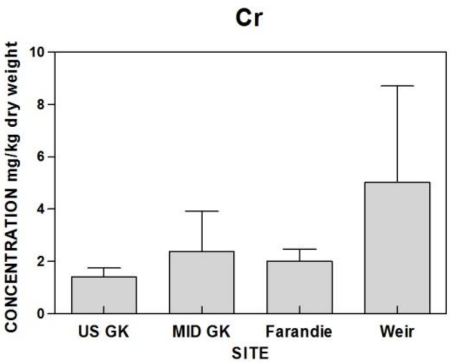

Cr
CONCENTRATION mg/kg dry weight
10
8
6
4
2
0
US GK
MID GK
Farandie
Weir
SITE

Figure 41. Bioaccumulation of metals in the Faleme River (Source: Tate, 2014)

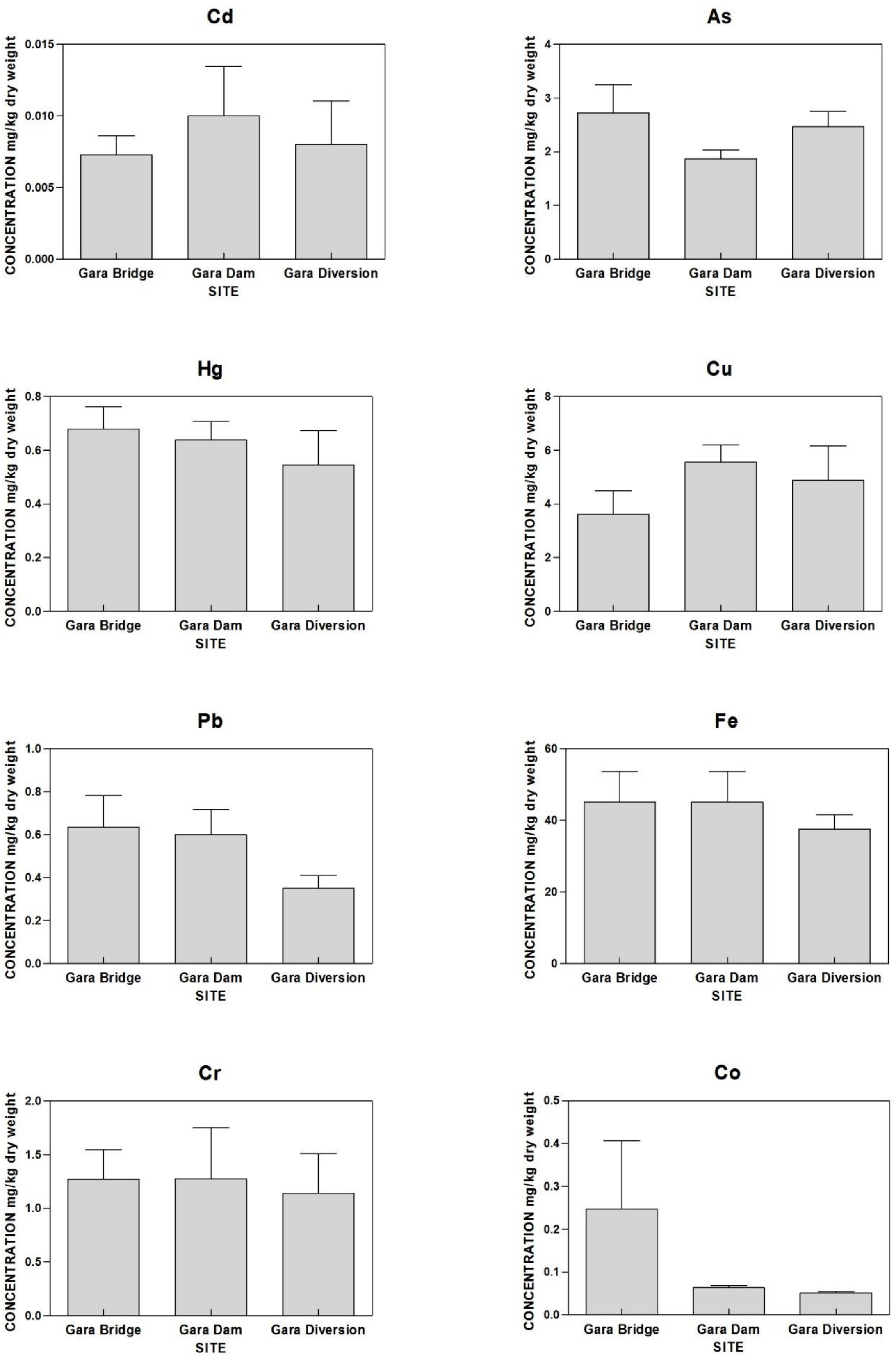


Figure 42. Bioaccumulation of metals in the Gara River (Source: Tate, 2014)

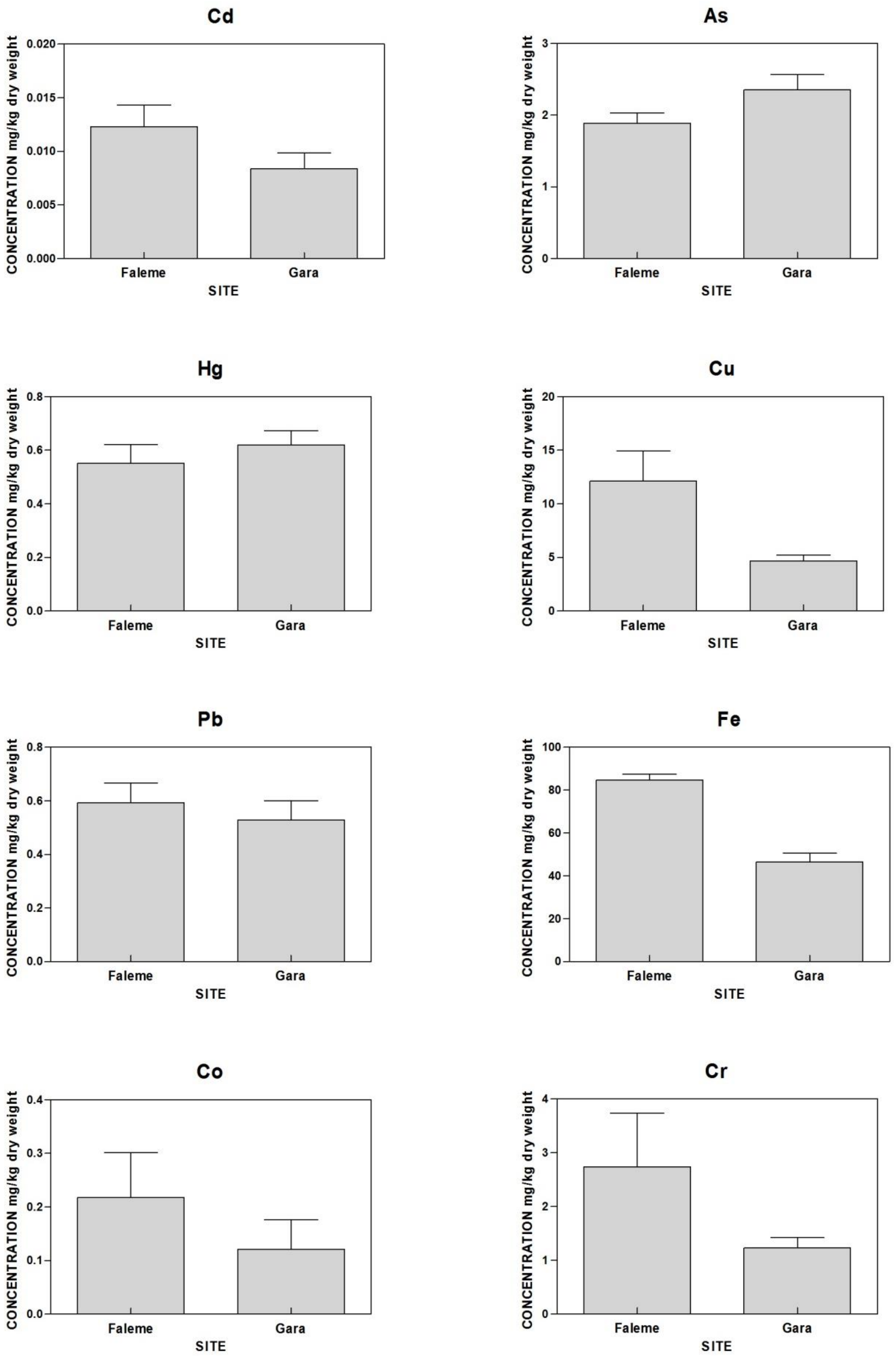


Figure 43. Comparison of metal bioaccumulation between the Gara and Faleme River (Source: Tate, 2014)

8 Gara Underground Effluent treatment

Two types of pollutants occurred in the Gara discharge as described in the risk characterization – underground effluent section: Total suspended solids (TSS) and High nitrate (100 – 400 mg/l) with Sulfate level gradually increasing. The pollutants together present a complex treatment system. It was therefore necessary to isolate each pollutant and determine its source, transfer pathway and devise solutions accordingly with associated risks.

8.1. Proposed Solutions

8.1.2. Source of pollutants

Specialist input was seeked to describe the contributing factors to the effluent quality issue. Below is a summary of the findings from Digby wells in 2013 assessment.

Total Suspended Solids (TSS)

- Poor settling of water in the shallow underground sumps and settling dams (see **Figure 44**) prior to pumping to surface resulting in the water containing high content of solids;
- Poor housekeeping in terms of solids and water separation. The dams and sumps do not have a bund wall thus solids easily enter the dams;
- Due to the high volume, there is a high flow and this adds to mixing of water particularly in the last settling dam before pumping water to surface;
- The lack of a thickener exacerbates the issue. There is definitely more solids content and the settling dams are silted. There is also poor housekeeping at Gara where the solids are washed on the surface and have formed a layer at least 0.2 m thick on the surface. The discharge washes away this silt straight into the river;
- The use of the settling dams with inlet and outlet serves no purpose in trying to achieve a good sedimentation.

Figure 44. Surface settling dams showing large amount of suspended solids

Heavy Metals

- Geology (released with solids and pyrite oxidation)
- Hydrocarbon spillage

Nitrate Source

- No major agricultural activity where large amount of fertilizers/ Herbicides and pesticides are used;
- No major sewage source exists;
- Natural groundwater is low in nitrates;
- Nitrate based explosives seem to be the only real source.

8.1.3. Recommended Solutions

A number of expert advice has been seeked in the past as to the most effective way of treating the effluent prior to discharge. The last two consultations were in January 2011 when Digby Wells Environmental undertook a site visit to evaluate the issues and to recommend measures. Proposed measures were to settle the solids in a thickener and construct a wetland/reedbeds to deal with the nutrient rich – effluent. Then sulphate was not identified to be a problem like it appears to be today. The International Network for Acid Prevention (INAP) in 2003 published a report on the treatment of sulphate in mine effluents (“Lorax report”) where it was shown that out of the existing methods, biological treatment seems to have the greatest potential for sulphate removal at a low cost – however it was pointed out in the same report that more research and development is required to design a wetland that can achieve expected results as it seems the least effective among the biological methods- energy and carbon are key drivers of the cost. Another visit undertaken in October 2013 recommended a more elaborated action plan as stated below.

- Use of reeds/ plants, lignocellulose, sewage sludge, rock and soil in a wetland to remove. use gabions[4] (as indicated in Figure 45 and Figure 46)
  - Residual sulphate;
  - Residual nitrate;
  - Heavy Metal;

[4] **gabion** (from Italian *gabbione* meaning "big cage"; from Italian *gabbia* and Latin *cavea* meaning "cage") is a cage, cylinder, or box filled with rocks, concrete, or sometimes sand and soil for use in civil engineering, road building, and military applications (Source: Wikipedia)

Figure 45. Gabion system conceptual design (DWA, 2013)

Figure 46. Gabions (left) and gabions meshed cages (right) (DWA, 2013)

The following sections below cover the design of the constrcuted wetalnd together with that of the pre-treatment system to remove the suspended solids.

8.2. Constructed Wetland – conceptual design

Digby Wells Environmental has been commissioned to propose a design based on the available information (effluent data, site climate and topography and discharge quality requirement). Part of Information from the report has been used to propose design for the purpose of this study.

8.2.1. Definition of wetland

Hammer (1994) defines a constructed wetland (CW) as man-made systems designed, built and operated to emulate functions of natural wetlands for the removal of pollutants from wastewater in a more controlled environment. Understanding and designing a constructed wetland require the involvement of expertise in a variety of fields, including chemistry, hydrology, soil science, plant biology, natural resources, environmental management, ecology, environmental engineering, surveying and project management.

8.2.2. Classification of wetlands

Constructed wetlands are classified into two groups (Kayombo et al, 2004; Wetland International, 2003): horizontal flow system (HFS) and the vertical flow system (VFS). The horizontal flow systems are classified into two types: the surface flow (SF) and the subsurface flow (SSF) systems. In the horizontal flow systems, water is fed through an inlet and flows horizontally through the bed to the outlet and in the vertical flow systems, water is fed intermittently and drains vertically through the bed via a network of drainage pipes. Below are figures showing examples of a surface flow and a sub-surface flow systems.

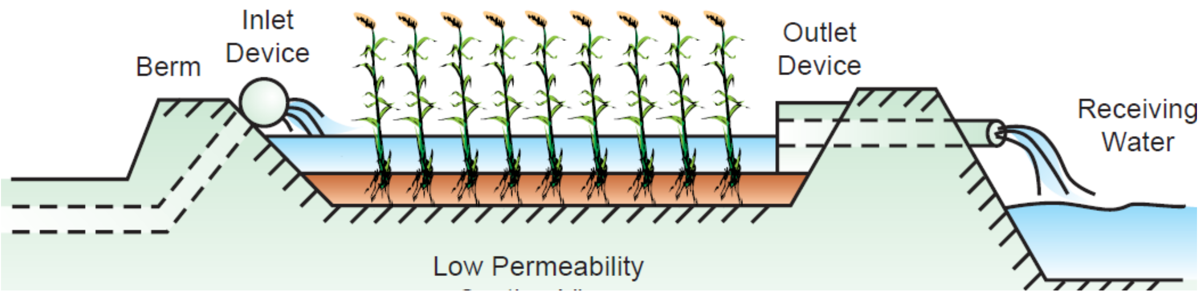


Figure 47. Free Surface flow (FSW) constructed wetland – section view (Source: Wetland International, 2003)

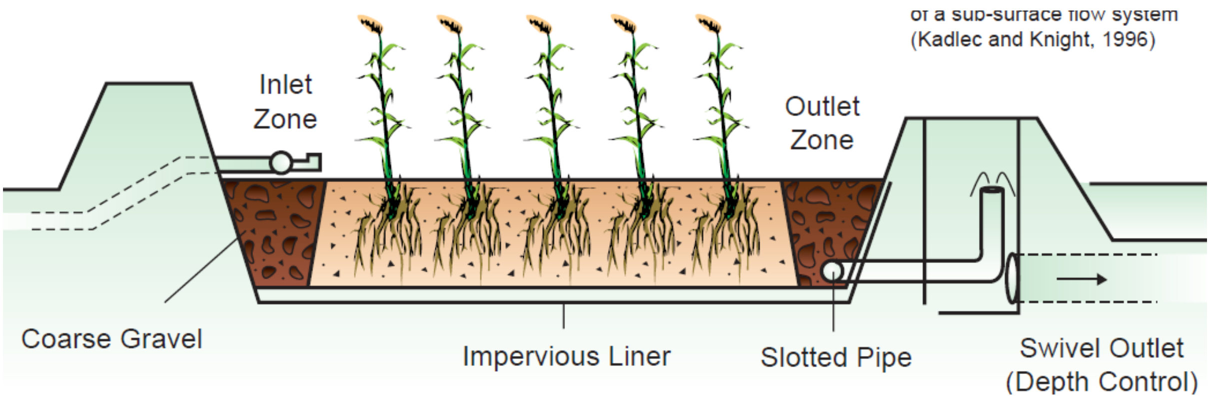


Figure 48. Sub-Surface flow (SSF) constructed wetland (Source: Wetland International, 2003)

8.2.3. History of wetlands

The editorial of the ecological engineering journal (issue no. 25) in 2005 (p. 475-477) describes the history of wetlands development around the world.

It states that the first attempts to use the wetland vegetation to remove various pollutants from water were conducted by K. Seidel in Germany in early 1950s. The first full-scale free water surface (FWS, surface flow) CW was built in The Netherlands to treat wastewaters from a camping site during the period 1967–1969. Within several years, there were about 20 FWS CWs built in The Netherlands. However, FWS CWs did not spread throughout the Europe but constructed wetlands with horizontal sub-surface flow (HF CWs) became the dominant type of CWs in Europe. The first full-scale HF CW was built in 1974 in Othfresen in Germany. The early HF CWs in Germany and Denmark used predominantly heavy soils, often with high content of clay. These systems had a very high treatment effect but because of low hydraulic permeability, clogging occurred shortly and the systems resembled more or less FWS systems. In late 1980s in the United Kingdom, soil was replaced with coarse materials (washed gravel) and this set-up has been successfully used since then. In the 1980s, treatment technology of constructed wetlands rapidly spread around the world.

In 1990s, increased demand of nitrogen removal from wastewaters led to more frequent use of vertical flow (VF) CWs which provide higher degree of filtration bed oxygenation and consequent removal of ammonia via nitrification. In late 1990s, the inability to produce simultaneously nitrification and denitrification in a single HF or VF CWs and thus remove total nitrogen lead to the use of hybrid systems which combine various types of CWs. The concept of combination of various types of filtration beds was actually suggested by Seidel in Germany in the 1960s but only a few fullscale systems were built (e.g. Saint Bohaire in France or Oaklands Park in UK) in 1980s and early 1990s. At present, hybrid CWs are commonly used throughout Europe as well as other parts of the world. VF–HF combination is the dominant set-up but HF–VF combination is also used and FWS CWs are commonly used in hybrid systems. In 1970s and 1980s, constructed wetlands were nearly exclusively built to treat domestic or municipal sewage. Since 1990s, the constructed wetlands have been used for all kinds of wastewater including landfill leachate, runoff (e.g. urban, highway, airport and agricultural), food processing (e.g. winery, cheese and milk production), industrial (e.g. chemicals, paper mill and oil refineries), agriculture farms, mine drainage or sludge dewatering. they offer a cheaper, low raw material, sustainable and energy-efficient alternative technology to wastewater treatment. They cater for secondary and tertiary treatment of wastewaters. Wetlands have many functions: creation of natural habitat, water quality improvement, flood control and the production of food and fiber (production of biomass). They are now well-established methods for wastewater treatment in tropical climate (Kayombo et al, 2004; Wetland International, 2003).

8.2.4. Conceptualization of wetland

Morgan (2014) described the steps for the design of a wetland.

Conceptualisation begins with the theoretical understanding of the entire wetland system, followed by data collection and the refinement of that understanding. Characterization of natural (ambient background or baseline) conditions involves the following tasks:

- Locating, collecting, and organizing basic types of data from available published and unpublished sources; and
- Conducting specifically designed field, laboratory, and modelling studies for the sites selected.

It is imperative to develop a broad overview of the site and identifying those issues that may assist or hamper the overall delivery of the wetland objective. This would specifically respond to the site conditions. Careful assessment and interpretation of the site conditions is a fundamental part of designing and development of the constructed wetland that can be effective. There are several key characteristics of a site that need to be understood as these can influence the level of confidence in providing an effective design. For simplistic purposes these should include the following factors; i.e. climate, soils, average slope, depth to groundwater. An overall water management plan should provide;

- Site plan showing location, size and dimensions of the wetland and associated measures, and
- Conceptual design calculations to establish the quantitative estimates.

Effective environmental planning often demands qualitative and quantitative predictions of the effect of future management activities. The conceptual design and appropriate models can be applied to solve a wide range of wetland related problems under very different situations. This study will also identify the most important variables in the development of the constructed wetland, since the combination of flow, transport and processes in models is often only possible when simple solutions for each problem are applied to keep the mathematical complexity of the model low.

Development of an appropriate conceptual design (specifically the macrophyte zone) of water flow and pollution transport within the constructed wetland is critical for developing adequate predictive modelling methods and designing cost effective remediation techniques. These processes must still take into account the changes under episodic natural climate. The complexity resulting from the effects of episodic infiltration and preferential flow on a field scale must be taken into account when predicting flow and transport and developing the constructed wetland. The change of water flow and contaminant transport, which is difficult to detect, poses unique and difficult problems for characterization, monitoring, modelling, engineering of the constructed wetland, and remediation of contaminants. Lack of understanding in this area has led to severely erroneous predictions of contaminant transport and incorrect remediation actions. Therefore, it is imperative to develop a strategy to investigate the macrophyte zone including a comprehensive plan to assess these conditions specifically.

Kayombo et al, 2004, published a design manual for constructed wetlands and waste stabilization ponds. Most of the following paragraphs refer to their work together with the Wetland International's 2003 publication on the use of constructed wetlands in wastewater treatment. Focus is placed on the sub-surface flow systems (Figure 48) as they appear to outperform the free surface ones (Hammer, 1989).

8.2.5. Pollutants Removal Mechanism

Wetlands have been found to be effective in treating BOD, TSS, N and P as well as for reducing metals, organic pollutants and pathogens. The principal pollutant removal mechanisms in constructed wetlands include biological processes such as microbial (bacteria, fungi, algae and protozoa) metabolic activity and plant uptake as well as physico-chemical processes such as sedimentation, adsorption and precipitation at the water-sediment, root-sediment and plant-water interfaces (Reddy and DeBusk, 1987). A pollutant may be removed as a result of more than one process at work. Since Nitrate and heavy metals appear to be our main pollutants- focus has been placed on their removal mechanism.

Nitrate removal mechanism

Before describing the processes at work for Nitrogen removal, it is important to remind the nitrogen cycle. Below extract was taken from Bosman, 2009.

The Nitrogen Cycle refers to the inter-conversion between nitrogen (N), nitrite (NO2), nitrate (NO3), ammonia (NH3), and ammonium (NH4+) in the environment. A simplified illustration of the natural (not altered by anthropogenic activity) nitrogen cycle is outlined in Figure 1 below:

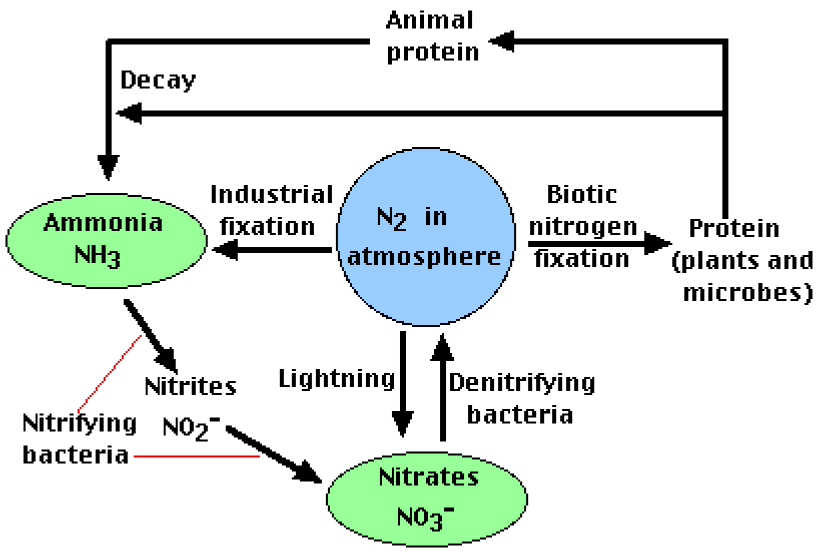


Figure 49. Nitrogen cycle (Source: http://users.rcn.com/jkimball.ma.ultranet/BiologyPages/N/NitrogenCycle.html**)**

Nitrate (NO3-) is the end product of the oxidation of elemental nitrogen (N), ammonium (NH4+) and/or nitrite (NO2-) and is measured either as the salt, NO3-, or as the amount of Nitrate-Nitrogen (N). Natural soil is generally Nitrate-rich. Nitrates and Nitrites occur together in soil from natural erosion of geological Nitrogen. In normal geological processes such as erosion, desertification and soil formation, nitrate release occurs slowly over long periods of time, allowing the release of low levels of nitrogen that is essential for the formation of fertile soil. Metasedimentary and metavolcanic lithologies, such as greenstone and slate, typically contain high levels of elemental Nitrogen which could be released as nitrate in this manner. The Nitrogen Cycle thus entails the uptake of atmospheric or soil Nitrogen by plants or animals, and the conversion and use there-of by plants and animals as essential building blocks for amino-acids and genetic material. As a result of animal excretion and plant decay, ammonia (NH3) or ammonium (NH4+) is formed, which readily oxidises to nitrite (NO2-) and nitrate (NO3-) under aerobic (presence of oxygen) conditions (process of nitrification). Denitrifying bacteria can convert nitrate back to ammonium, ammonia, or atmospheric Nitrogen under reducing circumstances (process of de-nitrification).

The Nitrogen cycle is modified by anthropogenic activities such as the introduction of oxidizing or reducing circumstances or chemicals, or by the large scale disturbance of Nitrogen-rich geological formations. Ammonium (NH4+) will convert to nitrite (NO2), and nitrate (NO3-) under oxidising conditions, such as aeration or excavation, while nitrate (NO3) will convert to ammonium under reducing circumstances, or in the presence of a reducing agent, such as acids. Large scale anthropogenic disturbances to the natural Nitrogen Cycle are a serious cause of concern, since this can cause nitrate to be released in large quantities into water resources, which has significant detrimental ecological and human health effects.

There are sufficient studies to indicate some roles being played by wetland in Nitrogen removal but the significance of plant uptake vis-à-vis nitrification/denitrification is still being questioned (Wetland International, 2003). Nitrogen (N), as per the cycle described above, can exist in various forms, namely Ammoniacal Nitrogen (NH3 and NH4+), organic Nitrogen and oxidised Nitrogen (NO2- and NO3-). The removal of Nitrogen is achieved through nitrification/denitrification, volatilisation of Ammonia (NH3) storage in detritus and sediment, and uptake by wetland plants and storage in plant biomass (Brix, 1993). A majority of Nitrogen removal occurs through either plant uptake or denitrification. Nitrogen uptake is significant if plants are harvested and biomass is removed from the system.

At the root-soil interface, atmospheric oxygen diffuses into the rhizosphere through the leaves, stems, rhizomes and roots of the wetland plants thus creating an aerobic layer similar to those that exists in the media-water or media-air interface. Nitrogen transformation takes place in the oxidised and reduced layers of media, the root-media interface and the below ground portion of the emergent plants. Ammonification takes place where Organic N is mineralised to NH4+-N in both oxidised and reduced layers. The oxidised layer and the submerged portions of plants are important sites for nitrification in which Ammoniacal Nitrogen (AN) is converted to nitrite N (NO2-N) by the Nitrosomonas bacteria and eventually to nitrate N (NO3-N) by the Nitrobacter bacteria which is either taken up by the plants or diffuses into the reduced zone where it is converted to N2 and N2O by the denitrification process . The first reaction in the nitrification process produces hydroxonium ions (acid pH), which react with natural carbonate to decrease the alkalinity (Mitchell, 1996a). In order to perform nitrification, the nitrosomonas must compete with heterotrophic bacteria for oxygen. The BOD of the water must be less than 20 mg/l before significant nitrification can occur (Reed et al., 1995). Temperatures and water retention times also may affect the rate of nitrification in the wetland. Denitrification is the process in which nitrate is reduced in anaerobic conditions by the benthos to a gaseous form. The reaction is catalyzed by the denitrifying bacteria Pseudomonas spp. and other bacteria.

Denitrification requires nitrate, anoxic conditions and carbon sources (readily biodegradable) (Kayombo et al, 2004). Nitrification must precede denitrification, since nitrate is one of the prerequisites. The process of denitrification is slower under acidic condition (Kayombo et al, 2004). At a pH between 5-6, N20 is produced. For a pH below 5, N2 is the main nitrogenous product (Nuttall et al., 1995). NH+4 is the dominant form of ammonia-nitrogen at a pH of 7, while NH3 (present as a dissolved gas) predominates at a pH of 12. Nitrogen cycling within, and removal from, the wetlands generally involves both the translocation and transformation of nitrogen in the wetlands, including sedimentation (resuspension), diffusion of the dissolved form, litter fall, adsorption/desorption of soluble nitrogen to soil particles, organism migration, assimilation by wetland biota, seed release, ammonification (mineralisation) (Orga-N – NH+4), ammonia volatilization (NH+4 – NH3 (gas)), bacterially-mediated nitrification/denitrification reactions, nitrogen fixation (N2, N2O (gases – organic-N)), and nitrogen assimilation by wetland biota (NH+4, Nox organic – N, with NOx usually as NO-3). Precipitation is not a significant process due to the high solubility of nitrogen, even in inorganic form. Organic nitrogen comprises a significant fraction of wetland biota, detritus, soils, sediments and dissolved solids (Kadlec and Knight, 1996).

Denitrification is the permanent removal of Nitrogen from the system, however the process is limited by a number of factors, such as temperature, pH, redox potential, carbon availability and nitrate availability (Johnston, 1991). The annual denitrification rate of a wetland could be determined using a Nitrogen mass-balance approach, accounting for measured influx and efflux of Nitrogen, measured uptake of Nitrogen by plants, and sediment, and estimated NH3 volatilisation (Frankenbach and Meyer, 1999).

The extent of Nitrogen removal depends on the design of the system and the form and amount of Nitrogen present in the wastewater. If influent Nitrogen content is low, wetland plants will compete directly with nitrifying and denitrifying bacteria for NH4+ and NO3-, while in high Nitrogen content, particularly Ammonia, this will stimulate nitrifying and denitrifying activity (Good and Patrick, 1987).

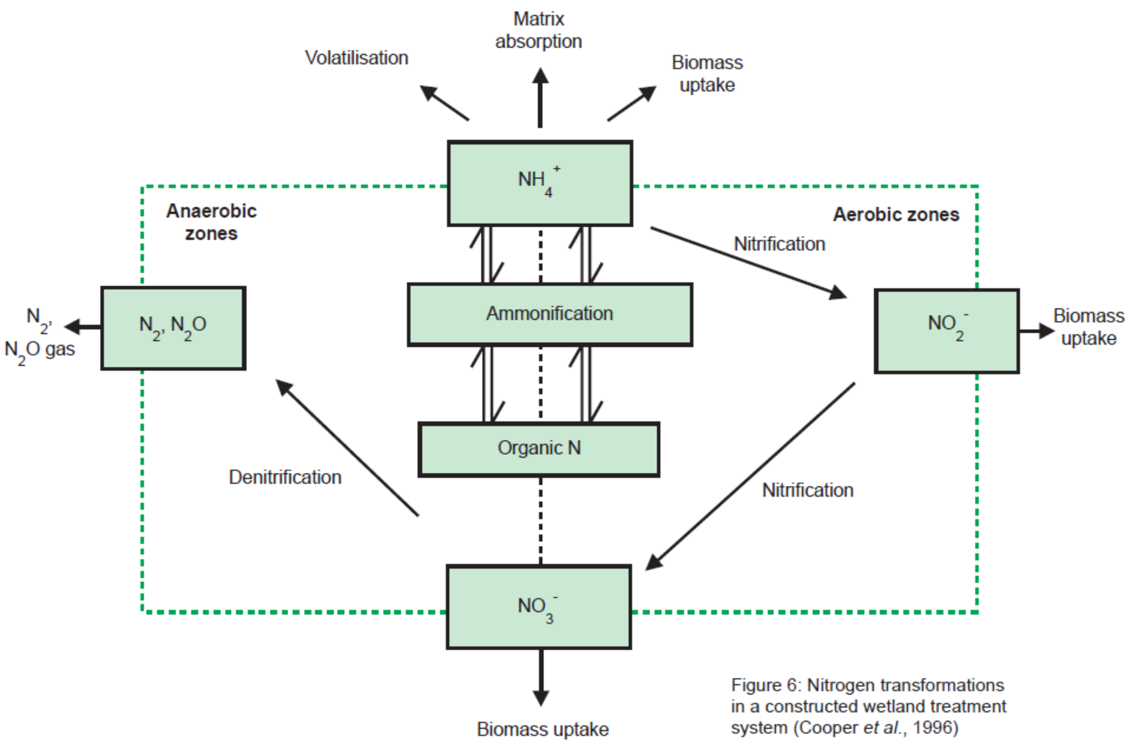


Figure 50. Nitrogen transformations in a constructed wetland treatment system (Source: Cooper et al., 1996)

Nitrogen will also be taken up by macrophytes in a mineralised state and incorporated it into plant biomass. Accumulated Nitrogen is released into the system during a die-back period. Plant uptake is not a measure of net removal. This is because dead plant biomass will decompose to detritus and litter in the life cycle, and some of this Nitrogen will leach and be released into the sediment. Johnston (1991) shows only 26-55% of annual N and P uptake is retained in above-ground tissue, the balance is lost to leaching and litter fall.

Heavy Metals removal mechanism

Heavy metals is a collective name given to all metals above calcium in the Periodic Table of Elements, which can be highly toxic, and which have densities greater that 5g/cm^3 (Skidmore and Firth, 1983). The main heavy metals of concern in freshwater include lead, copper, zinc, chromium, mercury, cadmium and arsenic. There are three main wetland processes that remove heavy metals (Kayombo et al, 2004); namely, binding to soils and organic material, sedimentation and particulate matter, precipitation as insoluble salts, and uptake by bacteria, algae and plants (Kadlec & Knight, 1996). These processes are very effective, with removal rates reported up to 99% (Reed et al., 1995). A range of heavy metals, pathogens, inorganic and organic compounds present in wetlands can be toxic to biota. The response of biota depends on the toxin concentration and the tolerance of organisms to a particular toxin. Wetlands have a buffering capacity for toxins, and various processes dilute and break down the toxins to some degree.

Evapotranspiration as a pollutant removal mechanism

Evapotranspiration is one of the mechanisms for pollutant removal. Atmospheric water losses from a wetland that occurs from the water and soil is termed as evaporation and from emergent portions of plants is termed as transpiration. The combination of both processes is termed as evapotranspiration. Precipitation and evapotranspiration influence the water flow through a wetland system. Evapotranspiration slows water flow and increases contact times, whereas rainfall, which has the opposite effect, will cause dilution and increased flow.

8.2.6. Design Requirements

The principal design criteria for a constructed wetland system includes substrates types, pollutant loading rate and retention time, choice of wetland plant species, and area of reed bed (Kayombo et al, 2004).

Substrates

Substrates may remove pollutants by ion-exchange, specific adsorption/precipitation and complexation. Hydraulic permeability is one of the substrate selection criteria. The long term efficiency of an emergent bed system is improved if the effluent is pre-treated prior to discharge to the active bed.

The media depth should be about 0.6 m and the bottom is a clay layer to prevent seepage (Kayombo et al, 2004). Media size for most gravel substrate range from 5 to 230 mm with 13 to 76 mm being typical. Wastewater flows by gravity horizontally through the root zone of the vegetation about 100-150mm below the gravel surface. Outlet is typically 0.3 to 0.6 mm below bed surface. The environment within the SSF bed is either anoxic or anaerobic. Oxygen is supplied by the roots of the emergent plants and is used up in the Biofilm growing directly on the roots and rhizomes, being unlikely to penetrate very far into the water column itself. SSF systems are good for nitrate removal (denitrification), but not for ammonia oxidation (nitrification), since oxygen availability is the limiting step in nitrification (Kayombo et al, 2004). The most common problem with SSF is, according to Kayombo et al, 2004, blockage, particularly around the inlet zone, leading either to short circuiting, surface flow or both. This occurs because of poor hydraulic design, insufficient flow distribution at the inlet, and inappropriate choice of porous media for the inlet zone. Properly-designed SSF systems are very reliable.

Wetland plant species

While there is a recognition that the improvement of water quality in treatment wetland applications is primarily due to microbial activity (Faulwetter et al., 2009; Kadlec and Wallace, 2009), experience has shown that wetland systems with vegetation or macrophytes has a higher efficiency of water quality improvement than those without plants (Coleman et al., 2001; Tanner, 2001; Brisson and Chazarenc, 2009). The emphasis of constructed wetland technology to date has been on soft tissue emergent plants including *Cyperus* *papyrus, Phragmites, Typha* and *Schoenoplectu*s (Okurut, 2000; Kadlec and Wallace, 2009). A higher reduction efficiency for mass balances of N and P could be achieved by Phragmites if water retention time is more than 5 days.

Wetland International, 2003, also extends on the role of vegetation in wetlands. The most significant functions of the wetland plants in relation to water purification are their physical effects. They provide a huge surface area for attachment and growth of microbes. Therefore they play a vital role in the retention and removal of nutrients and help in preventing the eutrophication of wetlands. A range of plants have shown their ability to assist in the break down of wastewater. As good examples, there are the common reed (Phragmites karka) and cattail (Typha Angustifolia) – these plants have large biomass both above (leaves) and below (underground stem and roots) the substrate surface. Below a figure showing the extensive root system of the plant:

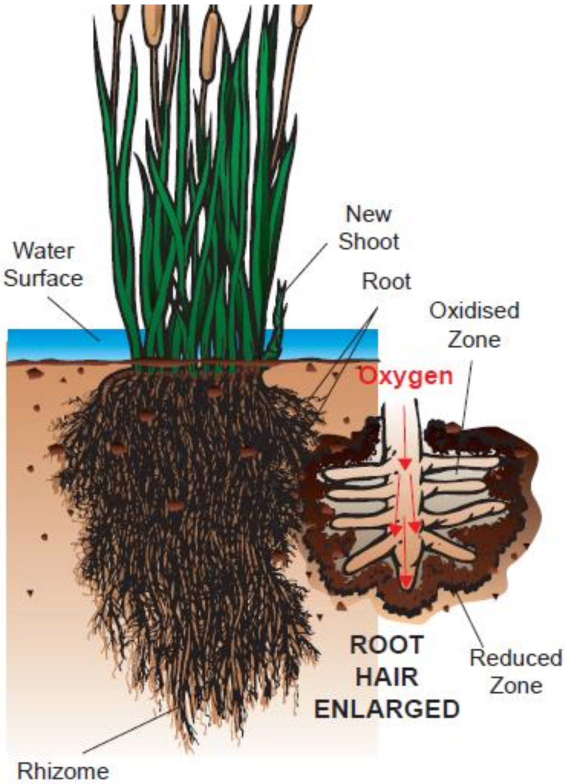


Figure 51. Extensive root system of plants (source: modified from Cooper et al., 1996)

The other five roles of the wetland plants, besides the physical one, are:

- Soil hydraulic conductivity,
- Organic compound release through the root system at rates up to 25% of the total photosynthetically fixed carbon which may act as a source of food for the microorganisms (Brix, 1997),
- Microbial growth,

- Creation of aerobic soil – nitrification requires a minimum of 2 mg O2/l to proceed at a maximum rate. It is evident that the rate of nitrification is most likely the rate limiting for overall nitrogen removal from a constructed wetland system (Sikora et al., 1995),
- Aesthetic values.

The vegetation tends to increase the rates of water loss through evapotranspiration when compared to rates of evaporation from bodies of open water (Jones and Humphries, 2002). Therefore, the aim of establishing the macrophyte zone will increase hydraulic retention time; consequently increased biomass will facilitate evapotranspiration.

The ability for soft tissue macrophytes to grow and perform well has been documented, especially for the high latitudes, temperature climate regions. Empirical exploitation of plants is a common practice. Availability, expected water quality, normal and extreme water depths, climate and latitude, maintenance requirements and project goals are among the variables that determine the selection of plant species for constructed wetlands (Stottmeister et al., 2003).

Climate

Precipitation and temperature must be monitored on site and must be used in the climatic water balance. In terms of the climate monitoring, rainfall and actual evaporation rate are the driving forces for determining the water balance (Morgan, 2014). Understanding the wetland water balance will play an important role in establishing the success or failure of the system, which is again determined by monitoring and understanding the meteorological variables. These will be further used in the understanding of the macrophyte conditions, specifically the water retention characteristics. Thus rainfall is measured directly with site rain gauges and the potential evaporation can be determined by an empirical equation or literature if the latter becomes impossible.

Potential evaporation (ET_o) is a measure of the ability to remove water from the surface through the processes of evapotranspiration and assuming non-limiting water conditions (Clark et al. 1989). Actual evaporation (ET) is the quantity of water that is actually removed from the surface through evapotranspiration. No single method of ET_o determination is likely to be ideal for all circumstances. Depending on the availability of data, common methods may infer potential ET_o for the modelling calculated from the potential evaporation by application of an appropriate crop coefficient through a direct measure of evaporation from a Class A-pan or an indirect estimate using an empirical equation, for example, the Penman - Monteith equation.

The Food and Agriculture Organisation (FAO) methodology is considered the international standard for predicting crop water requirements (Allen, 1998). Reference crop evapotranspiration refers to ET from a uniform green crop surface, actively growing, of uniform height, completely shading the ground, under well-watered conditions.

Sufficient data must be made available for calculating ET_o using the Penman – Monteith method, thus this method would be used in this study as presented in the equation, below.

$$ET_0 = \frac{= \ 0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

Where

ET_0 is the potential evaporation [mm/day],

R_n is the net radiation at the crop surface [MJ/m^2/day],

G is the soil heat flux density [MJ/m^2/day],

T is the mean daily temperature at 2m height [℃],

u is the wind speed at 2 m height [m/s],

e_s is the saturated vapour pressure [kPa],

e_a is the saturated vapour pressure [kPa]

$e_s - e_a$ is the saturated vapour pressure deficit [kPa]

Δ is the slope of vapour pressure curve [kPa/℃], and

γ is the phychometric constant [kPa/℃]

With Δ the slope of the saturation vapour pressure curve in kPa/℃

$$\Delta = \frac{4098e_s}{(T_a + 273.3)^2}$$

And G the soil heat flux (MJ/m^2/day) calculated form the current day's (DOY) and pervious days (DOY-1) average air temperature (T_{avg}).

$$G = 0.38\left[T_{avg}(DOY) - T_{avg}(DOY-1)\right]$$

Where

$$T_{avg} = \frac{(T_{max} + T_{min})}{2}$$

γ is the psychrometer constant (kPa/℃) and is calculated as:

$$\gamma = \frac{0.00163P_a}{\lambda}$$

With λ = 2.501 – 2.361X 10$^{-3}T_{avg}$

Therefore, the climatic water balance components of the wetland consist of:

$S = I + P + ET – D$

where:

S is the change in volume of water held in storage per unit area (mm)

P is the volume of precipitation per unit area (mm)

ET is the water lost through evaporation (climate and porous media dependent) and transpiration (species dependent) per unit are (mm), and

D is the volume of water draining out the bottom of the macrophyte zone per unit area (mm)

The constructed wetland should have the following key design features;

- An inlet zone pond/basin that acts as a sedimentation pond and buffer to disperse the water flows into the constructed wetland system. This feature reduces the velocity of inflows, traps remaining coarse sediments and generally protects the macrophytes zone. Wherever possible, sedimentation ponds should be separate from the macrophytes zone so they can be isolated for maintenance.
- Connection of the inlet to the macrophyte zone can be either by pipe or porous rock weir. Where pipe connections are used it is important to have an initial open water section in the macrophyte zone to help disperse flows. A high flow bypass channel (to protect the macrophyte zone from scour and vegetation damage).
- An extensively vegetated macrophyte zone. The vegetation is predominantly emergent aquatic plants that support a complex of algal and bacterial microscopic organisms, known as biofilms, which grow on the surface of the plants. This zone also traps finer sediments and potential soluble pollutants.
- Outlet zone which will allow for aeration of water before discharge into the river.

The disadvantages of a constructed wetland are (1) the land requirements (cost and availability of suitable land), (2) current imprecise design and operation criteria, (3) biological and hydrological complexity and our lack of understanding of important process dynamics, (4) the costs of gravel or other fills, and site grading during the construction period, and (5) possible problems with pests. Mosquitoes and other pests could be a problem for an improperly designed and managed SSF (Kayombo et al, 2004).

8.2.7. Design of the constructed wetland

Design of a Settling system

tests

Samples of the Gara underground effluents were sent to Paterson & Cooke (Johannesburg) to carry out some test on the effluent and advice on the thickener design. Samples of Gara decant water and bench-top thickener underflow samples were sent for comprehensive water quality analysis and solids elemental study at SGS respectively; and samples of the settled solids removed from the effluents as received from the mine were sent for standard fire assay at Mintek to determine the gold content in the material.

The following suite of laboratory tests was conducted in order to characterize the static sedimentation behavior of the solids in the effluent and to determine the optimum process conditions for flocculation and settling within a thickener:

- Water quality and specific gravity tests
- Particle size distribution (PSD)
- Flocculant type screening (performed in 100 ml measuring cylinders)
- Optimisation of feed effluent solids concentration
- Optimisation of flocculant dose
- Settling rate envelope under static consolidation conditions (un-raked)
- Static mud bed consolidation (24h raking)

The results of the static sedimentation tests also provided the operating parameters for set-up of the dynamic thickening test. The bench top dynamic thickening test is designed to determine the critical solids flux rate and/or rise rate values for calculating the optimum thickening area required for a specific process load (t/h). The data generated is required to adequately size the diameter and number of thickeners required by the process. This test was conducted in a 100 mm diameter bench-top dynamic thickening rig (see Figure 52 below). The Gara effluent characteristics was also determined in the laboratory to understand the nature of the initial state of the effluent and the preliminary thickener feed effluent solids concentration was determined through a series of 250 ml cylinder settling tests at a range of effluent feed solids concentrations.

Figure 52. Bench-top dynamic thickening rig (P&C, 2011)

Results

Table 22 below shows the characteristics of the Gara effluent - The conductivity of the effluents, which is higher than that of the process water due to the solids content, falls within the moderately high range (1.5 to 3 mS/cm). Settlings effluents could be expected in the presence of clay ores as a result of the double layer compression effect at effluent conductivity values of 2 mS/cm and above.

It was observed that Gara effluents were coagulated in the natural state (prior to flocculation). A naturally coagulated material is defined in layman's terms as a material that settles overnight (without any flocculation) and producing a layer of clear supernatant water above a settled bed of solids. As a result, no further effluent conditioning measures is required and therefore no flocculation and/or settling problems are expected based on the natural coagulated state of the thickener feed effluents.

Table 22. Effluent characteristics (SGS, 2011)

Parameter	Gara effluent
pH	8.0
Conductivity (mS/cm)	1.6
Specific gravity (g/cm3)[5]	
Solids	2.72
Liquid	1.00
Particle size distribution[6]	

5 Water pycnometer method

6 Laser particle size analysis method

Parameter	Gara effluent
d10	1.80
d50	9.16
d80	19.90
% clay size material[7]	~ 27
Natural colloidal state	settling

The particle size distribution also is shown below – more than 30% of solids of the effluent is less than 5 micron.

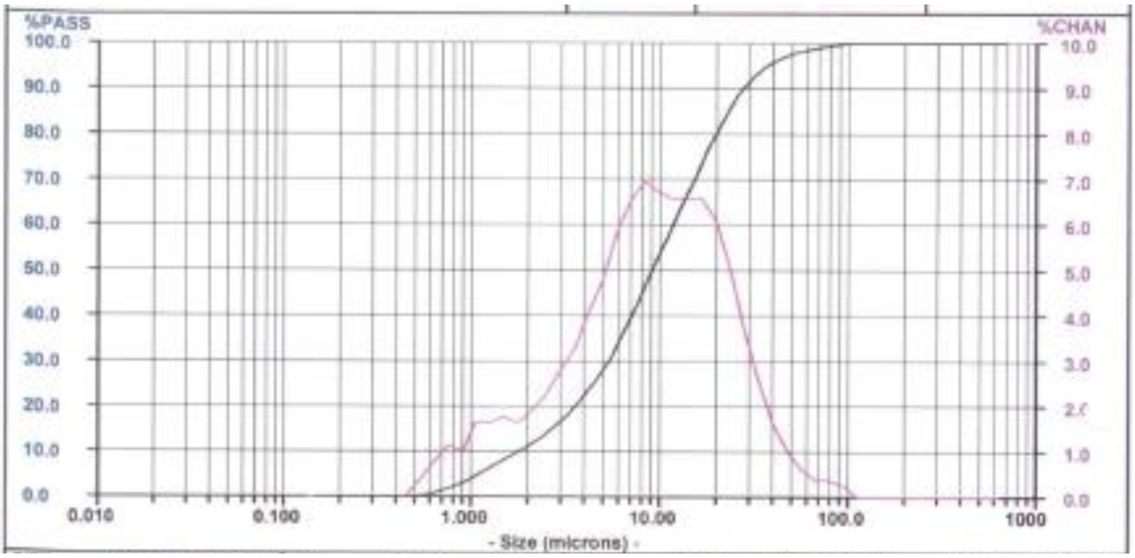


Figure 53. Particle size distribution of the solids in effluent (P&C, 2011)

Flocculant DP8629 performs better in the gara effluent than thenother tested flocculant (see figure below)

7 Clay size refers to the minus 5 micron fraction and has no reference to the clay mineral content.

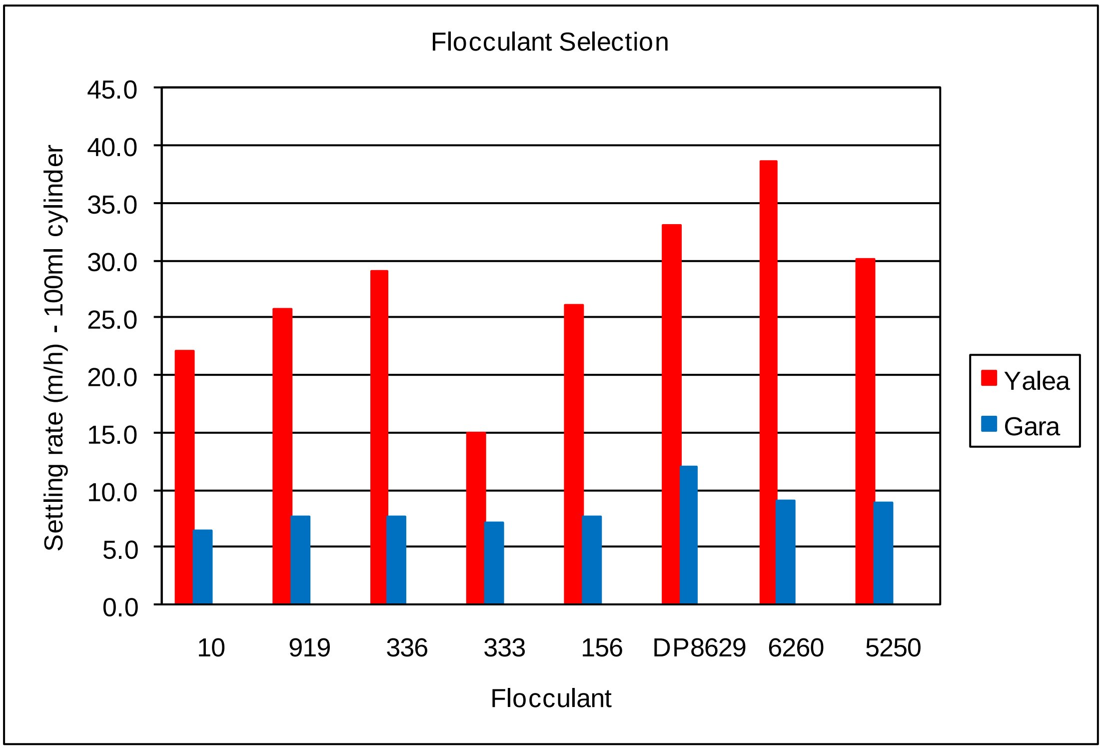


Figure 54. Flocculant screening results (SGS, 2011)

The preliminary thickener feed slurry solids concentration was determined through a series of 250 ml cylinder settling tests at a range of slurry feed solids concentrations.

Figure 55 and Figure 56present the results of the thickener feed slurry solids concentration tests

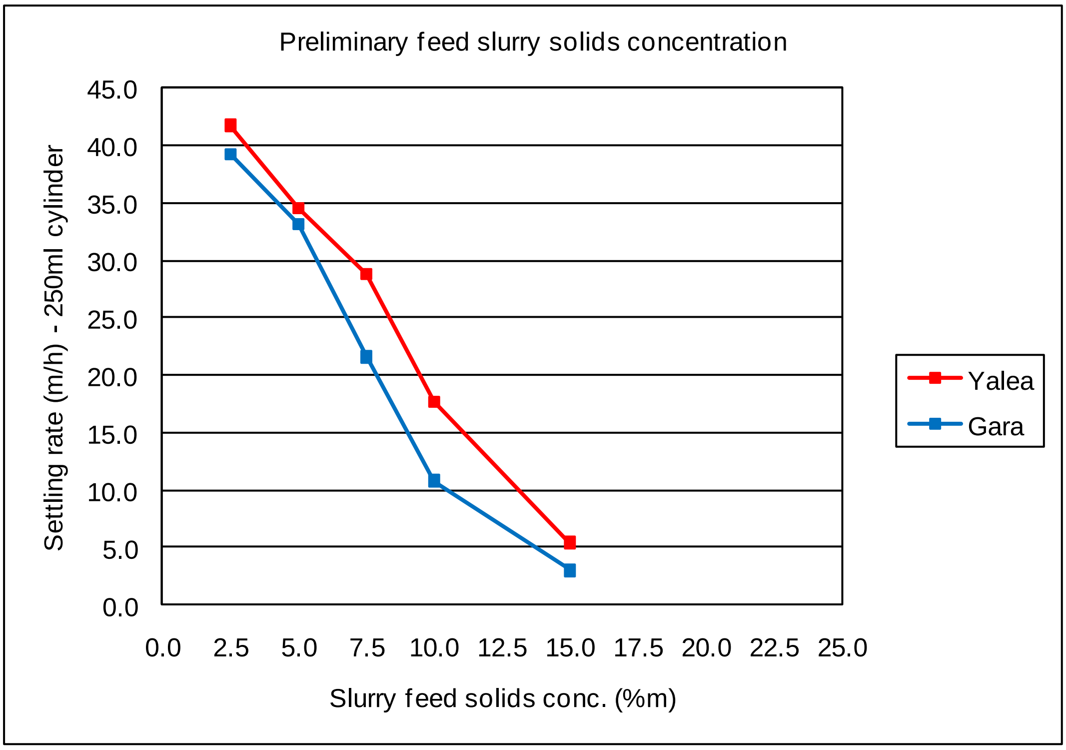


Figure 55 : Thickener Feed Effluent Solids Conc. (settling rate)

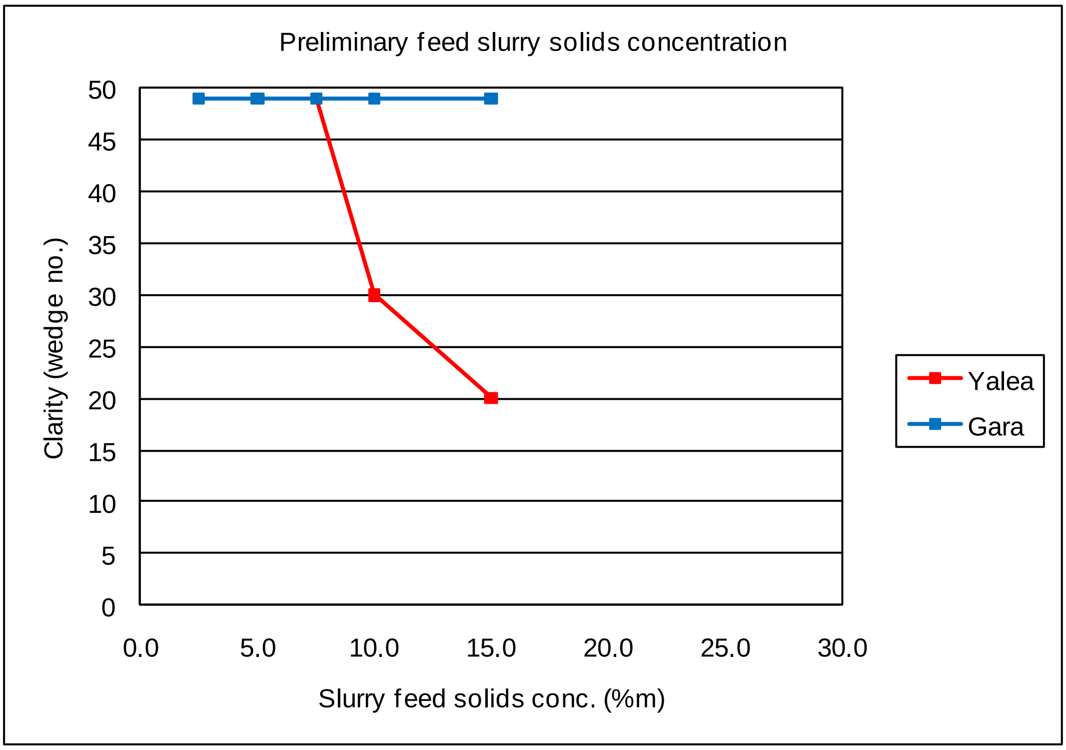


Figure 56 : Thickener Feed Effluent Solids Conc. (clarity)[8]

8 The clarity value was measured in a turbidity wedge and represents a relative clarity measurement where 0 represents completely unclear supernatant and 50 presents the clarity of tap water.

Bearing in mind that this optimization is conducted prior to the optimization of flocculant dose rate, this range of settling tests have been conducted at an arbitrary flocculant dose.

These conservative design parameters should assist in ensuring that the equipment is able to deal with fluctuating water qualities and quantities. The actual suspended solids readings are much less than 5%.

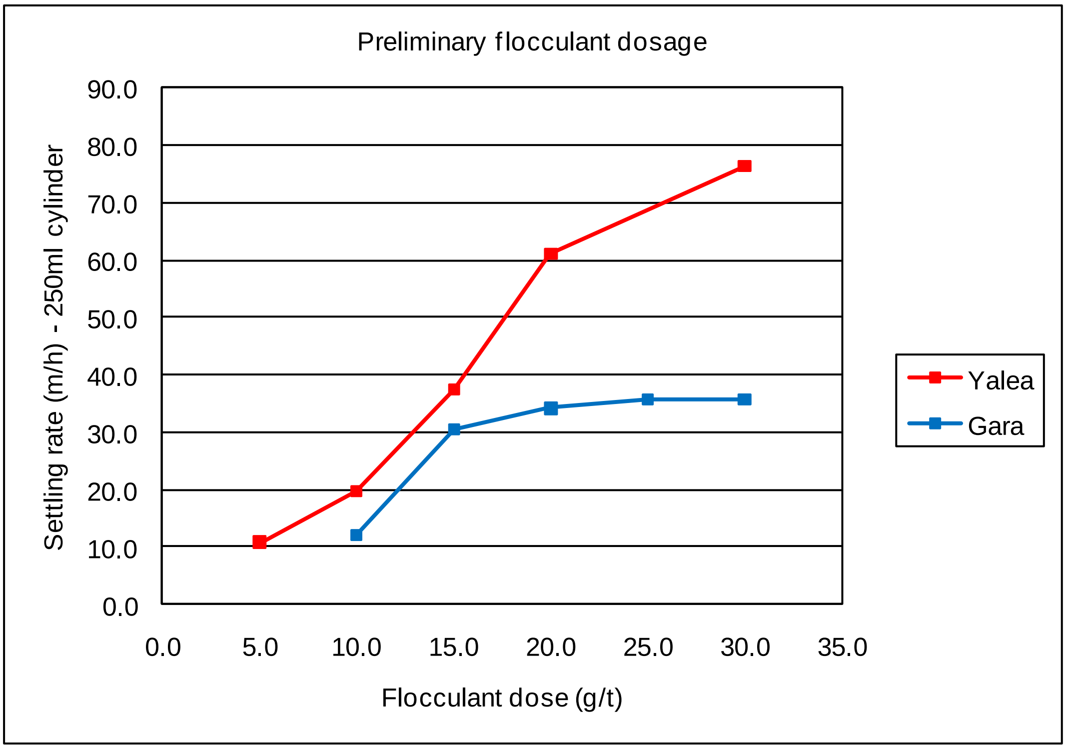


Figure 57 : Flocculant Dose (settling rate)

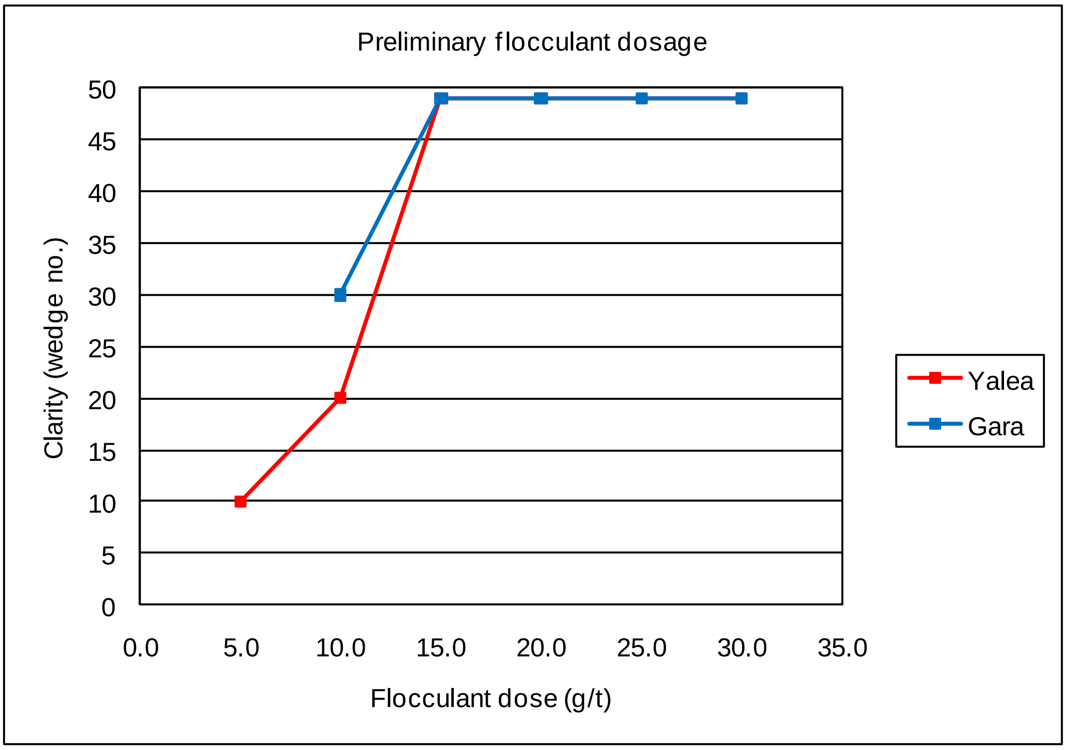


Figure 58 : Flocculant Dose (clarity)Error! Bookmark not defined.

The preliminary flocculant dose was verified during the subsequent settling rate envelope and dynamic thickening tests to be 25 g/t for gara effluent.

Figure 59 and Figure 60 present the static settling rate as a function of flocculant dose and effluent solids concentration as determined through 1 litre cylinder tests.

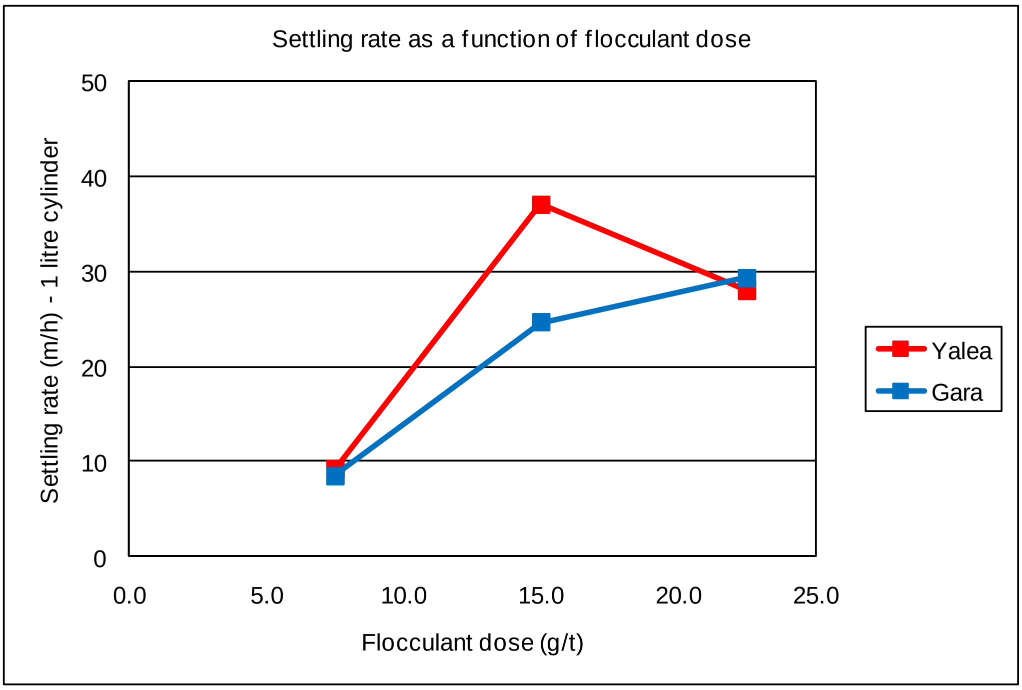


Figure 59 : Static Settling Rate

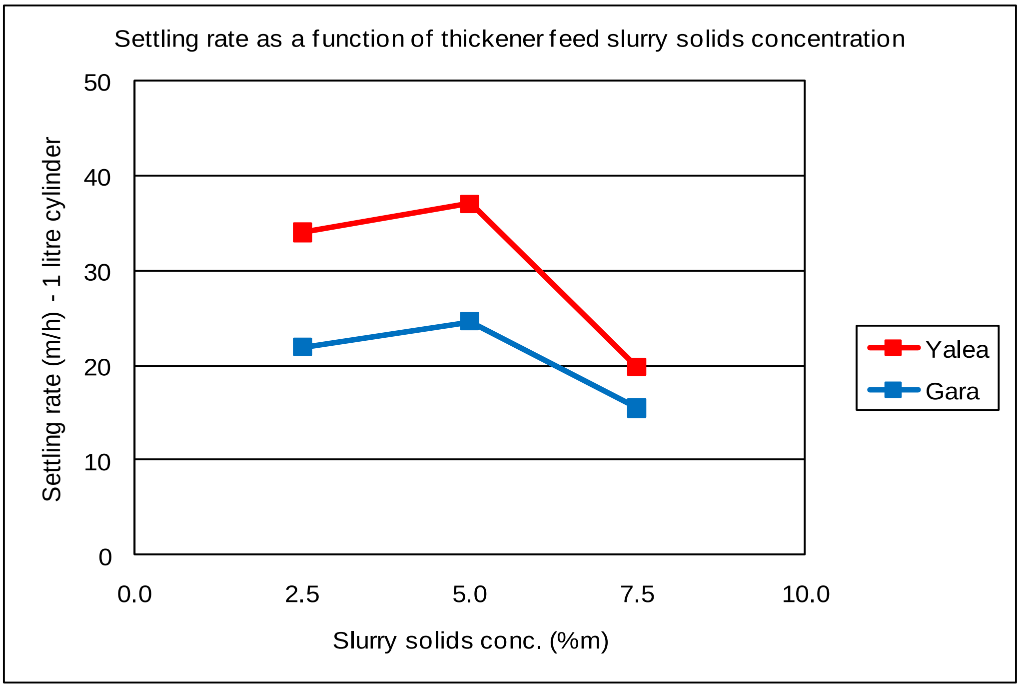


Figure 60 : Static Settling Rate (P&C,2011)

Figure 61 presents the underflow solids concentrations achieved in the 1 litre cylinder settling tests under static un-raked conditions vs. the underflow solids concentrations achieved after a static 24 hour raking period.

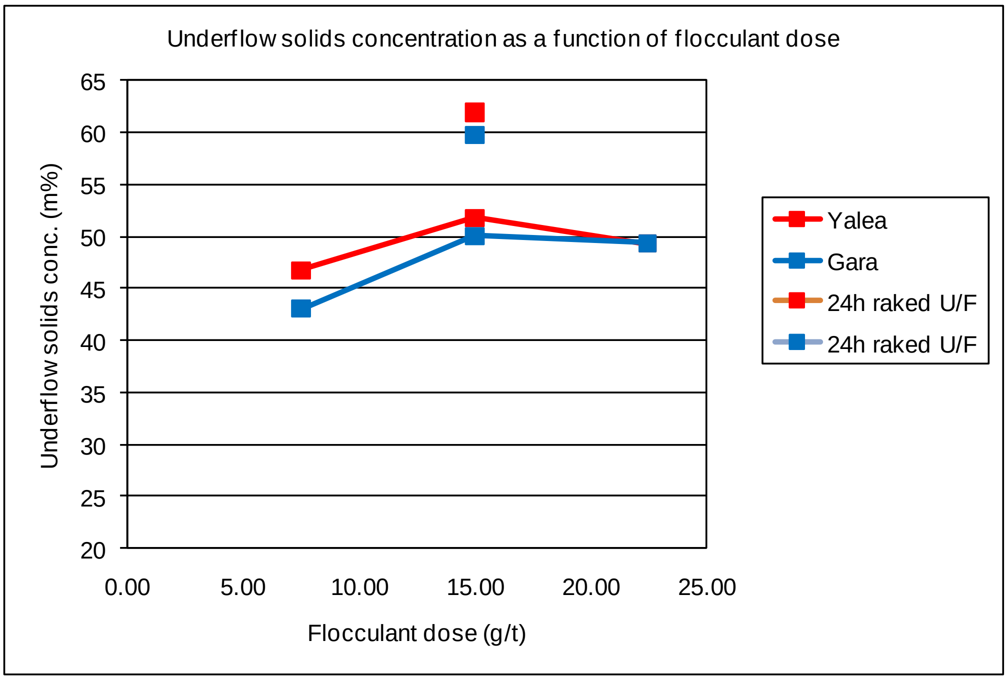


Figure 61 : Static Mud Bed Compaction

The results of the different laboratory dynamic tests are presented below tables and figures -

Figure 62 and Figure 63 present the solids flux and hydraulic flux (rise rate) curves that were generated for each of the two underground discharge effluent samples in a 100 mm diameter bench-top dynamic thickener at the following test conditions:

Table 23. Dynamic Thickening Test Settings and Data

Test Settings						***Results***	
Solids flux ($t/m^2.h$)	Rise rate (m/h)	Mud bed height (mm)	Rake speed (rpm)	Feed slurry solids conc. (%m)	Avg floc dose (g/t)	Overflow clarity (wedge)	Underflow solids conc (%m)
YALEA							
0.2	3.5	100	2.5	5.5	25	25	59.3
0.3	5.3	100	2.5	5.5	25	25	56.4
0.4	7.1	100	2.5	5.5	25	25	55.1
GARA							
0.2	4.1	100	2.5	4.8	25	49	51.9
0.3	6.1	100	2.5	4.8	25	49	51.4
0.4	8.2	100	2.5	4.8	25	49	47.7

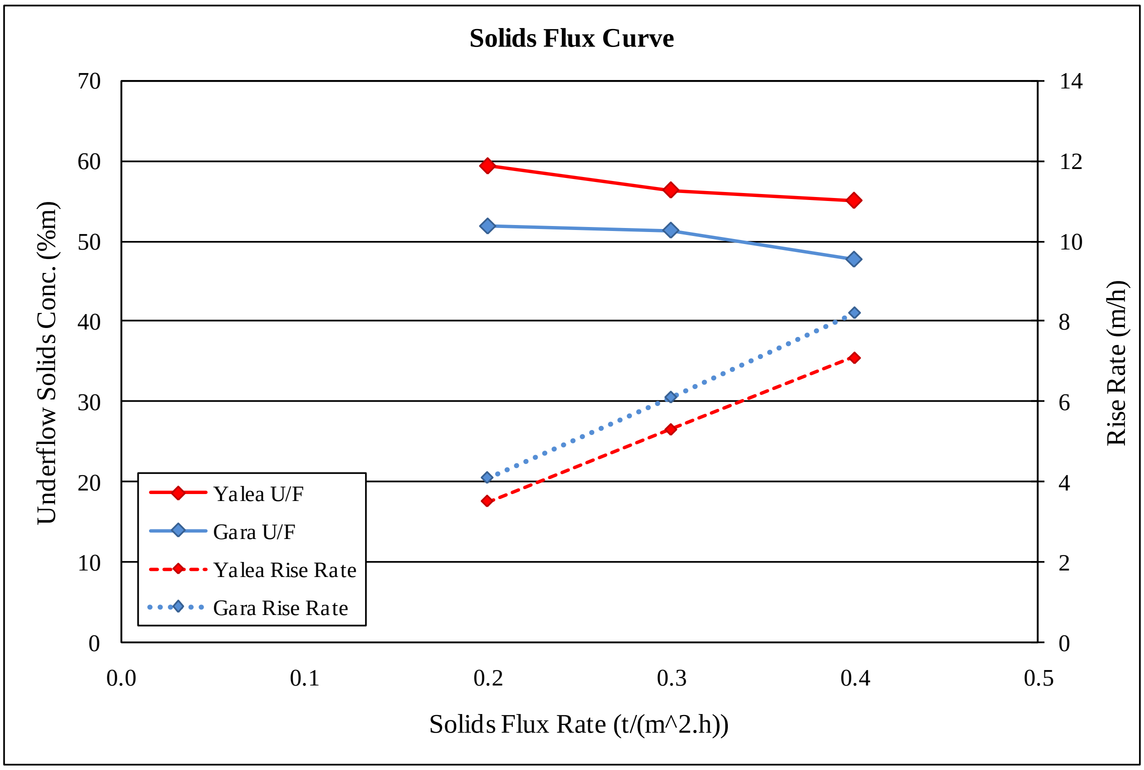


Figure 62 : Solids Flux Curves

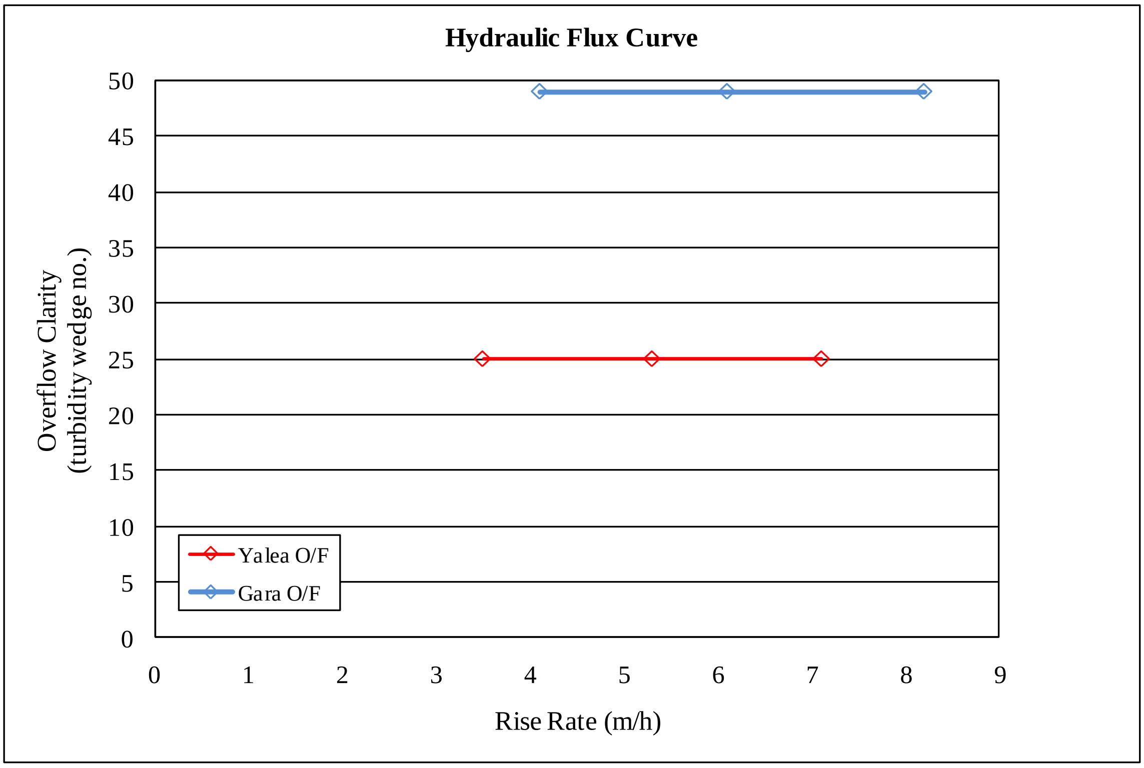


Figure 63 : Hydraulic Flux Curves

Design parameters

Table 24 presents the recommended thickener operating parameters for the Gara samples based on the combined results of the static sedimentation and dynamic thickening tests.

Table 24. Thickener Operating Parameters

Parameter	Gara effluent
Optimum flocculant type	DP8629
Flocculant dosing concentration (%m)	0.025
Thickener feed solids concentration (%m)	5
Optimum flocculant dosage (g/t)	25

Table 25 presents the recommended thickener sizing parameters for the Gara samples based on the combined results of the static sedimentation and dynamic thickening tests.

Underground discharge thickeners are typically sized on rise rate as the critical sizing parameters due to the low solids concentration expected in the thickener feed. A maximum rise rate of 4 m/h, corresponding to a solids flux rate of 0.2 t/(m^2h), is therefore recommended for thickener sizing.

Table 25. Thickener Sizing Parameters

Parameter	Gara effluent
Optimum solids flux rate (t/m2.h)	0.2
Hydraulic rise rate (m/h)	4
Overflow clarity (turbidity wedge no.) - estimate	49
Underflow solids concentration (%m) - estimate	50

Table 26 presents the minimum thickening area and estimated thickener diameter to treat the above process flows based on a critical rise rate of 4 m/h.

Table 26. Minimum Thickening Area (P&C, 2011)

Process stream	Critical Rise Rate (m/h)	Max Flow Rate (m3/h)	Thickening Area (m2)	Thickener Diameter (m)
Gara underground discharge	4	160	40	7

Table 27 presents a more conservative approach were the thickener sizes are rounded up to the next available standard size, which thereby incorporates a large safety factor. This approach is preferred due to the following reasons:

- Thickener sizes are small and therefore cost implications of going larger should not be prohibitive
- The larger thickening area for the Yalea material would in all probability sort out the somewhat poor overflow clarity
- Operational problems around surges of high solids concentration effluents or larger volumetric flow rates should be reduced due to the larger available thickening area.

Table 27. Recommended Thickener Diameter (P&C, 2011)

Process stream	Critical Rise Rate (m/h)	Max Flow Rate (m3/h)	Thickening Area (m2)	Thickener Diameter (m)
Gara underground discharge	2.0	160	79	10

The underflow solids concentrations quoted in table above are based on a mud bed height of 100 mm and essentially exclude the consolidation effect of bed height. Typically, an increase of 10 to 15% in underflow solids concentration is expected at bed heights comparable to full scale (i.e. +1m).

Figure 64. A 3D representation of the proposed thickener design (TWP, 2011)

Inlet zone

The inlet zone of a constructed wetland is designed as a ponding basin and has two key functional roles.

- The primary role is to remove coarse to medium sized sediment (i.e. 125 μm or larger) prior to flows entering the macrophyte zone. This ensures the vegetation in the macrophyte zone is not smothered by coarse sediment and allows this zone to target finer particulates, nutrients and other pollutants.
- The second role of the inlet zone is the control and regulation of flows entering the macrophyte zone and bypass of flows during 'above design flow' conditions. The outlet structures from the inlet zone (i.e. sedimentation basin) should be designed such that flows up to the 'design flow' (typically the 80 percentile flow rate) enter the macrophyte zone whereas 'above design flows' are bypassed around the macrophyte zone. In providing this function, the inlet zone protects the vegetation in the macrophyte zone against scour during high flows.

Macrophyte Zone Design

The layout of the macrophyte zone needs to be configured such that system hydraulic efficiency is optimised and healthy vegetation sustained. Design considerations include:

- The range of suitable extended retention depths is 0.25-0.6 metres (providing suitable plant species are selected for deeper extended detention depths), depending on the underground pumping operations of the wetland and target pollutant.
- Flow velocities must be kept low and maintained through the zone.
- The ground contours under the water of the macrophyte zone should be designed to promote a sequence of ephemeral, shallow marsh, marsh and deep marsh zones in addition to small open water zones. The relative proportion of each zone will be dependent on the target pollutant and the wetland hydrologic effectiveness.
- The macrophyte zone is required to retain water permanently and therefore the base must be of suitable material to allow water flow at the effective rate. If in-situ soils are unsuitable for water retention, a clay liner (e.g. compacted 300 millimetres thick) should be used to ensure there will be permanent water for vegetation and habitat.
- The optimum treatment configuration is a wetland densely vegetated with species that provide a high density of stems in the submerged zone (thereby maximising the contact between the water and the surfaces on which microorganisms grow), while providing uniform flow conditions.
- The main potential advantage to an overall densely vegetated system (for this study) would be the reduction of dissolved oxygen in the near bottom water and the surface sediment layer. The presence of anaerobic sediment is desirable for denitrification.
- The macrophyte zone outlet structure needs to be designed to provide a detention time (usually 48 to 72 hours) for a wide range of flow depths.

(1) Retention Time and Hydrologic Effectiveness

Retention time is the time taken for each 'particle' of water entering the wetland to travel through the macrophyte zone assuming 'saturated' flow conditions. It should be noted that retention time is rarely a constant and the term 'retention time' is used to provide a point of reference in modelling and determining the design criteria.

Hydrologic effectiveness is a measure of the volume of water captured and treated within the wetland and is expressed as a percentage of the water pumped form the underground. For example the constructed wetland presented in this study is designed for 80% percentile of the measured pumping rates. Analysis of the flow rates indicates this to be approximately 2800m^3/day, which is equivalent to 32 L/s.

The range of retention times achieved in a constructed wetland is influenced by the type of structure used. The volume of the permanent pool also has a significant effect on the range of retention times achieved. Water level control is desirable in wetland design to enable maintenance and to assist with vegetation establishment. The HEC RAS[9] Model was set up to simulate the flow conditions based on the input site characteristics. The main aim was to establish the flow inundation (water level height) and flow velocities within the wetland. The inputs into the model were based on the requirements for the wetland to be effective at the proposed location. Figure 65, is an illustration of the proposed wetland location, where Figure 66 provides the cross sectional profile of the current land topography against the proposed wetland topography. The proposed wetland characteristics where set up in the HECRAS Model. The output from the model is presented in the Appendix D, which aims to establish the height of water and flow boundaries/velocities for the proposed wetland.

The different sections of the constructed wetland are described below.

[9] HEC-RAS is designed to perform one-dimensional hydraulic calculations for a full network of natural and constructed channels. Designed by the US Army Corps of Engineers

Figure 65. Illustration of the constructed wetland layout (Source: DWA, 2014)

Figure 66. Illustration of the cross sectional through the constructed wetland layout. Inlet zone (0m – 250m), Macrophyte zone (250m – 650m) and Outlet zone (650m - 800m)

(2) Saturated Hydraulic Conductivity (Darcy's Law)

To determine the hydrologic properties of the macrophyte zone material, a comparison is made based on the material tests (by example only). A one cubic metre (1 m^3) volume of empty space would hold to 1000 L of water. If this same volume is filled with dry macrophyte material it will be able to hold, for example 240 L of water as total storage, which represents a porosity of 24%. However, if this volume is drained under gravity, only 80L (8%) of the total volume will drain. This is an important physical property of the material known as specific yield. The specific yield represents 33% of the porosity and the rest of the water (160 L) is retained in the material particle grains. It is therefore not available as water as it is trapped in the material, only plants can use it via root uptake as moisture.

Specific yield is one of the most important parameter as it is the component of water that can drain from the material under gravity, basically allowing for flow in the wetland. Below the saturation level of specific yield, the material will retain the water. The retained component of the water in the material will be only accessible by plants such as reeds. Therefore, if water into the macrophyte zone is greater it will force water out the macrophyte material and flow above surface.

A very basic relationship for the one dimensional flow in porous macrophyte zone/media is established through Darcy's Law. The formula derives the volumetric flow rate through the function of flow area, and elevation for saturated flow conditions. Based on the Darcy's equations it was calculated that the required hydraulic conductivity ($K = 0.32m/s$), to allow for residence time within the macrophyte zone of 48 hours. The K value in this very basic example will be in-line with a gravel material for the constructed wetland dimensions which have been setup in this study. A very basic illustration of the macrophyte zone of this study is illustrated in the Figure 67.

Porous Media		Units
K =	0.32	m/s
ϕ =	3	
d*h* = (h_2 - h_1) =	1.00	m
J = d*h*/d*x* =	-0.004	m/m
q = -*KJ* =	1.28E-03	m/s
Q = *qA* =	6.40E-02	m3/s
v = *q*/*ϕ* =	4.27E-04	m/s
Hydraulics		
		h
Area	5529.6	m3/d
Flow through macrophyte zone	110.5920	m/d

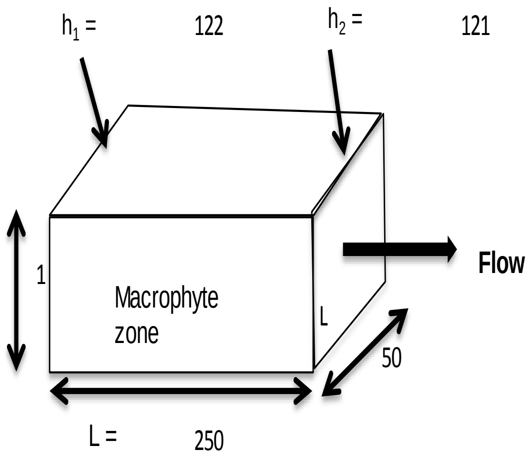


Figure 67. Darcy's flow equation for saturated flow through the macrophyte zone

Modelling horizontal flow in the constructed wetlands with intermittent loadings requires transient variably saturated flow models as these systems are highly dynamic, which adds to the complexity of the overall system. Based on professional experience of applicable models the two dimensions such as HYDRUS-2D model can be used to provide an improved estimate of the saturated flow conditions. It is thus suggested, for practical application:

- Undertake experiments to measure the porosity and the saturated hydraulic conductivity parameters of the macrophyte zone material;
- Instrumentation and monitoring methods for determining the macrophyte zone material saturation should be assessed as these collective parameters are used to determine the flow rates. These parameters should be assessed as they are used in the HYDRUS-2D model for simulations of the water flow and ultimately assess the achievable targets of the wetland.
- It may be possible to further establish the influence of the particulates and biomass growth on the hydraulic properties of the macrophyte zone, as these estimates could further increase its prediction water quality through the wetland.

The HYDRUS-2D model is a finite-element model, which numerically solves the Richards' equation for saturated-unsaturated water flow. Richards equation for one dimensional flow requires knowledge of the soil hydraulic functions, i.e., the soil water retention curve, $\theta(h)$, describing the relationship between water content (θ) and the pressure head (h), and the unsaturated hydraulic conductivity function, $K(h)$ defining the hydraulic conductivity (K) as a function of (h).

The above equation presents a very broad understanding of the Darcy's Law through the macrophyte material, but it is essential that experiments be undertaken for composite samples. In order to adequately quantify the flow in the macrophyte zone, it is imperative that sufficient information of the porous media hydraulic characteristics and the dynamics of the interstitial water are assessed. There are numerous techniques for measuring and monitoring these variables. For example, the porosity is defined as the ratio of volume of voids to the total volume of the macrophyte material. The effective porosity defines the volume of water that a given volume of bulk porous medium can contain. Water content reflects the volume of the void space that is filled with water, relative to the bulk porous medium.

Soil hydraulic properties will required in order to model transport of water in the macrophyte zone. The ability of a porous media to retain and transmit water is characterized by the relationships between water content, (θ), matric pressure head, (h), within the profile and the hydraulic conductivity, (K). The most substantial challenges for experimental and theoretical investigations of fluid flow in unsaturated porous media result from the extremely nonlinear behaviour of the hydraulic properties as a function of saturation and the highly irregular nature of pore geometry. The aim of these macrophyte zone studies must provide a perspective of saturated and unsaturated hydraulic characterization and measurement used in the suitable material.

(3) Soil Water Measurements and Field Monitoring Experiments

It is important also to provide understanding into direct observations into key hydrological processes and techniques in measuring soil hydraulic properties, monitoring soil water dynamics. The understanding of these measurements and data adds value as a reference for the evaluations of the soil and macrophyte media hydraulic behaviour, which ultimately is used in a model. Measurements of the macrophyte media may include;

- soil physical characteristics,
- water retention properties, and
- hydraulic conductivity characteristics as well and *in-situ* hydraulic characteristics.

Soil hydraulic characterisation may involve both *in-situ* and laboratory measurements. A consistent procedure must be adopted for characterising macrophyte media profile. An undisturbed core is taken and the water retention characteristic, bulk density and particle size distribution are determined in the laboratory. The particle size distribution and bulk density may be used to develop pedotransfer relationships, within the macrophyte zone material. However, since the macrophypte zone will be developed ensuring heterogeneity, only a few samples may be analysed. Contractors should therefore be scrutinized and consistently monitored during construction. One could look at relating STP tests to the hydraulic properties, since it would be assumed heterogeneous and the spatial distribution of the hydraulic characteristics will therefore be constant.

Monitoring the pore water for contaminants is a difficult task and requires the use of indirect methods. There are, however, a number of sensing techniques for detecting moisture or the electrical changes due to moisture change that will be considered for long-term monitoring. These techniques include tensiometers and TDR probes.

(4) Water retention characteristic

Conventional methods of soil water retention characteristic determination include both laboratory and field techniques (Klute, 1986; Bruce and Luxmore, 1986). Although many of the standard laboratory techniques can be used to determine the water retention characteristics of the porous media, the modified controlled outflow method is reported in detail. This method holds some promise for the accurate characterisation of the soil pore structure over the range of moisture contents close to saturation.

Accurate measurements over this range are desirable to characterise the larger pore characteristics which conduct water rapidly during intense rainfall. The retention characteristics samples can be used used together with field measurements of both saturated and unsaturated conductivity to define the possible macrophyte material composite.

Recent emphasis on characterising unsaturated hydraulic characteristics of soils in hydrology, soil science and chemical transport studies has fostered renewed interest in liquid retention measurements. It is recommended that the methodology for defining the liquid retention characteristic of macrophyte material established by monitoring equilibration of the matric pressure rather than equilibration of the liquid volumetric content, as in conventional methods.

(5) Macrophyte zone monitoring

Wells and piezometers should be installed to measure the saturated water level dynamics through this zone.

Soil moisture alone does not provide information on the driving force for unsaturated fluid flow in the macrophyte zone or allow the direction of water movement to be determined. The driving force for water movement in macrophyte zone soils is the matrix (or suction) potential, which is usually expressed in terms of a vacuum (using negative pressure units). The matrix potential of a given soil is determined by the texture and moisture content of the soil. If two soils of two different textures (one fine, the other coarse) are placed in contact with each other and allowed to reach equilibrium, water will move between them until they come to the same matrix potential. The moisture content of the fine-textured soil, having more small pores, will be appreciably higher than that of the coarse-textured soil. With knowledge of the soil texture, the matrix potential can be estimated from the measured soil moisture content; however, it is much better to measure the matrix potential directly with a tensiometer.

Tensiometers should be considered for measurement of the macrophyte zone material and ultimately establishing water pressure, which would translate to the water at the surface. Tensiometers can also be used to measure positive pressure in soils that are saturated and thus can be used for monitoring perched water tables, which is an objective of the constructed wetland. Tensiometers have the advantage in that they provide a direct measure of the water potential. They require a continuous water column that extends from the measurement point to the pressure transducer located at the surface. A tensiometer typically consists of a porous ceramic cup or plate attached to a nonporous tube, with some means to measure a vacuum inside the tube. When the porous cup is placed in hydraulic contact with soil, and the cup and tube filled with water and sealed, a vacuum will develop in the tube as water flows from the ceramic into the soil. At equilibrium, the measured vacuum inside the tensiometer is equal to the matrix potential of the soil. An example of how the position of the tensiometers would be placed in the macrophyte zone in order to study the water within this zone is illustrated in Figure 68.

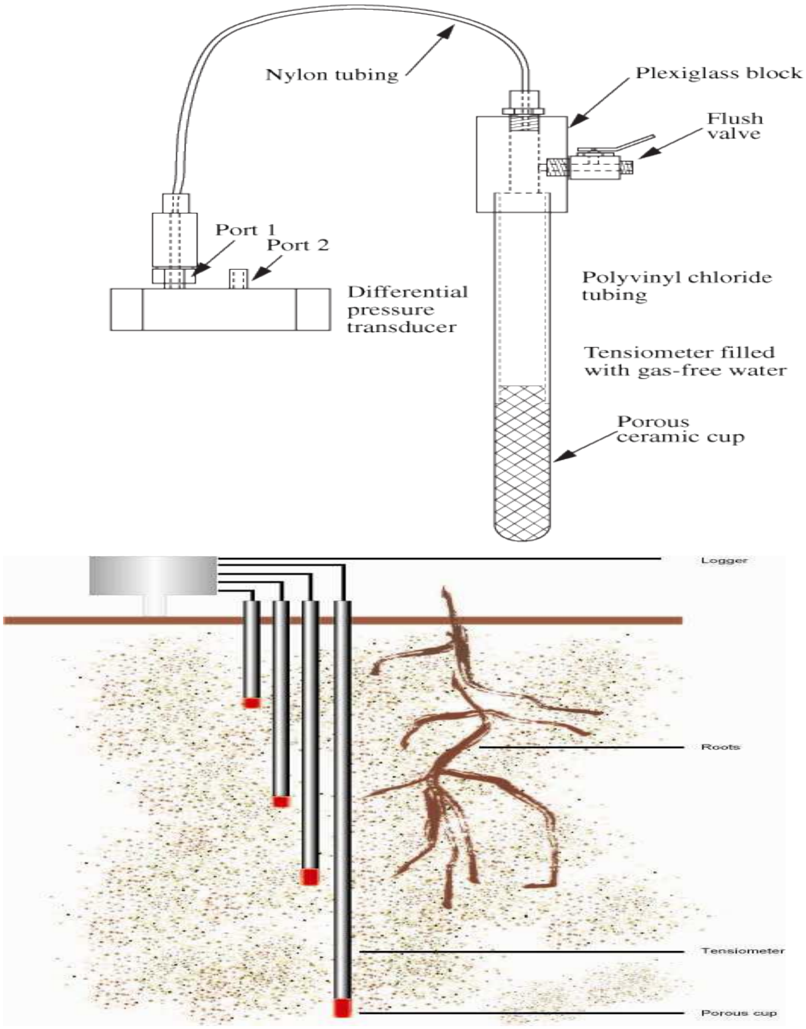


Figure 68. Schematic of the root zone and components of the tensiometers

Surface flow can be monitored within the macrophyte zone consisting mainly of successive runoff plots, (20 x 3 m) may be installed to further develop understanding of the surface flow.

(6) Quantification of the hydrological processes

The macrophyte zone will be constructed as an isolated catchment; therefore the boundary conditions will be the sides and the bottom of the wetland. In order to quantify the hydrological processes detailed observations of the surface and subsurface dynamics will need to be made at various experimental sites. Developing understanding of these mechanisms at these respective sites allow for some generalisation or insight into the classification of critical wetland flow criteria for estimating the outflow responses. Consequently, the wetland flow generation processes and nitrate breakdown can then be deduced from the hydrometric observations of the dynamics of soil water, and flow responses to the inflow and evaporation. It is recommended that these mechanisms will initially be quantified using, physically based techniques. These techniques may be applied to the wetland in order to predict the outflow estimate and to define algorithms and methodologies for application to the macrophyte zone deterministic hydrological models.

(7) Material and stratigraphy

The landscape of the wetland must be characterised by a broad flat drainage system, with no dendritic drainage systems especially in the macrophyte zone. This will aim to ensure the ability for water to be spread evenly throughout the zone. If the material conditions are constant, theoretically the floor gradients would ensure flow velocity in the macrophyte zone. The flow gradients may also be established by developing stratigraphic material units of varying hydraulic properties. For example, horizontal sandy units and be developed allowing water to build up (like sponge), spread the water throughout the unit and only flow out (at the bottom) when saturated.

Problems associate with clogging of macrophyte zone is the clogging of the gravel media, which in turn creates surface flow. This results in reduced treatment efficiency since the water does not come into contact with the macrophyte material.

Wetland plants

In the subtropical and tropical climate, *C. papyrus* is one of the most interesting macrophytes because it is among the most productive plants in wetlands (Kansiime et al., 2005; Heers, 2006; Perbangkhem and Polprasert, 2010).

Figure 69. Photos of the above ground *Cyperus papyrus* in the water body

In natural and constructed wetlands, macrophyte root structures provide microbial attachment sites. In an experimental microcosm set-up, Gagnon *et al.* (2007) found that microbes were present on substrates and roots as an attached biofilm and abundance was correlated to root surface throughout depth. Indeed planted wastewater treatment systems outperform unplanted ones, mainly because plants stimulate below ground microbial populations (Gagnon *et al*., 2007). Plant species root morphology and development seems to be a key factor influencing microbial– plant interactions. Kyambadde *et al*. (2004) measured a higher root surface and microbial density in a constructed wetland planted with

C. papyrus (average root surface area 208.6 cm^2), where the root recruitment rate per constructed wetland unit was 77 roots per week for *C. papyrus*, and *C. papyrus* had more adventitious roots and larger root surface area. Furthermore, *C. papyrus* seems to promote greater nitrogen removal efficiencies, through nitrification and denitrification rates of bacteria associated with it roots (Morgan *et al*., 2008).

The average daily water vapour flux from the papyrus vegetation through canopy evapotranspiration in a wetland located near Jinja (Uganda) on the Northern shore of Lake Victoria was approximated by Saunders *et al.* (2007) as 4.75 kg H_2O m^2 d^{-1} (= 4.75 mm/d), which was approximately 25% higher than water loss through evaporation from open water (approximated as 3.6 kg H_2O m^2 d^{-1}). Jones and Muthuri (1985) reported an evapotranspiration rate of 12.5 mm/day at the fringing papyrus swamp on Lake Naivasha, while Kyambadde *et al.* (2005) reported 24.5±0.6 mm/d for a subsurface horizontal flow wetland in Kampala (Uganda). Evapotranspiration rates vary sharply since they depend on numerous factors influencing the ecosystem's prevailing micro-climate, as listed by Kadlec and Wallace (2009). For example, common reed transpiration rates oscillate between 4.7-12.4 mm/day depending on meteorological conditions (Holcová et al., 2009). Evapotranspiration (*ET*) by plants can significantly affect the hydrological balance of treatment wetlands. The water lost through *ET* concentrates pollutants within the wetland, while the volume reduction results in longer hydraulic retention times (Kadlec and Wallace, 2009). For low loaded systems or systems with longer retention times, such evapotranspiration rates can exceed the influent wastewater flow, leading to a zero discharge.

The Outlet Zone

A outlet will have the primary purpose of the outlet zone provides a cascade of water at the outlet before the discharge point. This will facilitate the aeration of water by allowing water to drop over an elevated area. The drop zone will have gabions over the surface to prevent erosion and facilitate the mixing of the water.

9 Conclusions & Discussions

9.1. Impact of the Underground Effluent on the Faleme river

9.1.1. Characteristics of the effluent discharged

Discharge into the Faleme river started from 2010 to date indicating there has been an effective 4 years of effluent being discharged into the Faleme after passing through the existing settlers. Flow monitoring records indicated an average 1671m^3/day has been discharged. Quality issues (refer to the discharge limits in Table 2) with the effluent as per the analyses record include elevated total suspended solids (TSS), relatively high arsenic (As) levels in the solids, elevated aluminium (Al) and iron (Fe) levels, high nitrate (NO_3) and increasing sulphate (SO_4) concentrations.

Average TSS value recorded over the reporting period is 1435.7 mg/l with As content varying from 64 to 78 mg/kg (vs. 33 mg/Kg as guideline – McDonald, 2000a) and Manganese (Mn) level reaching 2050 mg/Kg vs. a guideline 1100 mg/Kg (McDonald, 2000a). No dissolved Cr & As (mobile form) was picked up in the past analyses, only in July 2014 when traces (0.017 mg/l versus a limit of 0.01 mg/l) of dissolved As were identified. The Gara ore being relatively Arsenic (As) depleted (Lawrence et al., 2013), that being locked up in pyrite (<1 wt.% As), As identified in the settling ponds sediments maybe due to localised arseno pyrite zones which hasn't been picked up in previous petrography work. The high Manganese (Mn) levels (2050 mg/Kg vs. 1100 mg/Kg guideline) are likely sourced from the Kofi limestones, which are common along the Senegal-Mali Shear Zone. It is to be however noted that the recent TSS analyses showed Mn level at 150 mg/kg (much below the 1100mg/kg guideline). With regard to its As & Cr content, the TSS of the effluent is classified as toxic according to McDonald et al. (2000a).

2014 survey indicated the nitrite (NO_2) value of 10.2mg/l, the nitrate (NO_3) value of 96.5 mg/l and Ammonia (NH_3) of 3.59 mg/l in the effluent are within the water discharge limits (15mg/l for Ammonia and no limit is specified for Nitritre) except Nitrate which exceeded the Malian discharge limit of 30 mg/l. Average nitrate level over the reporting period is 159 mg/l. the most probable source of the nitrate is the explosive used in mining.

Fe and Al, although not analyzed for in the 2014 survey, record over the 4-years reporting period indicated high levels of these two elements in solution. Iron level is fluctuating around an average of 19.8 mg/l with a maximum of 110 mg/l recorded on May 2013 (vs. a limit is 2 mg/l) and the maximum value recorded was 51.3 mg/l (May 2013) and the last aluminum value was at 4.79 mg/l which is above limit of 1mg/l. the source of both Fe and Al is believed to be the local and regional geology.

Sulfate level is below the guideline of 1000 mg/l but has increased since 2010. The levels should continue to be monitored as it is possible that it may increase over time as the mine working ages and continue to access new areas exposing new faces to oxidation.

From above, it is clear that Gara effluent could only impact on the Faleme through sedimentation (with associated relatively small amount of immobile As in the sediments) and Eutrophication through the elevated NO_3 levels. Although below the discharge limit, SO_4 which is traditionally known to be associated to mining, should be seen as a potential pollutant.

9.1.2. Characteristics of the faleme

Faleme water quality

When water quality results are compared to guidelines derived from appropriate sources (DWAF, 1996, Bain and Stevenson, 1990) the water quality in the Faleme River can be considered fair. The pH values obtained from the *in situ* analysis at the sites considered in the 2014 survey were found to be mostly neutral and would not be seen as limiting factor for local aquatic biota.

The concentrations of dissolved ions (conductivity) in the Faleme River were found to be relatively consistent, with few fluctuations as sites move downstream. Although anthropogenic activities are occurring adjacent to the rivers, the activities were not dramatically influencing dissolved ion concentrations. The consistent conductivity results also indicate that the dilution capacity of the Faleme River is sufficient to dilute dissolved salts to an extent whereby negligible effects would be observed in local aquatic biota. The conductivity was seen to slightly increase between the upstream and downstream sites of the Gara settling pond discharge. This increase may be attributed to the discharge itself which had a conductivity of 1332 µS/cm resulting in a slight increase between the sites. The conductivity then returned to normal levels at the Faleme Weir site.

Sulphate concentrations are on average low (2 -5 mg/l) in the Faleme River, sulphate levels increased downstream of the artisanal mining areas and then decrease again at the nearest downstream site, possibly as a result of dilution. The Gara settling pond was found to contain elevated concentrations of sulphate, at 198 mg/l, which decreased to 94 mg/l at the confluence point between the Gara settling pond discharge and the Faleme River. Dilution is occurring to such an extent in the Faleme River that no negative effects on aquatic biota would be observed at downstream regions.

Nitrate molecules were found to be exceeding guideline concentrations in the Gara settling discharge point at the confluence with the Faleme River. Although high concentrations were observed at this site, the concentrations measured immediately downstream of the site, at DS Gara settling, was found to be below guideline values indicating a negligible effect on local aquatic biota. This is evident by the absence of any algae bloom on the water surface.

No dissolved As & Cr could be observed in the sites located within the upper reaches of the study focus area indicating that limited sources exist between these sites. Dissolved As concentrations were observed to increase and were in excess (24 times), above guideline values downstream of the artisanal mining village Sasanba. These concentrations were such, that negative effects would be observed in local aquatic biotic structures. Furthermore, the elevated As concentrations provide an indication that artisanal mining activities can produce dissolved As metals in associated water sources. Dissolved concentrations of Cr were observed to be elevated at sites associated with artisanal mining activities and these included sites downstream of Sasanba as well as artisanal activities in the Gara River. These results indicate that artisanal activities are elevating Cr concentrations in the local river systems.

Concentrations of Cadnium (Cd) and Mercury (Hg) were found to be below detection limits at most sites with the exception of sites associated with artisanal activities which served to increase these dissolved metals to concentrations which were detectable. Dissolved Lead (Pb) concentrations were also observed to be above threshold effect levels at the site downstream of Sasanba indicating that lead is possibly produced as a result of artisanal mining activities as Pb is found in batteries and fuels/lubricants extensively used in artisanal mining activities.

Above shows that the quality of the faleme is largely impacted by anthropogenic activities such as artisanal mining activities and very negligible impact from the gara effluent.

Faleme sediment quality

Arsenic (As) and Chromium (Cr) are above acceptable levels at Faleme downstream of the operation. These sediments according to McDonald et al. (2000a) are classified as toxic and constitute a threat to the aquatic biota. These same results are observed at the Faleme upstream of the Gounkoto operation with even higher concentrations in the past surveys – indicating that the mine effluent is not the only source for this high level of metals. As and Cr seem to be occurring naturally even though sediments sample from the settling ponds (PC1) returned also a high value of As. The Chromium (Cr) enrichment maybe coming from the mafic-intermediate intrusive/extrusive Faleme rocks or younger dolerites, or sericite alteration associated with the As-rich ore bodies.

The analysis of Hg in sediments revealed elevated and enriched concentrations in sites located downstream of artisanal mining activities. The highest concentrations of Hg were obtained at the artisanal area at Djidian and can be linked directly to gold washing practices in place there. As seen in the figure below (Figure 70) Hg is used and left adjacent the river and thereby can be seen as a point source of the pollutant.

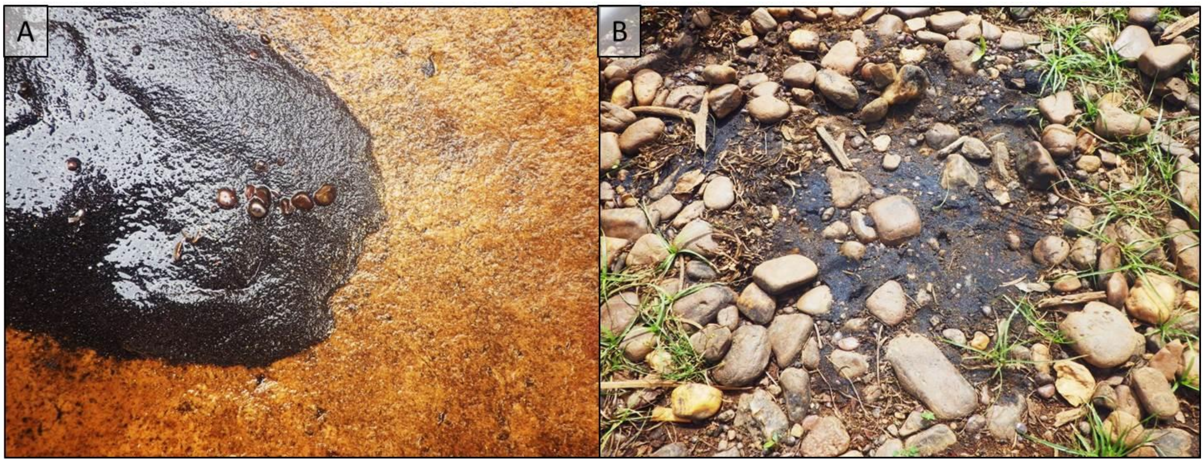


Figure 70. Artisanal gold processing chemicals. A: Mercury and other metals used in gold processing. B: Processing chemicals left adjacent the river

The Faleme sediments are classified as toxic according to McDonald et al. (2000a) and constitute a threat to the aquatic biota. The primary source of the pollutants is from the surrounding geology followed by artisanal mining activities. The mine through discharge has a negligible contribution to the Faleme polluted sediment.

Aquatic Macroinvertebrates

The macroinvertebrate assemblages at the sites generally represented medium term conditions in the local aquatic habitats. Due to the time of the July survey, water quality constituents may have been diluted, due to rainfall and increased flow, allowing for the presence of improved water quality based on water quality analyses. However, macroinvertebrate assemblages at the sites were composed of largely pollution tolerant taxa. This is confirmed by low ASPT and EPT % contribution values obtained at the sites. This is further confirmed by the absence of families such as Perlidae, Prosopistomatidae and in general the Ephemeroptera and Trichoptera groups.

Based on these results the long term conditions at the sites in the Gara River can be considered fair/poor whilst conditions in the Faleme River can be considered poor at sites in the upper reaches (artisanal mining areas) and fair in the lower reaches (improved due to the presence of the Weir). Furthermore, it can be stated that there is a definite overall modified status result for the macroinvertebrate communities present and identified at sites due to numerous anthropogenic activities as seen in the figures below.

Figure 71. Possible negative impacts at Farandie. A: Dredging, B: Hydrocarbon pollution.

Figure 72. Heavily impacted faleme cobble bed due to sand mining at 13.001471°; -11.405753°

Figure 73. Photographs illustrating urban pollutants. A: washing of vehicles and clothing; B: urban runoff/solid waste.

Figure 74. Extensive artisanal activities in the Gara River

Fish and Bioaccumulation

The different fish species sampled at shown in Table 21 and the metal contents in Figure 41, Figure 42, and Figure 43.

The use of the bioaccumulation analysis of metals in fish tissue provides a measure of conditions that were occurring *approximately* 12 months prior (long term) to the moment of sampling (Zhou et al., 2007). Based on this, it can be stated that bioaccumulation analyses provide tertiary evidence of what the true aquatic conditions are, and can establish which factors are influencing aquatic conditions prior to and during the moment of sampling.

The bioaccumulation of metals in aquatic biota often allows for the magnification of elements to detectable limits and therefore allows for the accurate determination of contaminants, despite potential low concentrations in the ambient environment (Tate and Husted, 2014). This previous statement was observed when considering the concentrations of Cd in fish tissue from the Faleme River, which were determined to be highest at the Faleme Weir followed by the GK Midstream site. Based on this information it can be stated that Cd concentrations in the ambient environment are such that bioaccumulation occurs to a greater extent at these sites. Based on sediment analyses presented earlier in this study, Cd was found to be predominantly below detection limits in the sediment, with exception of the GK Midstream site. Although Cd was below detection limits in the sediment of the downstream site (Faleme Weir) it has been determined to be present in elevated concentrations in previous assessments (during different seasons). Therefore, based on these results it can be stated that Cd concentrations are elevated in the Faleme Weir. This increased concentration may be due to the effects created by the impoundment and activities at the Weir, which includes artisanal mining that makes use of batteries and therefore presents a potential source resulting in increased concentrations of Cd in habitat utilized by *T. zillii* and subsequent increased bioaccumulation.

When considering the bioaccumulation trends of As in the Faleme River, the largest concentrations were observed at Farandie followed by the Faleme Weir and then the Upstream GK site. When considering the sediment and water quality results of the study these trends do not directly confirm this at the site, however, when considering previous studies, as well as the location of the sites, it can be stated that As was confirmed in elevated concentrations at these sites, being at 252mg/kg at the Upstream GK site and 44mg/kg at the downstream Faleme Weir site during the previous low flow 2012 survey. Furthermore, the location of the Farandie site immediately downstream of artisanal village Sasanba, which was shown to emit high concentrations of As dissolved in the water column, could be responsible for these increased As concentrations as dissolved As would be more bioavailable than As which is present in the sediment.

Based on this information the following hypothesis can be stated. The concentrations of As at the site GK Upstream is elevated as a result of upstream artisanal mining activities during the low flow period, as established in the sediment analysis of the 2012 survey. After rainfall and subsequent increased flow, sediments are deposited in the pool at the GK Midstream site where they were determined to be at highly elevated concentrations in this study. The bioaccumulation of As at the Upstream GK site is therefore higher as fish would be representing conditions prior to the survey (in the low flow period) with the Midstream GK fish showing lowered concentrations as sediments had not yet settled into the pools associated with sites. It is therefore further hypothesized that after the high flow period the fish in the GK Midstream site would have higher concentrations of As when compared to the upstream site (Upstream GK) as a result of this increased concentration during the high flow period.

To conclude, the concentrations of As in fish from Farandie are a result of the presence of extensive artisanal mining upstream of the site producing increased dissolved As concentrations (as determined in this study) and therefore a greater component of bioavailable As resulting in the site having the highest bio-concentration of As when compared to the other sites. Concentrations of As in fish from the Faleme Weir were elevated due to the cumulative effects of the impoundment (weir) and the upstream artisanal activities resulting in the second highest concentrations. Although sediment analyses in this study determined lowered concentrations of As in the Faleme Weir, it is hypothesized that recent high flows diluted As concentrations in the sediment and therefore the more accurate/representative bioaccumulation results would be favored.

The bioaccumulation trends of Hg in the Faleme River were found to closely emulate trends seen in the Cd concentrations, in that the concentrations of Hg in the sites Upstream GK, Farandie and the Faleme Weir were below detection limits in the sediment. Bioaccumulation concentrations of Hg were found to be highest at the Faleme Weir, which is expected due to the large extent of artisanal miners at the site, as observed during the 2014 survey. The second highest concentration was observed at the GK Midstream site with the metal also being picked up in the Midstream GK sediment possibly indicating rapid uptake by local *T. zillii* populations and further confirming aquatic contamination from upstream mining activities and deposition at the site.

The bioaccumulation trends of Pb showed similar trends as As bioaccumulation levels and were determined to be highest in the Faleme Weir followed by Farandie and then the Upstream GK site. Possible explanations for this will be similar as the explanation of As and Cd concentrations as dissolved Pb was also observed at the site downstream of Sasanba but is possibly accumulating in fish at the Faleme Weir to a greater extent because of impoundment effects.

The bioaccumulation concentrations of the metal Cr were found to be highest in the Faleme Weir and this can be explained through the continued high concentrations of the metal observed in the Faleme Weir sediments (2010, 2012 and 2014).

9.1.3. Conclusion

Although the mine effluent had a few quality issues (suspended solids with high arsenic content due to the nature of the rocks, and elevated nitrate concentrations), the aquatic assessment indicated that it has not had any significant impact on the Faleme River over the past 4 years of discharge. The current deterioration of the Faleme ecosystem is associated primarily with the artisanal mining activities, aggregate mining and other uncontrolled activities by the riverine communities. Going forward it is of paramount importance that the mine develop an adequate treatment system to isolate the solids and nitrate from the effluent before discharged as it is believed that continued discharge of the effluent may have a long term impact on the Faleme locally (i.e. immediately at the discharge point).

9.2. Design of the Gara Effluent Treatment System

For an effective design of a treatment system it was necessary to predict the future discharge volume from the gara underground. A predictive geohydrological model was constructed for the gara area by Digby Wells Environmental and it was found that an inflow rate of 2,199.5m^3/d, comparable to the average discharge rate of 2,528m^3/d, was simulated as steady state groundwater inflow rate into the modelled decline. An average flow of 2600 m3/day and a maximum peak flow of 3840m3/day is used for the purpose of this assessment.

Digby Wells Environmental recommended a thickener as a measure to remove the solids from the effluent before discharge and a wetland to remove the nitrate. The rationales behind these choices are not covered; instead the approaches used to design the two systems (thickener and wetland) form the basis of the next section.

9.2.1. Removal of solids

Patterson and Cooke (P&C) in Johannesburg was contracted to help with the design of the thickener. The final water quality objective (Malian discharge limit) is <30 mg/l before discharge.

The conductivity of the slurry falls within the moderately high range (1.5 to 3 mS/cm). A high clay size (-5 micron) percentage of more than 30% could indicate high flocculant dose rates. Settlings slurries could be expected in the presence of clay ores as a result of the double layer compression effect at slurry conductivity values of 2 mS/cm and above.

It was observed that solids in gara samples coagulated in the natural state. A naturally coagulated material is defined in layman's terms as a material that settles overnight (without any flocculation) and producing a layer of clear supernatant water above a settled bed of solids. As a result, no further slurry conditioning measures is required and therefore no flocculation and/or settling problems are expected based on the natural coagulated state of the thickener feed effluent. But because of the relatively high volume of effluent, it was necessary to induce a quicker settling rate via flocc addition. The current plant flocculant (DP6829) performed well for the Gara materials – this is easier as it will save both cost and time. For this exercise, a reasonable maximum solids concentration of 5%m was selected as the basis for all further test work.

Due to the irregular nature of the solids in the effluent (see Figure 23), inclusion of an internal thickener feed-well dilution system in the thickener design is important in order to deal with possible surges of high solids concentration material that might come through.

Because of the solids quality concerned raised in the characterization of the effluent, the overflow clarity was the overriding factor that led to the selection of a preliminary flocculant dose rate of 25 g/t for Gara samples to achieve a minimum settling rate of 20 to 30 m/h and also ensure acceptable overflow clarity (+40 on clarity wedge).

Underground discharge thickeners are typically sized on rise rate as the critical sizing parameters due to the low solids concentration expected in the thickener feed. A maximum rise rate of 4 m/h, corresponding to a solids flux rate of 0.2 t/(m^{2}h), is therefore recommended for thickener sizing. Based on all the test results and assuming a discharge rate of 160m^3/h below is a table with the minimum parameters.

Process stream	Critical Rise	Max Flow	Thickening	Thickener

	Rate (m/h)	Rate (m^3/h)	Area (m^2)	Diameter (m)
Gara underground discharge	4	160	**40**	7

The thickener is expected to provide a physically good quality water to feed the constructed wetland for the nutrients and heavy metals removal. A carefully designed and constructed wetland is able to remove the pollutants in the discharge water. However, from the discussion, it is evident that wetlands represent complex pollutants removal systems and their constructions require some knowledge in many disciplines. The hydraulic properties of the macrophyte zones and climate are the parameters controlling retention time, macrophyte growth, therefore the rate of pollutant removal – it is therefore of paramount importance to get them right.

9.2.2. Removal of nitrate and heavy metals

The wetland has been designed to treat high nitrate levels and high dissolved heavy metals and to protect the wetland should there be a lot of suspended solids entering the system.

The new mechanical settler will be used for primary removal of solids but there needs to be a system which will stop solids from entering the wetland if the settlers are not operational. This will prevent blinding of the wetland.

The clear water will be fed into the constructed wetland which be divided into two different compartments/zones, the first one will include aerobic and anaerobic zones, with aerobic zones near the surface and anaerobic zones below. The last one will be an aerobic zone and being the maturation pond/cascading pond.

The anaerobic part will employ the use of bacteria and macrophytes to provide a biological treatment activity, where the metals will be removed by the process of rhizofiltration (removal of pollutants from the contaminated waters by accumulation into plant biomass). The heavy metals could also form compounds with the ferricrete rocks where these are placed in the wetland or precipitate as metal sulphides with the sulphides generated by sulphate reduction in the anaerobic zone.

Plants or microorganisms can assimilate nitrate, or anaerobic bacteria may reduce nitrate (denitrification) to gaseous nitrogen (N_2) when nitrate diffuses into anoxic (oxygen depleted) water. The gaseous nitrogen volatilizes and the nitrogen is eliminated as a water pollutant. Thus, the alternating reducing and oxidizing conditions of wetlands completes the needs of the nitrogen cycle and maximize denitrification rates (Johnston 1991).

The wetlands would have to be deep (at least 500mm depth) in order to create an anoxic/anaerobic environment that is required for the reduction of sulphate to sulphide and to achieve the required retention time for a biological activity to take place. The produced sulphide would precipitate the metals and the precipitate would settle out and sediment over time. The macrophytes planted in the wetland would serve a purpose of metal uptake through rhizofiltration. Ferns, *Pteris vitta* commonly known as Braken fern has been identified as an As hyperacumulator. It can accumulate up to 7500 mg As/kg on a contaminated site (Ma et al., 2001) without showing toxicity symptoms. The ecological status of this species in the area would have to be established to ensure it is not a potential invasive.

The effluent would be aerated through a cascading pond prior to discharge to the environment. The wetland would require regular but infrequent maintenance over the long-term for clearing the site of weeds, harvesting the reeds, ensuring that the pipes aren't clogged and collecting water quality samples. The declining slope would also be useful in terms of gravitationally feeding the wetland and ensuring that a required retention time is achieved. Gravity flows ensure that the system is operated cheaply.

De-silting of the settling areas and wetland will be needed dependant on the effectiveness of the settlers.

Removal of Arsenic will also be influenced by two main mechanisms which are; co-precipitation with Fe-oxides caused by the oxidation of Fe II to Fe III and Mn-oxides, and adsorption on organic matter. Thus, the As behaviour is governed by redox chemistry of Fe(III) and Mn(IV) oxides under oxidising conditions. Increases in sediment redox potential equally increased the affinity of both Fe (III) and Mn (IV) oxides for As, while a decreases in sediment redox potential results in high affinity between particulate organic matter and As.

Water will then flow to the cascaded pond designed to remove as much residual Mn and Fe as possible (by aeration at higher pH and allowing the precipitates to settle) prior to discharging the water into the surface water environment through oxidation cascade to help with the oxygenation of water.

The oxidation cascade will serve as a post-treatment pond and the following are proposed requirements of the post-treatment pond:

- 200 – 500mm shallow clay/concrete/plastic lined earth pond;
- constructed at a slight decline (5 to 15^{o} angle) to facilitate mixing and aeration of the water;
- None-reactive stone (+50mm) to facilitate mixing of the flow and to enhance aerobic conditions; and
- Monitoring of the water quality must be implemented and the frequency of monitoring should be adhered to in order to monitor the success of the implemented technology.

This could be achieved by monitoring the quality of the underground water after the settlers and at the wetland outlet.

The use of coarse material and large pipes is imperative to maintain continuous flow. This recommendation is from experience gained by constructing trail sized wetlands in the past. Finer sediment and/or thinner pipes will clog or choke and endless frustration will be experienced.

9.2.3. Conclusion

The design of the solid removal system was straight forward as the thickening system is a well understood field and involved relatively simple calculation. A 10m diameter thickener will provide the necessary surface area to remove the solids from the gara effluent before entering the wetland. Designing a horizontal flow subsurface constructed wetland, however, revealed to be very complex as many physical, biological and chemical processes are involved in the system. The research has allowed an understanding of the different processes and because of the complexity of their interaction a broad design has been proposed with a set of designs to be trial tested (real life situation) in order to select the most effective pollutants system. Figure 75 below shows the design of the proposed treatment integrated system and the different wetland designs to be trial tested:

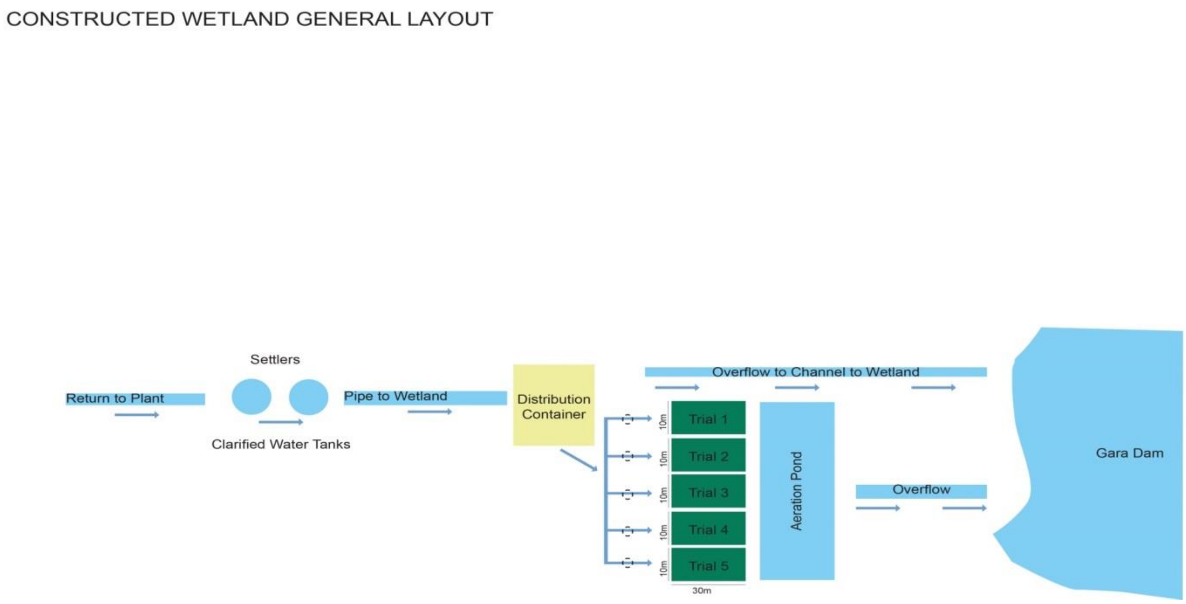
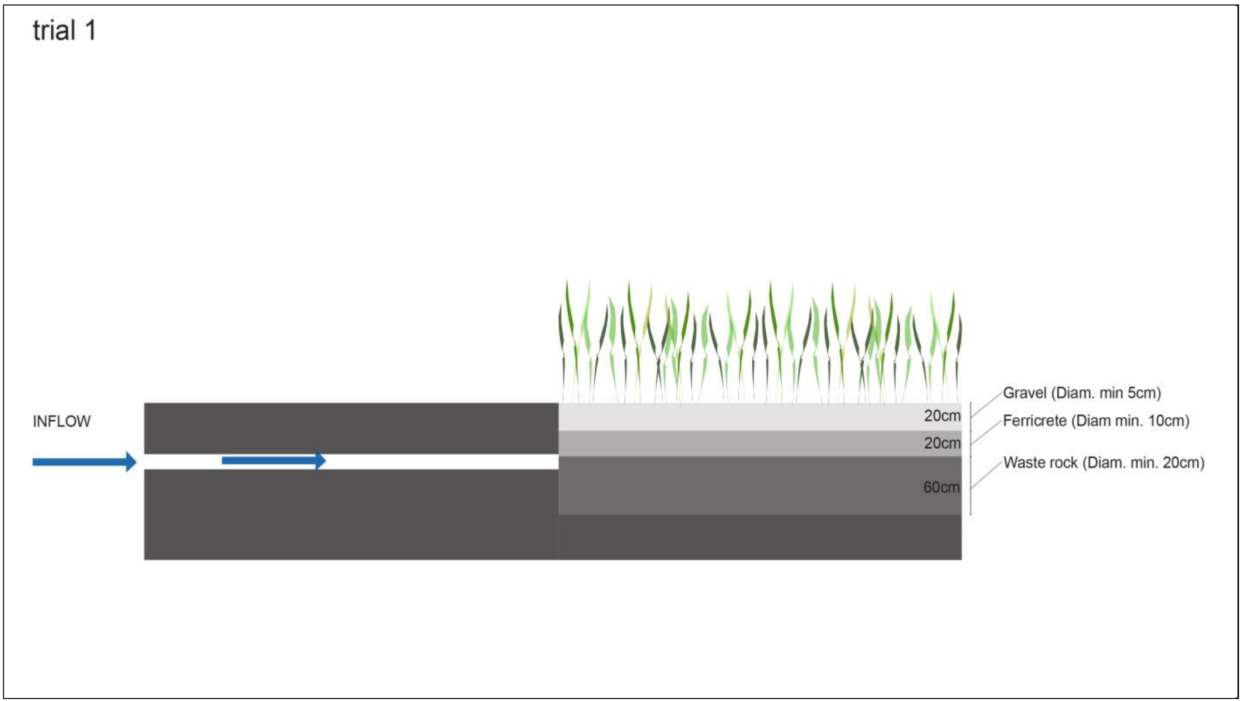


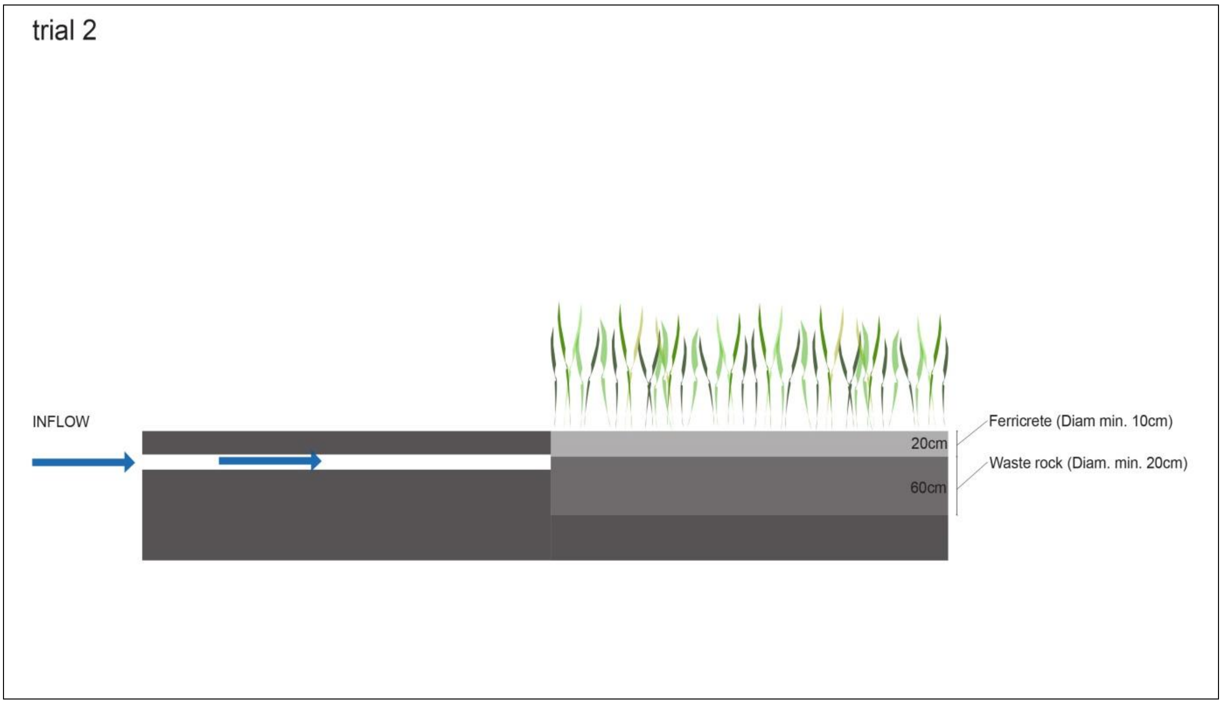
Figure 75. Proposed surface treatment system (Source: DWA, 2014)

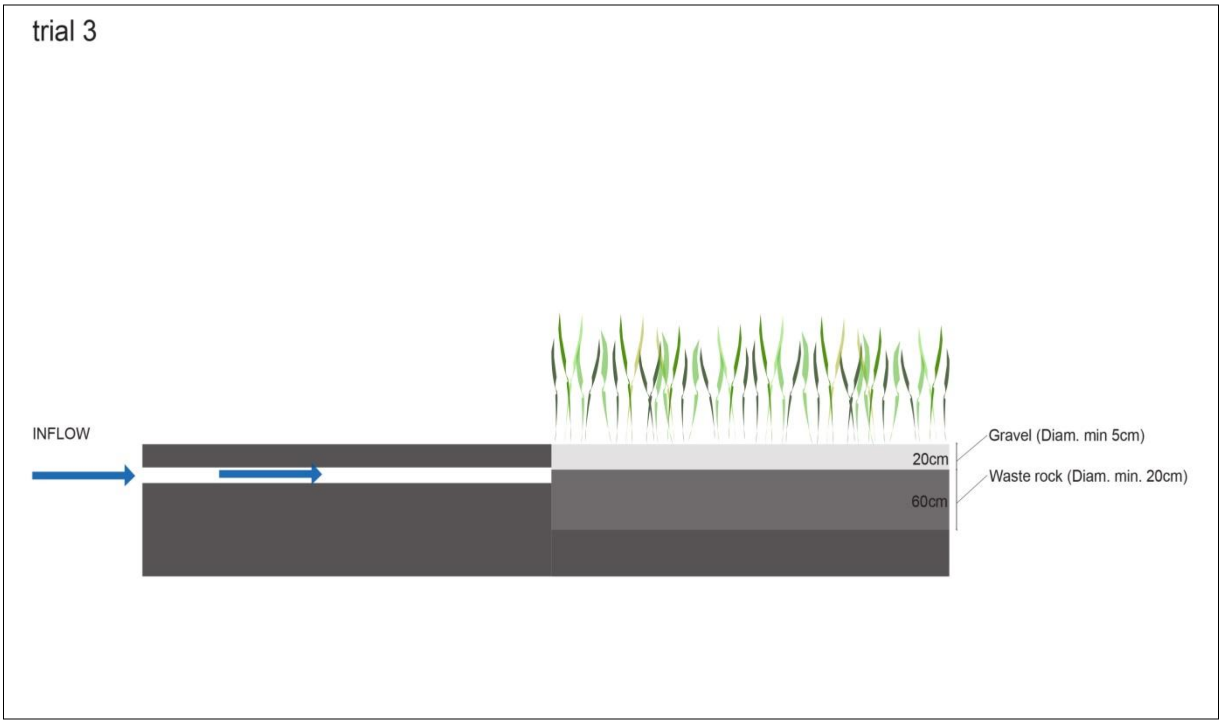
A summary of requirements for each design trial is shown in table below

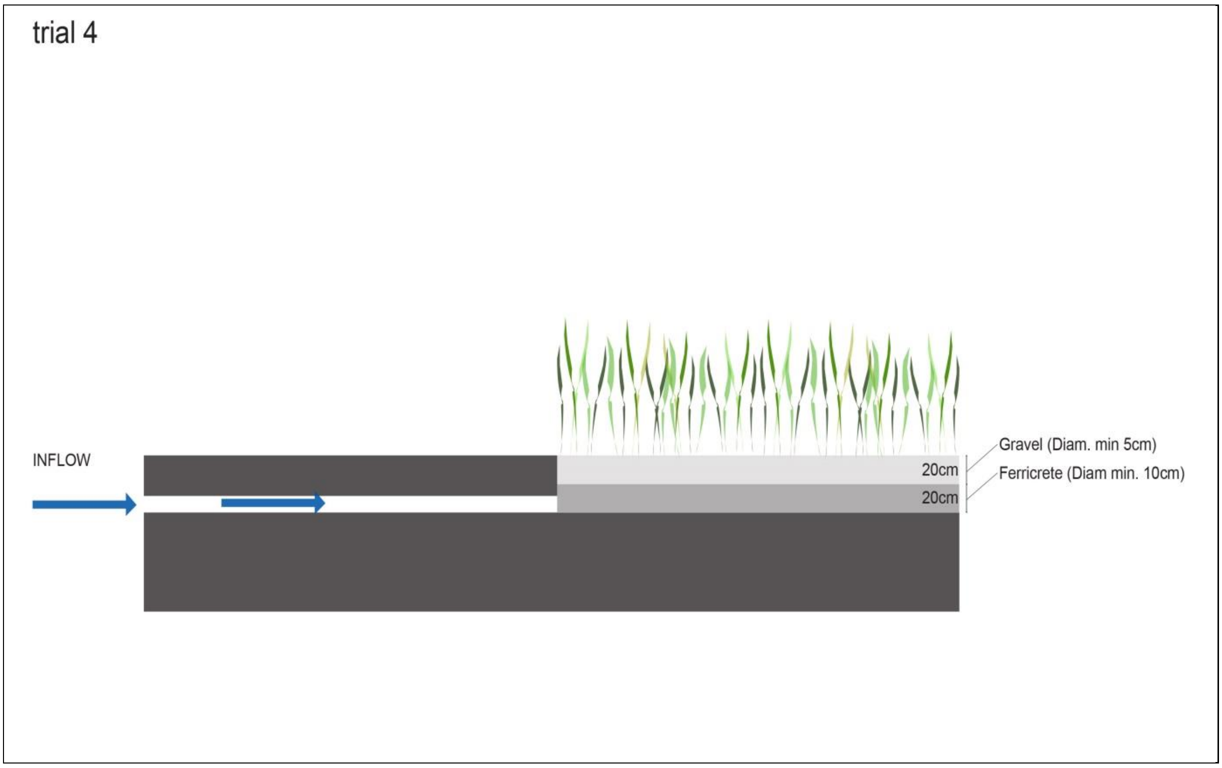
	Design requirements
Trial 1	The secondary compartment is filled with a later of waste rock of >200mm as a base layer. Large rock is used to facilitate subsurface flow. Previous trials at Western Areas Gold Mine have shown that consistent flow is a challenge if uniform finer material is used. The layer above the rock is gravel (<50 mm), the middle layer will be ferricrete layer with fragmented ferricrete blocks >100mm. Again the size is chosen to facilitate subsurface flow and maintain anaerobic conditions. The ferricrete will increase surface area for the bacteria to establish and as a secondary benefit facilitate arsenic removal. The surface layer will be waste rock with a minimum diameter 200 mm or similar material which is rounded and allows maximum interstitial space to be maintained. Hydrophytes are maintained as a floating mass on wooden/reed/bamboo frames. Roots may enter the scat size layer.
Trial 2	will vary with the first trial by excluding the gravel and only use ferricrete layer with fragmented ferricrete blocks >100mm as well as the surface layer which will be waste rock with a minimum diameter 200 mm or similar material which is rounded and allows maximum interstitial space to be maintained.
Trial 3	this will only include gravel (<50 mm) and the surface layer will be waste rock with a minimum diameter 200 mm or similar material which is rounded and allows maximum interstitial space to be maintained. The hydrophytes are retained.
Trial 4	This will consist of the Gravel layer above (<50 mm), the middle layer will be ferricrete layer with fragmented ferricrete blocks >100mm. and the hydrophyte layer is retained. This should give a limited retention time and good hydrological performance.
Trial 5	This trial will have similar porous material as trial 1 but will not consist of any plants or hydrophytes. The compartment is filled with a later of waste rock of >200mm as a base layer. The layer above the rock is gravel (<50 mm), the middle layer will be ferricrete layer with fragmented ferricrete blocks >100mm. Again the size is chosen to facilitate subsurface flow and maintain anaerobic conditions. The ferricrete will increase surface area for the bacteria to establish and as a secondary benefit facilitate arsenic removal

Size of the pilot	A surface size of 10 m wide by 30 m long is suggested. This is because the final expected size is 100m by 300m to deal with the full flow. The base needs to be sealed so that it is not permeable. This could be via concrete, clay or plastic lining. Concrete will enable for a more robust floor if rock needs to be changed or items need to be replaced.
Monitoring	A redox probe needs to be inserted into each wetland to determine the redox potential at different heights to determine regimes in this regard as biochemical reactions are dependant and driven by this variable. The pond exit should be such that the height of the pond could be managed to ensure full coverage of the surface area. Additionally carbon could be added in the form of leaves, sewage plant water, hay, manure, compost etc to increase ammonifying bacteria to assist in the nitrogen cycling. Various plants like papyrus and or other hydrophytes readily available can be used to determine effectiveness of nitrogen removal compared to the papyrus.




trial 2
INFLOW
20cm
60cm
Ferricrete (Diam min. 10cm)
Waste rock (Diam. min. 20cm)


trial 3
INFLOW
20cm
60cm
Gravel (Diam. min 5cm)
Waste rock (Diam. min. 20cm)



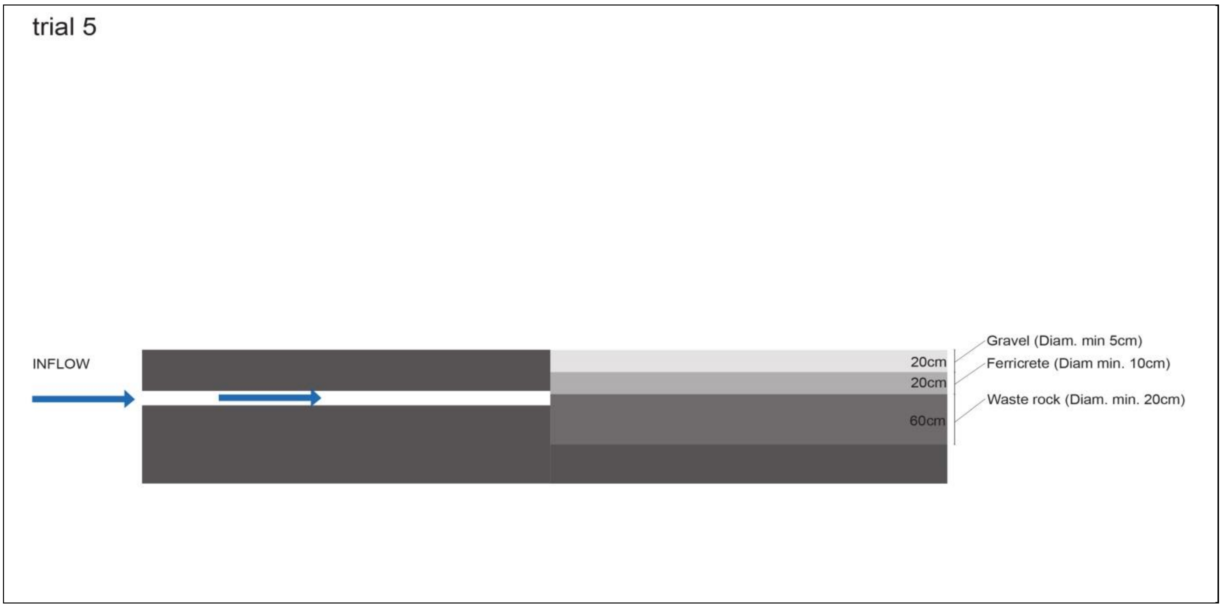


Figure 76. Examples of the trials that may be undertaken as iterative process for optimisation of the constructed wetland (Source: DWA, 2014)

Additionally trials will be used to see if crops can be produced without accumulating unwanted elements or compounds. Rice and/or Cassava for example can be included in the trails. Additionally a final polishing pond can be added and fish farming can be tested, specifically if algae populations can be maintained as a fish fodder.

Experience has shown that simulation results match the measured data when the hydraulic behaviour of the system can be described well. A good match of experimental data to reactive transport simulations can then be obtained using literature values for the model parameters (Langergraber, 2003; Langergraber and Šimůnek, 2005). For practical applications, it is advisable to measure at least the porosity and saturated hydraulic conductivity of the filter material to obtain reasonable simulation results for water flow.

10 Recommendations

Fish metal bioaccumulation assessment

Due to the presence of potentially toxic metal elements within the fish associated with the project area a requirement of a human health risk assessment arises. Due to the low confidence in standalone threshold comparisons metal concentrations will be used in human health risk indices such as the (du Preez *et al*., 2003). This work is currently not complete owing to the fact that particular threshold effect metal concentrations need to be confirmed, however some preliminary findings suggest the following.

- The Faleme River has As, Co, Cu, Pb and Hg which show Hazard Quotients over 1.0 as standalone values (not a mixture) with As concentrations showing a level that is 13x its recommended safety level. Further, As concentrations present a high risk to consumers and show a 3 in 1000 chance of generating cancer in consumers.
- Similarly in the Gara River, As, Hg and Pb all exhibit Hazard Quotients higher than 1.0 with As 15 times above the recommended safety level presenting a 3 in 1000 chance of acquiring cancer and therefore presenting a high risk to consumers.
- As stated above it has been recommended that a full Human Health Risk Assessment (HHRA) be undertaken. Through the completion of this assessment safe consumption guidelines could be established to limit the potential harmful effects of metal toxicity. The model used to generate the above information is largely adapted from the following reference du Preez *et al*. (2003; 2004).

This has not been completed as yet and the results will be presented to Randgold at a later stage.

Effluent Solids removal system

Table below presents a more conservative approach were the thickener sizes are rounded up to the next available standard size, which thereby incorporates a large safety factor. This approach is preferred due to the following reasons:

- Thickener sizes are small and therefore cost implications of going larger should not be prohibitive

- The larger thickening area for the Yalea material would in all probability sort out the somewhat poor overflow clarity
- Operational problems around surges of high solids concentration slurries or larger volumetric flow rates should be reduced due to the larger available thickening area.

Table 28. Recommended thickener size (P&C, 2011)

Process stream	Critical Rise Rate (m/h)	Max Flow Rate (m^3/h)	Thickening Area (m^2)	Thickener Diameter (m)
Gara underground discharge	2.0	160	79	**10**

Nitrate removal system – constructed wetland

It is recommended that the constructed wetland systems will consist of five trial pilot scale cells of HSSF-CW receiving primary discharge from the underground mine. Examples of the trials are illustrated Figure 76, where an iterative process should be used to optimise the constructed wetland. The overall objective of the trials will be to establish under which materials the process of denitrification will perform best. In pilots holding basins or lagoons, wastewater discharge is stabilized in a confined environment. Area requirements will be based on volumetric and surface loading rates. In the of the HSSF-CW cells, the macrophyte *Cyperus papyrus* will planted and it may be further compared against test cell, which may be planted with other appropriate vegetation.

The area determination is initially based on a rule of thumb or first order design equations. This assumption will be checked during the operation of the trial wetlands to ensure that they operate sufficiently. In this case a primary assumption is that the rate of nitrogen removal is 2 g/m^2/day. We need to be able to control the rate at which the water enters our trial wetlands and to be able to measure this so that we can calculate rates of removal. We have assumed that the settlers will operate sufficiently for there not to be too many solids entering the system to clog it up but we have designed it so that some solids will be removed upfront to protect the wetland in case where the settlers are not functioning optimally. The trials further aim to prevent the clogging of the macrophyte material.

The biological conditions in these pilot systems will perform under similar conditions of the wetland; water near the bottom is in an anoxic/anaerobic state, while a shallow zone near the water surface tends to be aerobic. The source of oxygen is planned to be atmospheric reaeration, photosynthesis (in facultative pond) and root oxygen leaching. The treatment for the nitrate will be dealt with by the development of microorganisms on the plant roots and the solid medium. There will be no need to input chemicals or external energy, as treatment mechanisms are natural and wastewater flow within the systems is driven by gravity.

In the of the HSSF-CW cells, a pair of the cells will use the macrophyte *Typha* which already exist on site and vary the material in the macrophyte bed to ensure that results are comparable and establish the most effective material in achieving the set objectives.

Figure 77. Examples of pilot scale constructed wetlands (Source: Vymazal, 2009)

All trial are set to use the same plant species (typha/pyparus) which is available on site; the variation will only be on the macrophyte material, this will ensure the establishment of the most effective materials when comparing the results within the trials.

A sub surface flow inlet into a pre-impoundment will allow the remaining suspended solids or sediment to settle out and it will ensures anaerobic conditions as water is forced through the substrate.

.

Appendix A – Boreholes Logs

Appendix B – Gara Discharge water quality

Site Name	DateTimeMeas	pH	EC mS/m	TDS mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	MALK mg/l	Cl mg/l	SO4 mg/l	Nitrate N mg/l	F mg/l	Al mg/l	Fe mg/l	Mn mg/l	Amonia mg/l	NO2-N mg/l	TotalSuspendedSolids	PO4 mg/l	TotalHardness-CaCO3 mg/l	Cd mg/l	Cu mg/l	Ni mg/l	Hg mg/l	As mg/l	Cr mg/l	Cr6 mg/l	Zn mg/l	Pb mg/l	DBO	COD	Oil & Grease	CN-Free mg/l	CN-Total mg/l	Wcn mg/l
IFC		6-9													2				50			0.05	0.30	0.50	0.002	0.10		0.10	0.50	0.20	50.00	150.00	10.00	0.10	1.00	0.50
Malian		6.5-9.5	250							1200	1000	30	6	1	2	2	15		30			0.02	0.10	2.00	0.005	0.50		0.20	0.50	0.20	50.00	150.00	20.00	0.50	1.00	
	2010/07/01 00:00	7.70	135.00	850.00	50.00	24.70	26.00	8.70	216.00	3.00	26.00	406.00		1.80	1.10	0.03		6.08	90.00	0.01	227.00	0.00	0.02	0.01	0.00	0.01	0.04		0.07	0.01	2.50	180.00	0.05	0.03	0.09	0.03
	2010/08/01 00:00	7.20	69.80	440.00	69.30	31.80	26.00	3.40	177.00	2.30	113.00	51.30	0.54	1.12	1.00	0.04		25.60	55.00	0.01	304.00	0.00	0.01	0.01		0.01	0.02		0.08	0.01	7.00	12.50		0.04	0.07	0.04
	2010/09/01 00:00	7.70	98.30	528.00	104.00	34.20	40.00	5.00	236.00	4.30	196.00	64.00		8.50	8.70	0.12	14.00	3.33	230.00	0.01	402.00	0.00	0.03	0.02		0.02	0.03		0.03	0.01	2.50	51.00	0.05			
	2010/09/02 00:00	7.30	66.40	400.00	87.20	33.50	38.00	3.50	201.00	0.40	113.00	6.75		5.34	4.90	0.08	0.01	0.22	140.00	0.01		0.00	0.01	0.01	0.00	0.01	0.02		0.06	0.01	2.50	31.00	0.05	0.01	0.01	0.01
	2010/09/03 00:00	7.00	124.00	958.00			57.00	5.50	210.00	0.90	169.00	204.00	0.51	5.38	6.60	0.20		0.87	565.00	0.01	409.00	0.00	0.01	0.01			0.03		0.06	0.01	13.00	115.00	0.05	0.01		
	2010/09/04 00:00	7.30	67.20	468.00	68.30	28.30	48.00	2.80	286.00	1.70	89.00	0.10		0.02	0.05	0.01		0.03		0.01	287.00	0.00	0.01	0.01			0.01		0.03	0.01	2.50		2.50	0.01	0.01	0.01
	2010/09/05 00:00	7.30	83.00	590.00	90.00	26.20	15.00	4.30	202.00	2.30	179.00	44.70		7.26	7.90	0.11		0.03	350.00	0.33	332.00	0.05	0.02	0.01	0.00	0.01	0.01		0.03	0.01	16.00	89.00	2.50			
	2010/09/06 00:00	7.00	97.80	490.00	69.00	22.10	40.00	4.90	213.00	3.10	181.00	86.90		7.80	9.80	0.26		0.03	495.00	0.01	264.00	0.00	0.03	0.01		0.01	0.04		0.10	0.01			2.50			
	2010/09/07 00:00	7.20	48.30	294.00	57.30	29.20	6.00	0.90	232.00	0.10		0.25			0.01	0.00		0.03		0.03	263.00	0.00	0.00	0.00			0.00		0.02	0.00			2.50			
	2010/09/08 00:00	7.10	104.00	582.00	200.00	58.90	59.10	15.90	228.00	6.80	190.00	180.00		11.50	14.10	0.21		0.03	605.00	0.01		0.00	0.01	0.03		0.02	0.04		0.12	0.00						
	2010/09/09 00:00	6.60	86.50	564.00	168.00	51.10	59.70	10.30	169.00	6.70	194.00	83.50		10.70	13.10	0.31		18.20	550.00	0.01		0.00	0.01	0.02		0.02	0.02		0.14	0.01						
	2010/09/10 00:00	7.00	95.90	578.00	155.00	54.80	9.80	8.90	257.00	11.90	230.00	99.00			21.00	0.34		2.38	965.00	0.01	2.50	0.00	0.02	0.04		0.02	0.05		0.09	0.01	2.50	44.00	2.50			
	2010/09/11 00:00	6.70	91.60	614.00	118.00	32.90	34.00	6.80	185.00		226.00	80.00		3.04	3.50	0.12		17.80	735.00	0.01	431.00	0.00	0.01	0.01		0.01	0.01		0.03	0.01	2.50					
	2011/01/03 00:00	7.10	117.00	732.00	120.00	41.70	52.00	9.10		12.30	263.00	180.00		7.77	8.50	0.18		0.03	343.00	0.01		0.00	0.01	0.01		0.02	0.02		0.18	0.01	2.50	12.50	2.50			
	2011/10/01 00:00	7.10	117.00	732.00	120.00	41.70	52.00	9.10	190.00	12.30	263.00	180.00		7.77	8.50	0.18		0.03	343.00	0.01	472.00	0.00	0.01	0.01		0.02	0.02		0.18	0.01	2.50	12.50	2.50			
	2011/12/01 00:00	6.80	172.00	634.00	78.00	27.40	53.00	8.00	213.00	6.90	221.00	63.20		12.30	14.90	0.28		0.03	759.00	0.01	308.00	0.00	0.03	0.03		0.02	0.03		0.05	0.01	2.50	110.00	2.50			
	2012/01/01 00:00	6.20	148.00	1080.00	108.00	57.50	55.00	17.30	8.00	11.30	287.00	520.00		0.41	0.80	0.04	10.70	66.10	18.00	0.32	505.00	0.00	0.02	0.01		0.11	0.01		0.09	0.01	2.50		2.50			

Site Name	DateTimeMeas	pH	EC mS/m	TDS mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	MALK mg/l	Cl mg/l	SO4 mg/l	Nitrate N mg/l	F mg/l	Al mg/l	Fe mg/l	Mn mg/l	Amonia mg/l	NO2-N mg/l	TotalSuspendedSolids	PO4 mg/l	TotalHardness-CaCO3 mg/l	Cd mg/l	Cu mg/l	Ni mg/l	Hg mg/l	As mg/l	Cr mg/l	Cr6 mg/l	Zn mg/l	Pb mg/l	DBO	COD	Oil & Grease	CN-Free mg/l	CN-Total mg/l	Wcn mg/l
IFC		6-9													2				50			0.05	0.30	0.50	0.002	0.10		0.10	0.50	0.20	50.00	150.00	10.00	0.10	1.00	0.50
Malian		6.5-9.5	250							1200	1000	30	6	1	2	2	15		30			0.02	0.10	2.00	0.005	0.50		0.20	0.50	0.20	50.0	150.0	20.00	0.50	1.00	
	2012/02/01 00:00	6.90	100.00	670.00	163.00	60.10	50.00	10.60	228.00	9.40	238.00	58.40		26.60	22.20	0.50		7.88	1240.00	0.10	655.00	0.00	0.05	0.05		0.03	0.06		0.21	0.01			2.50			
	2012/03/01 00:00	6.70	88.00	606.00	164.00	49.50	50.00	8.00	182.00	6.20	237.00	49.20		12.10	15.80	0.45		3.63	91.00	0.01	612.00	0.00	0.03	0.03			0.12	0.03		0.01	2.50	61.00	2.50			
	2012/04/01 00:00	6.80	90.60	672.00	330.00	77.70	54.30	12.40	2290.00	8.30	210.00	92.50		36.20	47.50	1.30		0.96	9290.00	0.02	1140.00	0.00	0.07	0.08			0.09		0.20	0.01	10.00	605.00				
	2012/05/01 00:00	6.7	111.	558.	196	60.3	59.1	11.1	296.	10.3	238.	142.		7.3	12	0.68	13.9	6.9	1660	0.01	738.	0.0005	0.015	0.033		0.025	0.038		0.13	0.006	14.	115.				
	2012/06/01 00:00	6.7	130.	760.	250.	64.8	143.	14.4	340.	17.4	308.	206.		4.77	7.5	0.81	19.1	23.4	3220	0.04	891.	0.001	0.04	0.01		0.12	0.01		0.08	0.005	10.	110.				
	2012/08/01 00:00	6.8	118.	680.	140.	45.9	56.4	9.5	181.	14.	291.	164.		7.71	9.1	0.49		3.51	892	0.55	537.	0.001	0.04	0.03			0.04		0.07	0.005		12.5				
	2012/07/01 00:00	6.5	98.1	582.	102.	28.1	45.5	6.2	162.	8.5	231.	102.		9.1	16.	0.38	1.86	26.8	1110	0.03	371.	0.05	0.04	0.03		0.044	0.04		0.06	0.005	2.5	33.				
	2012/09/01 00:00	6.5	121.	740.	189.	80.8	56.9	11.3	151.	10.4	254.	144.		31.5	34.5	0.91	3.74	23.	2700	0.01	805.	0.032	0.12	0.1		0.042	0.11		0.23	0.02	2.5					
	2012/10/01 00:00	6.8	105.	764.	222.	72.4	51.5	10.7	413.	8.9	251.	134.		22.7	33.3	0.74	0.01	0.025	2240	0.01	852.	0.001	0.07	0.05			0.07		0.11	0.005	9.	210.				
	2012/11/01 00:00	6.8	107.	744.	112.	38.1	51.9	8.3	179.	10.2	255.	140.		2.25	2.8	0.08		33.2	355	0.13	437.	0.001	0.02	0.01			0.005		0.025	0.005	5.	43.				
	2013/01/01 00:00	7.2	149.	892.	236.	110.	71.3	17.2	238.	18.4	313.	256.		34.	45.5	1.01	30.1	11.4	1360	0.04	1040.	0.001	0.15	0.1			0.1		0.15	0.005						
	2013/02/01 00:00	7.2	138.	900.	193.	74.2	67.3	14.6	202.	17.4	319.	216.		15.5	24.7	0.61	18.	16.7	1060	0.01	787.	0.001	0.06	0.04			0.04		0.16	0.01						
	2013/03/01 00:00	7.	142.	848.	201.	83.2	71.7	19.1	213.	19.2	305.	416.		23.7	32.4	0.5		18.9	1860	0.07	843.	0.001	0.06	0.04			0.05		0.09	0.005						
	2013/04/01 00:00	7.1	113.	752.	119.	9.2	55.9	9.2	149.	12.9	273.	142.		7.44	13.5	0.41		11.2	611	0.03	1050.	0.001	0.01	0.03			0.03		0.09	0.005	12.	120.				
	2013/05/01 00:00	6.8	143.0	1020.0	543.0	30.9	69.5	22.9	457.0	19.5	346.0	226.0		51.3	110	3.07		24	9870	0.08	1480	0.004	0.23	0.17			0.15		0.33	0.01						
	2013/06/01 00:00	7.2	112.0	722.0	133.0	36.2	57.7	13.9	309.0	13.0	251.0	130.0		14.3	30.2	1.14	6.63	21.4	2310	0.04	930	0.001	0.08	0.05			0.04		0.19	0.01	9	205				
	2013/11/01 00:00	7.2	102.0	710.0	155.0	45.9	59.0	10.4	167.0	12.8	318.0	152.0		12.2	33.4	0.69		0.025	2230	0.03	575	0.0005	0.044	0.05		0.12	0.048		0.078	0.007	8	225				
	2013/12/01 00:00	7.0	176.0	1190.0	150.0	39.9	81.7	15.2	210.0	22.5	471.0	372.0		38.7	87.6	2.38		25.4	2750	0.01	538	0.001	0.22	0.13		0.26	0.12		0.39	0.005						

Site Name	DateTimeMeas	pH	EC mS/m	TDS mg/l	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	MALK mg/l	Cl mg/l	SO4 mg/l	Nitrate N mg/l	F mg/l	Al mg/l	Fe mg/l	Mn mg/l	Amonia mg/l	NO2-N mg/l	TotalSuspendedSolids	PO4 mg/l	TotalHardness-CaCO3 mg/l	Cd mg/l	Cu mg/l	Ni mg/l	Hg mg/l	As mg/l	Cr mg/l	Cr6 mg/l	Zn mg/l	Pb mg/l	DBO	COD	Oil & Grease	CN-Free mg/l	CN-Total mg/l	Wcn mg/l
IFC		6-9													2				50			0.05	0.30	0.50	0.002	0.10		0.10	0.50	0.20	50.00	150.00	10.00	0.10	1.00	0.50
Malian		6.5-9.5	250							1200	1000	30	6	1	2	2	15		30			0.02	0.10	2.00	0.005	0.50		0.20	0.50	0.20	50.00	150.00	20.00	0.50	1.00	
	2014/01/01 00:00	6.7	222	1550	210	55.8	122	24.1	83	55.7	598	508		4.79	8.1	0.16	62.8	32.9	421	0.01	755	0.0005	0.011	0.02		0.024	0.014		0.028	0.013						
	2014/02/01 00:00	7	86.5	606	81	25	45.9	5	177	9.9	242	41.5			2	0.04		3.61	98	0.03	305	0.001	0.01	0.01		0.022	0.005		0.025	0.005						
	2014/03/01 00:00	6.6	116.	770.	92.	37.5	57.1	7.	149.	17.5	290.	108.		2.7	4.2	0.079		18.	75	0.04	385.	0.0001	0.011	0.024			0.011		0.048	0.002	2.5	37.				
	2014/04/01 00:00	6.9	171.	1230.	155.	52.6	106.	13.9	155.	37.5	468.	252.		3.16	5.3	0.036		5.75	112	0.01	603.	0.0003	0.004	0.03		0.021	0.005		0.019	0.003						
	2014/05/01 00:00	7.2	114.	810.	118.	42.5	68.2	10.1	154.	19.9	259.	100.			7.9	0.13		8.7	243	0.01	470.		0.014						0.07							
	2014/06/01 00:00	7.2	195.	1340.	143.	42.4	122.	34.4	93.	64.7	275.	288.		3.51	5.8	0.09	1.37	14.4	202	0.05	532.	0.0001	0.009	0.027			0.014		0.021	0.012	22.	74.				
	2014/07/01 00:00	7.5	133.	970.	112.	39.4	100.	18.3	191.	37.2	299.	106.		8.11	11.8	0.16	5.65	4.56	655	0.01	442.	0.0001	0.012	0.023		0.033	0.015		0.069	0.014	35.	70.				

Appendix C - STATIC SEDIMENTATION TESTS

Appendix C.1. Physical properties of the effluents

PCCS Number	pH	Conductivity (mS/cm)	Solids SG (g/cm^3)	Liquid SG (g/cm^3)
Yalea	8.27	2.040	2.749	1.000
Gara	8.00	1.600	2.716	1.000

Appendix C.2. settling test results

	M10				M919			
PCCS Number	Clarity	Settling distance (mm)	Settling time (s)	Settling rate (m/h)	Clarity	Settling distance (mm)	Settling time (s)	Settling rate (m/h)
Yalea	4.0	50	8.13	22.14	4.0	50	6.99	25.75
Gara	2.0	50	28.10	6.41	3.0	50	23.54	7.65

	M336				M6260			
PCCS Number	Clarity	Settling distance (mm)	Settling time (s)	Settling rate (m/h)	Clarity	Settling distance (mm)	Settling time (s)	Settling rate (m/h)
Yalea	4.0	50	6.20	29.03	5.0	50	4.65	38.71
Gara	3.0	50	23.61	7.62	4.0	50	20.00	9.00

	M156				DP8629			
PCCS Number	Clarity	Settling distance (mm)	Settling time (s)	Settling rate (m/h)	Clarity	Settling distance (mm)	Settling time (s)	Settling rate (m/h)
Yalea	4.0	50	6.89	26.12	4.0	50	5.43	33.15
Gara	3.0	50	23.21	7.76	4.0	50	15.00	12.00

Sample Number	Optimum flocculant type	Secondary flocculant type
Yalea	M6260	DP8629
Gara	DP8629	M6260

Appendix C.3. Thickener feed concentration determination

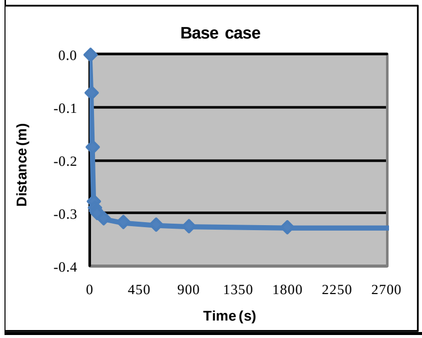
Sample Number	Gara				
Stock slurry solids conc.	24.97%	m% solids			
Parameters	Slurry % solids				
	2.5	5.0	7.5	10.0	15.0
Floc dose (g/t)	20				
Stock slurry volume (ml)	21	44	66	90	140
Stock slurry mass (g)	25.4	51.7	78.8	106.9	165.9
Stock slurry density (g/cm^3)	1.187	1.187	1.187	1.187	1.187
Process water added (ml)	229	206	184	160	110
Target slurry volume (ml)	250	250	250	250	250
Target slurry mass (g)	254.0	258.2	262.4	266.9	276.2
Target slurry density (g/cm^3)	1.016	1.033	1.050	1.067	1.105
Floc volume added (ml)	0.5	1.0	1.6	2.1	3.3
Settled distance (mm)	218	184	120	90	25
Settling time (s)	20.00	20.00	20.00	30.00	30.00
Settling rate (m/h)	39.24	33.12	21.60	10.80	3.00
Clarity	49.0	49.0	49.0	49.0	49.0

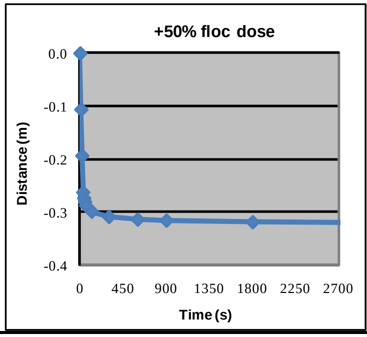
Sample Number	Prelim slurry solids conc
Yalea	5.0
Gara	5.0

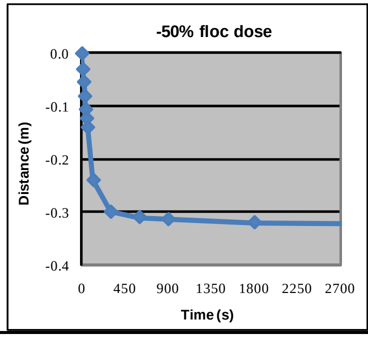
Sample Number	Prelim floc dose (g/t)
Yalea	15.0
Gara	15.0

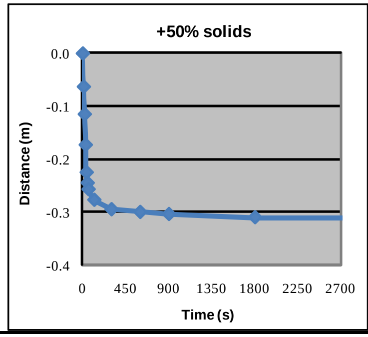
Sample Number	Gara				
Stock slurry solids conc.	**24.97%**	m% solids			
Parameters	**Floc dose (g/t)**				
	10.0	**15.0**	**20.0**	**25.0**	**30.0**
Optimum feed solids m%	**5**				
Stock slurry volume (ml)	44	44	44	44	44
Stock slurry mass (g)	51.7	51.7	51.7	51.7	51.7
Stock slurry density (g/cm^3)	1.187	1.187	1.187	1.187	1.187
Process water added (ml)	206	206	206	206	206
Target slurry volume (ml)	250	250	250	250	250
Target slurry mass (g)	258.2	258.2	258.2	258.2	258.2
Target slurry density (g/cm^3)	1.033	1.033	1.033	1.033	1.033
Floc volume added (ml)	0.5	0.8	1.0	1.3	1.5
Settled distance (mm)	**100**	**170**	**190**	**198**	**198**
Settling time (s)	**30.00**	**20.00**	**20.00**	**20.00**	**20.00**
Settling rate (m/h)	12.00	30.60	34.20	35.64	35.64
Clarity	**30.0**	**49.0**	**49.0**	**49.0**	**49.0**

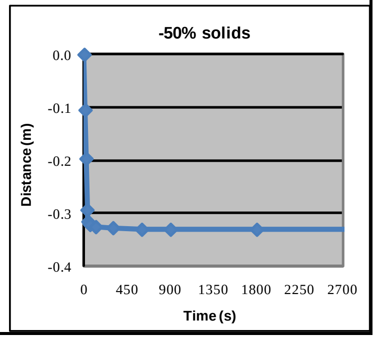
			Base case		+50% floc		-50% floc		+50% solids		-50% solids	
			Floc dose (g/t)	Floc needed (ml)	**Floc dose (g/t)**	Floc needed (ml)	**Floc dose (g/t)**	Floc needed (ml)	**Slurry % solids**	Floc needed (ml)	**Slurry % solids**	Floc needed (ml)
			15.00	3.1	**22.50**	4.6	**7.50**	1.5	**7.50**	4.7	**2.50**	1.5
Sample Number	**Slurry % solids**	**Time (s)**	Distance (mm)	Distance (m)	Distance (mm)	Distance (m)	Distance (mm)	Distance (m)	Distance (mm)	Distance (m)	Distance (mm)	Distance (m)
Yalea	**5.00**	0	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000
		10	72	-0.072	106	-0.106	30	-0.030	63	-0.063	105	-0.105
		20	175	-0.175	193	-0.193	54	-0.054	115	-0.115	197	-0.197
		30	278	-0.278	262	-0.262	81	-0.081	173	-0.173	294	-0.294
Slurry make-up		40	290	-0.290	273	-0.273	106	-0.106	225	-0.225	316	-0.316
Stock slurry solids conc. (%m)	**29.07%**	50	296	-0.296	280	-0.280	123	-0.123	245	-0.245	319	-0.319
Stock slurry volume (ml)	145	60	300	-0.300	287	-0.287	140	-0.140	257	-0.257	322	-0.322
Stock slurry mass (g)	177.6	120	310	-0.310	298	-0.298	240	-0.240	277	-0.277	326	-0.326
Stock slurry density (g/cm^3)	1.227	300	317	-0.317	308	-0.308	300	-0.300	295	-0.295	328	-0.328
Process water added (ml)	855	600	322	-0.322	313	-0.313	310	-0.310	300	-0.300	331	-0.331
Target slurry volume (ml)	1000	900	325	-0.325	315	-0.315	314	-0.314	304	-0.304	331	-0.331
Target slurry mass (g)	1032.9	1800	327	-0.327	318	-0.318	320	-0.320	310	-0.310	331	-0.331
Target slurry density (g/cm^3)	1.033	3600	327	-0.327	321	-0.321	323	-0.323	310	-0.310	331	-0.331
			Settling rate (m/h)	37.08	Settling rate (m/h)	28.08	Settling rate (m/h)	9.18	Settling rate (m/h)	19.80	Settling rate (m/h)	34.02
			Clarity	**49**	Clarity	**49**	Clarity	**15**	Clarity	**49**	Clarity	**49**



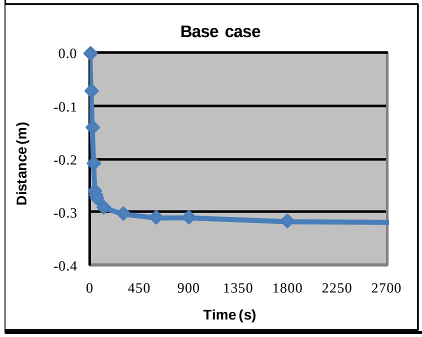


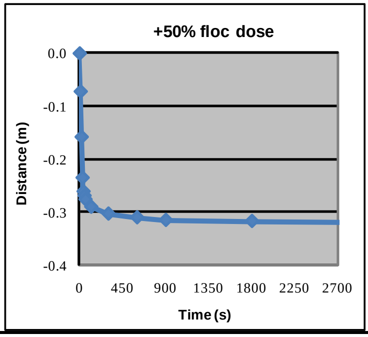


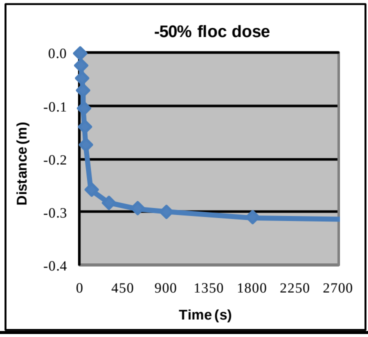


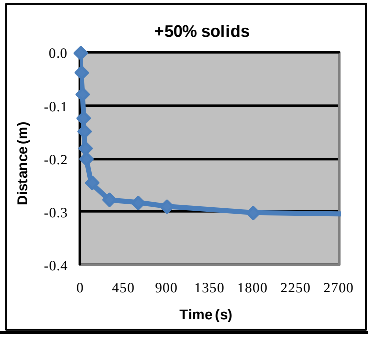


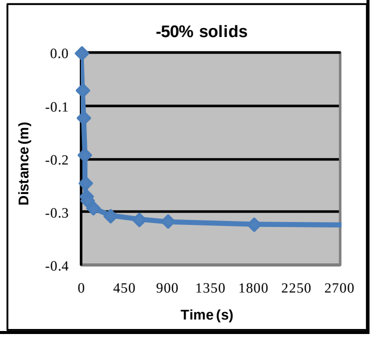
Sample Number	Slurry % solids	Time (s)	Base case: Floc dose (g/t) **15.00**	Base case: Floc needed (ml) 3.1	+50% floc: Floc dose (g/t) **22.50**	+50% floc: Floc needed (ml) 4.6	-50% floc: Floc dose (g/t) **7.50**	-50% floc: Floc needed (ml) 1.5	+50% solids: Slurry % solids **7.50**	+50% solids: Floc needed (ml) 4.7	-50% solids: Slurry % solids **2.50**	-50% solids: Floc needed (ml) 1.5
			Distance (mm)	Distance (m)	Distance (mm)	Distance (m)	Distance (mm)	Distance (m)	Distance (mm)	Distance (m)	Distance (mm)	Distance (m)
Gara	**5.00**	0	0	0.000	0	0.000	0	0.000	0	0.000	0	0.000
		10	71	-0.071	72	-0.072	23	-0.023	37	-0.037	70	-0.070
		20	140	-0.140	158	-0.158	47	-0.047	78	-0.078	122	-0.122
		30	208	-0.208	235	-0.235	70	-0.070	123	-0.123	192	-0.192
Slurry make-up		40	260	-0.260	261	-0.261	104	-0.104	148	-0.148	245	-0.245
Stock slurry solids conc. (%m)	**24.97%**	50	268	-0.268	269	-0.269	139	-0.139	180	-0.180	270	-0.270
Stock slurry volume (ml)	174	60	274	-0.274	276	-0.276	173	-0.173	200	-0.200	278	-0.278
Stock slurry mass (g)	206.8	120	291	-0.291	290	-0.290	258	-0.258	245	-0.245	292	-0.292
Stock slurry density (g/cm^3)	1.187	300	303	-0.303	303	-0.303	283	-0.283	277	-0.277	307	-0.307
Process water added (ml)	826	600	310	-0.310	310	-0.310	293	-0.293	283	-0.283	314	-0.314
Target slurry volume (ml)	1000	900	310	-0.310	315	-0.315	300	-0.300	290	-0.290	317	-0.317
Target slurry mass (g)	1032.6	1800	317	-0.317	317	-0.317	310	-0.310	302	-0.302	323	-0.323
Target slurry density (g/cm^3)	1.033	3600	320	-0.320	320	-0.320	315	-0.315	305	-0.305	325	-0.325
			Settling rate (m/h)	24.66	Settling rate (m/h)	29.34	Settling rate (m/h)	8.46	Settling rate (m/h)	15.48	Settling rate (m/h)	21.96
			Clarity	**49**	Clarity	**49**	Clarity	**25**	Clarity	**49**	Clarity	**49**











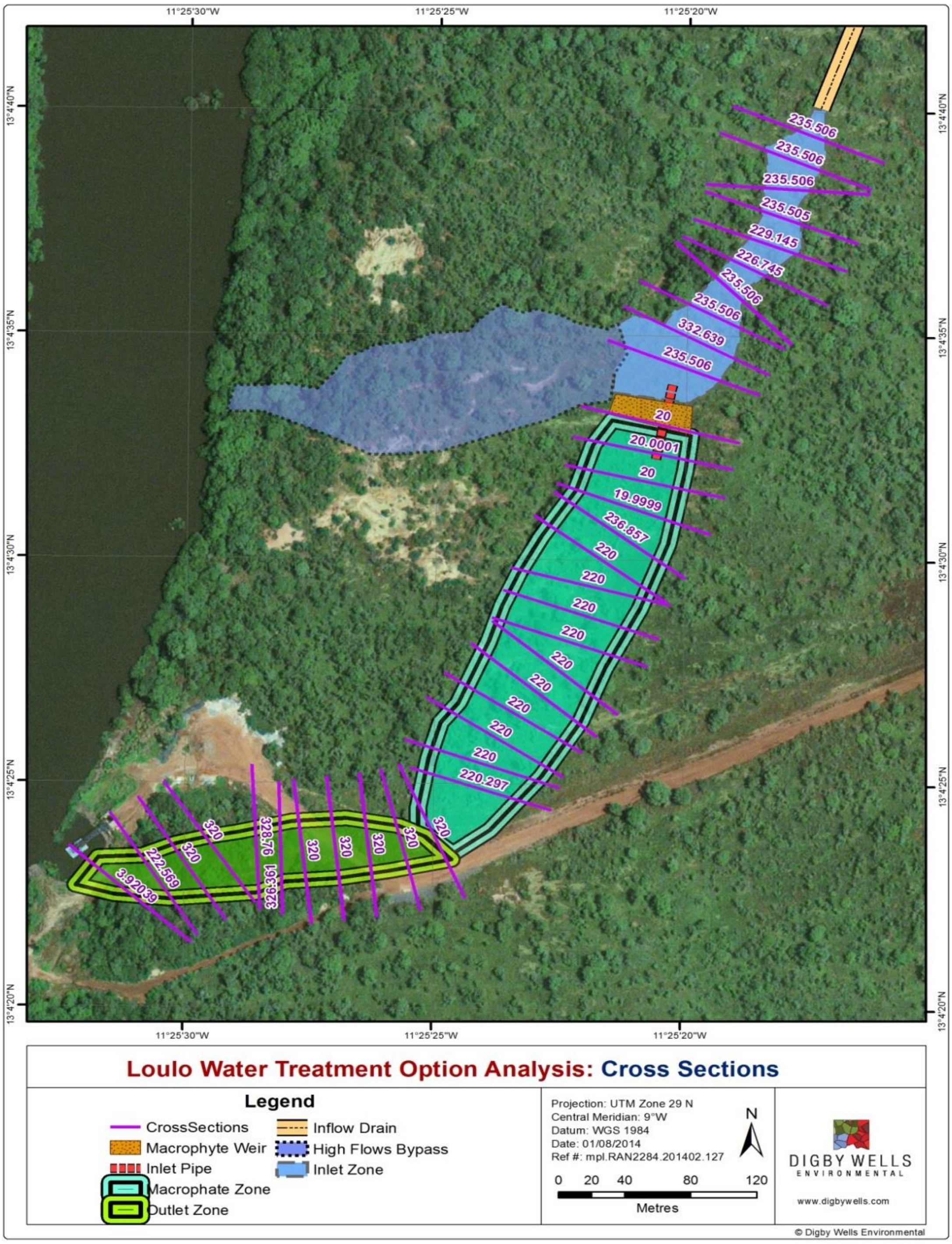
Appendix C.4. Flocculant dosage test

Sample Number	Yalea	Flocculant dose		Slurry % solids		24h rake test (2l cylinder)
Parameters	Base case	+50%	-50%	+50%	-50%	
Settling rate (m/h)	37.08	28.08	9.18	19.80	34.02	-
Floc dose (g/t)	15.00	22.50	7.50	15.00	15.00	**15.00**
Slurry solids conc. (%)	5.00	5.00	5.00	7.50	2.50	**5.00**
Underflow % solids	51.80	49.32	46.79	51.49	38.08	61.97
Supernatant clarity	49	49	15	49	49	**49**

Sample Number	Gara	Flocculant dose		Slurry % solids		24h rake test (2l cylinder)
Parameters	Base case	+50%	-50%	+50%	-50%	
Settling rate (m/h)	24.66	29.34	8.46	15.48	21.96	-
Floc dose (g/t)	15.00	22.50	7.50	15.00	15.00	**15.00**
Slurry solids conc. (%)	5.00	5.00	5.00	7.50	2.50	**5.00**
Underflow % solids	50.05	49.39	43.06	50.39	47.43	59.81
Supernatant clarity	49	49	25	49	49	**49**

Appendix D – HECRAS Output

Appendix D.1. cross section across the wetland previously proposed area

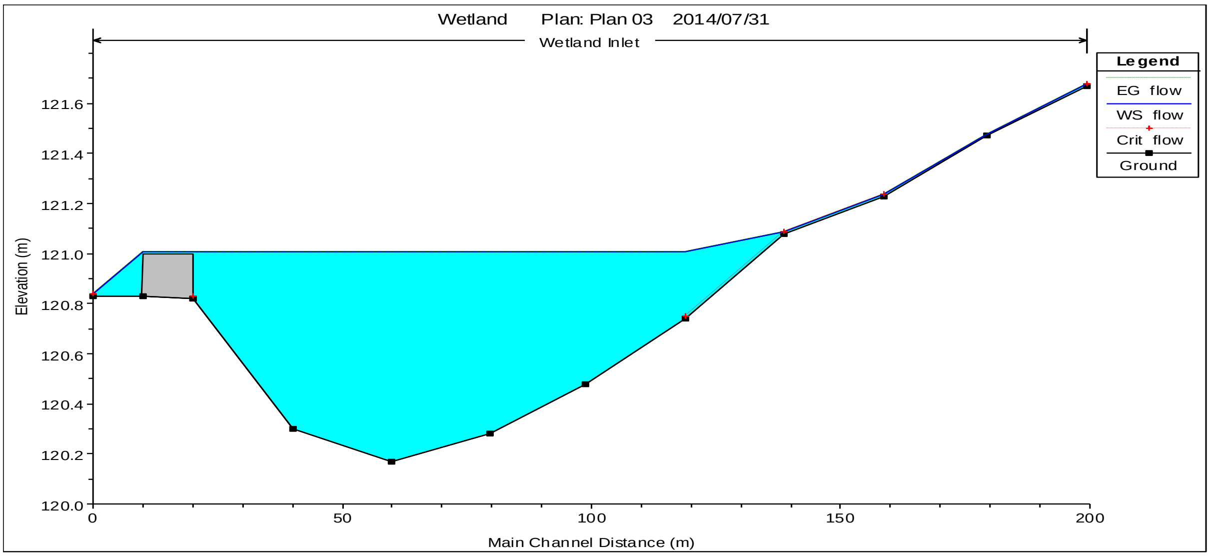


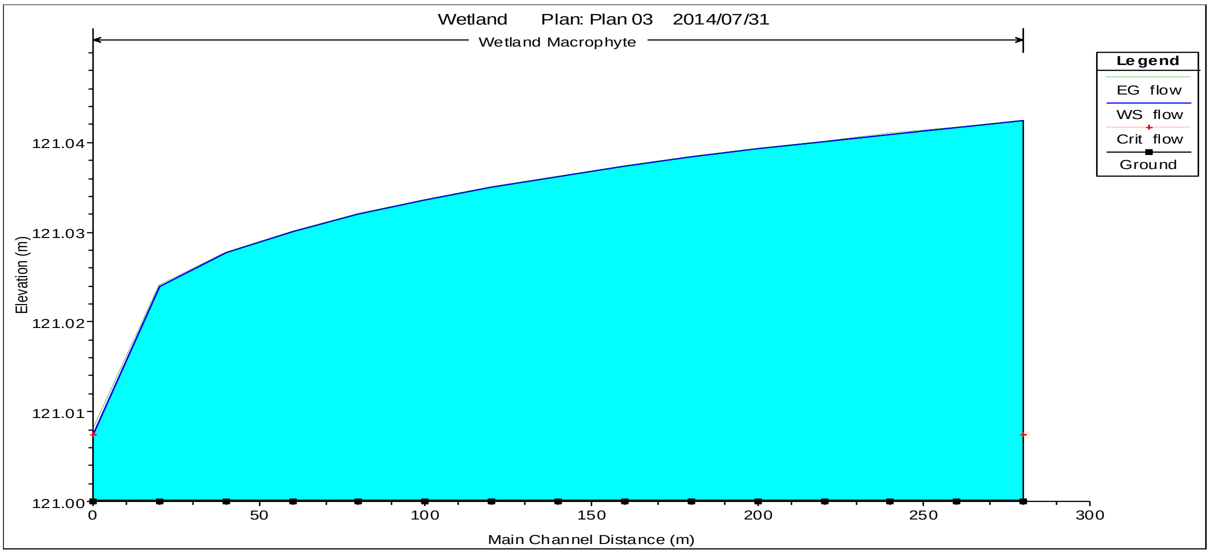
Appendix D.2. Cross section information for the wetland

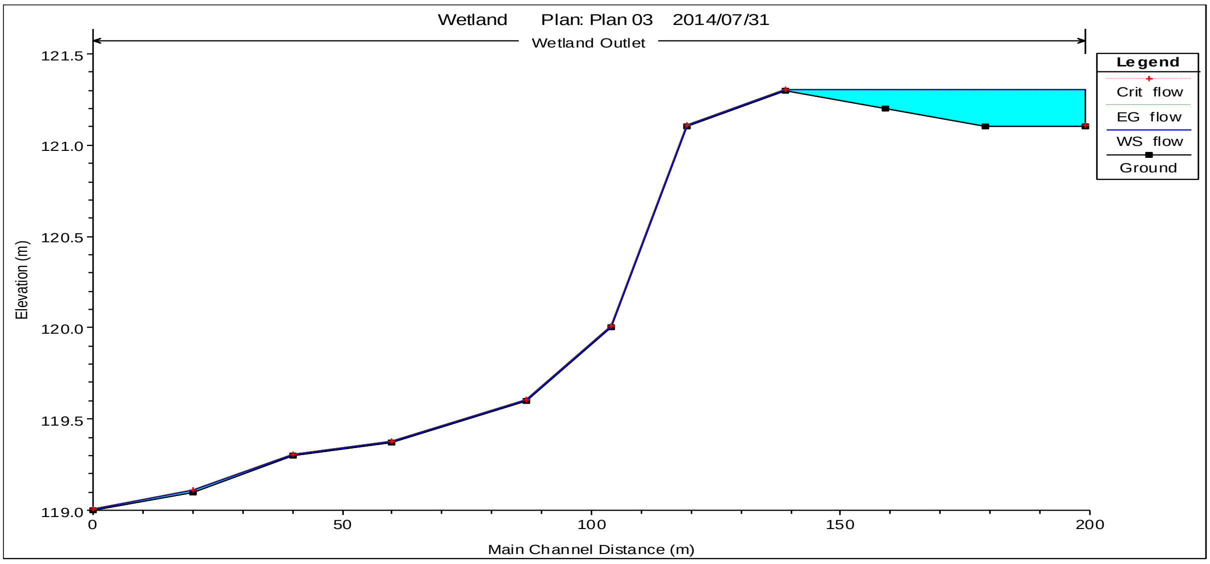
Reach	River Sta	Q (m3/s)	Min Chl El (m)	W.S Elev (m)	Crit. W. S (m)	E.G. Elev (m)	E.G.Slope (m/m)	Vel Chl	Flow Area (m2)	Top Width (m)	Froude No.
Outlet	203.9204	0.04	121.1	121.31	121.11	121.31	0	0	11.42	60.35	0
Outlet	183.9204	0.04	121.1	121.31	121.31		0	0	11.42	60.35	0
Outlet	163.9204	0.04	121.2	121.31	121.31		0.000001	0.01	5.67	55.95	0.01
Outlet	143.9203	0.04	121.3	121.31	121.31	121.31	0.008329	0.12	0.31	50.39	0.5
Outlet	123.9204	0.04	121.1	121.11	121.11	121.11	0.005626	0.11	0.35	50.35	0.42
Outlet	110.2809	0.04	120	120.01	120.01	120.01	0.007668	0.12	0.32	50.15	0.48
Outlet	92.68047	0.04	119.6	119.61	119.61	119.61	0.005609	0.11	0.35	50.14	0.42
Outlet	63.92042	0.04	119.37	119.38	119.38	119.38	0.002844	0.09	0.43	50.16	0.31
Outlet	43.92041	0.04	119.3	119.31	119.31	119.31	0.004521	0.1	0.37	50.13	0.38
Outlet	23.92037	0.04	119.1	119.11	119.11	119.11	0.003934	0.1	0.39	50.13	0.36
Outlet	3.920386	0.04	119	119.01	119.01	119.01	0.007032	0.12	0.33	50.1	0.46
Macrophyte	301.3511	0.04	121	121.04	121.01	121.04	0.000035	0.02	2.15	51.92	0.03
Macrophyte	281.3511	0.04	121	121.04	121.04		0.000037	0.02	2.12	51.89	0.03
Macrophyte	261.3511	0.04	121	121.04	121.04		0.000039	0.02	2.08	51.86	0.03
Macrophyte	241.3511	0.04	121	121.04	121.04		0.000042	0.02	2.04	51.82	0.03
Macrophyte	221.3511	0.04	121	121.04	121.04		0.000045	0.02	1.99	51.78	0.03
Macrophyte	201.3511	0.04	121	121.04	121.04		0.000048	0.02	1.95	51.74	0.03
Macrophyte	181.3511	0.04	121	121.04	121.04		0.000053	0.02	1.89	51.69	0.03
Macrophyte	161.3511	0.04	121	121.04	121.04		0.000059	0.02	1.84	51.64	0.04
Macrophyte	141.3511	0.04	121	121.04	121.04		0.000066	0.02	1.77	51.59	0.04

Macrophyte	121.3512	0.04	121	121.03	121.03		0.000076	0.02	1.7	51.52	0.04
Macrophyte	101.3511	0.04	121	121.03	121.03		0.000089	0.02	1.62	51.45	0.04
Macrophyte	81.35113	0.04	121	121.03	121.03		0.00011	0.03	1.52	51.36	0.05
Macrophyte	61.35114	0.04	121	121.03	121.03		0.000144	0.03	1.4	51.26	0.05
Macrophyte	41.3511	0.04	121	121.02	121.02		0.000234	0.03	1.21	51.08	0.07
Macrophyte	24.7913	0.04	121	121.01	121.01	121.01	0.012003	0.1	0.37	50.33	0.39
Inlet	200	0.04	121.67	121.68	121.68	121.68	0.00571	0.11	0.35	50.8	0.42
Inlet	180	0.04	121.47	121.47	121.48		0.022176	0.16	0.23	50.37	0.78
Inlet	160	0.04	121.23	121.24	121.24	121.24	0.007224	0.12	0.32	50.37	0.47
Inlet	140	0.04	121.08	121.09	121.09	121.09	0.007736	0.12	0.32	50.31	0.48
Inlet	120	0.04	120.74	121.01	120.75	121.01	0	0	14.6	59.78	0
Inlet	99.99999	0.04	120.48	121.01	121.01		0	0	30.57	66.23	0
Inlet	80	0.04	120.28	121.01	121.01		0	0	43.55	69.95	0
Inlet	60.00002	0.04	120.17	121.01	121.01		0	0	50.85	71.66	0
Inlet	39.99997	0.04	120.3	121.01	121.01		0	0	42.23	69.61	0
Inlet	20.00003	0.04	120.82	121.01	120.83	121.01	0	0	9.98	57.27	0
Inlet	1.420576	Macrophyte Zone Weir									
Inlet	0.5	0.04	120.83	120.84	120.84	120.84	0.003505	0.09	0.4	50.32	0.34

Appendix D.3. Hydraulic Output from the respective wetland sections.







11 References

Allen, R., G, Pereira, L. S., Raes, D., Smith, M., 1998. Guidelines for Predicting Crop Water Requirements. Food and Agriculture Organisation of the United Nations, FAO Irrigation and Drainage Paper 56, Rome.

Arrêté Interministériel No. 09-0767/MEA-MEIC-MEME-SG du 06 Avril 2009 rendant obligatoire l'application des normes maliennes de rejet des eaux uses ;

Barbour MT, Gerristen J, Snyder DB, Stribling JB (1999) Rapid bioaassessment protocols for Use in Stream and Wadeable Rivers: Periphton, Benthic Macroinvertebrates and Fish, Second Edition. EPA 841-B-99-002. US Environmental Protection Agency, Office of Water, Washington DC.

Bosman, C., 2009. The Hidden Dragon: Nitrate Pollution from Open-pit Mines – A case study from the Limpopo Province, South Africa. Carin Bosman Sustainable Solutions. PO Box 26442. Gezina, 0031, Pretoria, Gauteng, Republic of South Africa. Email: cbosman@global.co.za

Brix, H. 1993. Wastewater treatment in constructed wetlands: system design and treatment performance. In: Constructed wetlands for water quality improvement (ed Moshiri, G.A.). CRC Press Inc., Boca Raton. pp. 9-22.

Brix, H. 1997. The macrophytes play a role in constructed treatment wetlands? Water Science and Technology 35(5): 11-17.

Chapman, P.M., Wang, F., Janssen, C.R., Goulet, R.R., & Kamunde, C.N. (2003). Conducting ecological risk assessments of inorganic metals and metalloids: Current status. Human Ecol. Risk Assess. 9: 641–697.

Charte des Eaux du Fleuve Sénégal

Clark, G.A., Smajstrla, A.G. and Zazueta, F.S. 1989. Atmospheric Parameters Which Affect Evapotranspiration. University of Florida, Florida.

Convention d'Etablissement entre l'Etat du Mali et SOMLO SA du 02 Avril 1993

Cooper, P.F., Job, G.D., Green, M.B. & Shutes, R.B.E. 1996. Reed beds and constructed wetlands for wastewater treatment. WRc Swindon. 184 pp.

Décret no. 01-395/P-RM du 06 Septembre 2001 fixant les modalités de gestion des eaux usées et des gadoues ;

DWA.2007. Loulo Baseline Report. Loulo gold mine. Digby Wells Environmental. Fern Isle, Section 10, 359 Pretoria Ave Randburg Private Bag X10046, Randburg, 2125, South Africa

DWA.2009. environmental and social impact assessment. Loulo gold mine. Digby Wells Environmental. Fern Isle, Section 10, 359 Pretoria Ave Randburg Private Bag X10046, Randburg, 2125, South Africa

DWA. 2011. Report back on the environmental issues at Loulo. Loulo Gold Mine. Kenieba cercle. Mali. Unpublished report. Digby Wells Environmental. Fern Isle, Section 10, 359 Pretoria Ave Randburg Private Bag X10046, Randburg, 2125, South Africa

DWA (2012). Hydrogeological Investigation – Gara Underground Dewatering. Unpublished report. Digby Wells Environmental. Fern Isle, Section 10, 359 Pretoria Ave Randburg Private Bag X10046, Randburg, 2125, South Africa

Dickens C.W.S,. & Graham P.M. (2002). The South African Scoring System (SASS), Version 5, Rapid bioassessment method for rivers. African Journal of Aquatic Science. 27: 1–10.

European Commission (2001). Commission Regulation as regards heavy metals, Directive 2001/22/EC, no: 466/2001.

European Commission (2006). No 1881/2006 of 19 December 2006 setting maximum levels for certain contaminants in foodstuffs

Frankenbach, R.I. & Meyer, J.S. 1999. Nitrogen removal in a surface-flow wastewater treatment wetland. Wetlands 19(2): 403-412.

Gerber A, & Gabriel MJM. (2002). Aquatic Invertebrates of South African Rivers: Field Guide. Institute for Water Quality Services, Department of Water Affairs and Forestry, Pretoria.

Good, B.J. & Patrick, J.R. 1987. Root-water-sediment interface processes. In: Aquatic plants for water treatment and resource recovery (eds Reddy, K.R. & Smith, W.H.). Magnolia Publishing Inc., Orlando, Florida.

Hammer, D.A. 1989. Constructed wetlands for wastewater treatment - municipal, industrial and agriculture. Lewis Publishers, Chelsea, MI. 381 pp.

Hammer, D.A. 1994. Guidelines for design, construction and operation of constructed wetland for livestock wastewater treatment. In: Proceedings of a workshop on constructed wetlands for animal waste management (eds DuBowy, P.J. & Reaves, R.P.). Lafayette, IN. pp. 155-181.

Health Canada (2007). Canadian standards for various chemical contaminants in foods, Ottawa, Ontario. http://www.hc-sc.gc.ca/fn-an/securit/chem-chim/contaminants-guidelines-directives-eng.php.

International Network for Acid Prevention (INAP).2003. Treatment of Sulphate in Mine Effluents. Lorax Environmental.

International Finance Corporation (IFC). 2010. Environment, Health and Safety Guidelines. Mining. Table 1. Effluent guidelines – World Bank Group.

Joel Holliday. Geology map done by him….

Johnston, C.A. 1991. Sediment and nutrient retention by freshwater wetlands: effects on surface water quality. Critical Reviews in Environment Control 21: 461-565.

Journal of Ecological Engineering (2005). Constructed wetlands for Wastewater Treatment. Ecol. Eng. 25, 475–477. www.elsevier.com/locate/ecoleng

Joy B. Zedler, CRC Press, Boca Raton, FL. (2000). Handbook for Restoring Tidal Wetlands

Kadlec, R.H. & Knight R.L. 1996. Treatment wetlands. CRC Press. Boca Raton, Florida. 893 pp.

Kayombo, S.; Mbwette, T.S.A; Katima, J.H.Y; Ladegaard, N.; and JØrgensen, S.E. (2004). Waste Stabilization Pond (WSP) and Constructed Wetland (CW) Research Project. Prospective College of Engineering & Technology (University of Dar Es Salaam) and The Danish University of Pharmaceutical Sciences (Section of Environmental Chemistry – Copehhagen, Denmark)

Kleynhans CJ. (1996) A qualitative procedure for the assessment of the habitat integrity status of the Luvuvhu River. *Journal of Aquatic Ecosystem Health* 5: 41-54.

Kyambadde, K. J., G. F. and D. L., G., 2004a. A comparative study of Cyperus papyrus and Miscanthidium violaceum-based constructed wetlands for wastewater treatment in a tropical climate. Water Research, 38: 475-485.

Lawrence D.M; Treloar P.J; Rankin A.H; Harbridge P., and Holliday J (2013). The Geology and Mineralogy of the Loulo Mining District, Mali, West Africa: Evidence for Two Distinct Styles of Orogenic Gold Mineralization. ©2013 Society of Economic Geologists, Inc. Economic Geology, v. 108, pp. 199–227

Lawrence D.M (2010). Petrography studies at Gounkoto. GDD 2010 sample suite. Loulo Gold Mine

Loulo Gold Mine. 2012. Gara ore reserve statement. Underground department. December 2012

Loi no. 2012-015/AN du 27 Février 2012 portant code miner au Mali

Loi no. 02-006/AN du 31 Janvier 2002 portant code minier au Mali

Loi no. 01-020 du 20 mai 2001 relative aux pollutions et nuisances;

Loi no. 08-033 du 11 Aout 2008 relative aux installations classées pour la protection de l'environnement ;

MacDonald, D.D., C.G. Ingersoll, and T.A. Berger. (2000a). Development and evaluation of consensus based sediment quality guidelines for freshwater ecosystems. Arch. Environ. Contam. Toxicol. 39:20-31.

MacDonald, D.D., L.M. Dipinto, J. Field, C.G. Ingersoll, and E.R. Long. (2000b). Development and evaluation of consensus-based sediment effect concentrations for polychlorinated biphenyls. Environ. Toxicol. Chem. 19:1403-1413.

Malzbender, D. & Earle, A. (2007). Water Resources of the SADC: Demands, Dependencies and Governance Responses. Institute for Global Dialogue's (IGD) and the Open Society Initiative for Southern Africa's (OSISA) "Research Project on Natural Resources Dependence and Use in Southern Africa: Economic and Governance Implications". African Centre for Water Research (ACWR). Cape Town.

Margalef R. (1961). Information Theory in Ecology. General Systems 3: 36–71.

McMillan PH, (1998). An integrated habitat assessment system (IHAS v2) for the rapid biological assessment of rivers and streams. Division of the Environment and Forestry Technology, Report No. ENV-P-I 98132. CSIR, Pretoria.

Mitchell, M.J; Driscoll, C.T; Kahl, J.S; Likens, G.E; Murdoch, P.S; and Pardo, L.H. 1996. Climatic Control of Nitrate Loss from Forested Watersheds in the Northeast United States. Environmental Science and Technology 30: 2609-2612

Morgan (2014). Hydrological assessment of a constructed wetland. Unpublished report. Digby wells Environmental. Fern Isle, Section 10, 359 Pretoria Ave Randburg Private Bag X10046, Randburg, 2125, South Africa

Paterson & Cooke.2011. Thickening testwork on Yalea and Gara Underground Discharge Samples. Report No. SEN-RDG-8241.1 R01 Rev1. Unit 2, 33 Kyalami Boulevard, Kyalami Business Park, Kyalami, 1684, South Africa PO Box 14, The Woodlands, 2080, South Africa. unpublished

RDA, 1989 (Recommended dietary allowance (10th ed.). Washington, DC: National Academic Press) and WHO

Reddy, K.R. & De-Busk, T.A. 1987. State-of-the-art utilisation of aquatic plants in water pollution control. Water Science and Technology 19(10): 61-79.

Reed, S. C., Crites, R. W. & Middlebrooks, E. J. 1995. Natural systems for waste management and treatment. Second edition. McGraw-Hill Inc. New York, NY. 433 pp.

Rosgen D (1996) Applied river morphology. *Wild-land hydrology*, Pagosa Springs, Colorado

Shklomanov, I.A. (1998). World Water Resources. Prepared in the framework of the International Hydrological Programme. State Hydrological Institute. St Petersburg, Russia.

Sikora, F.J., Tong, Z., Behrends, L.L., Steinberg, S.L. & Coonrod, H.S. 1995. Ammonium removal in constructed wetlands with recirculating subsurface flow: removal rate and mechanisms (eds Kadlec, R.H. & Brix, H.). Water Science and Technology 32(3): 193-202.

Tate, R., 2014. Loulo Aquatic Ecological Report. Unpublished report. Digby wells Environmental Fern Isle, Section 10, 359 Pretoria Ave Randburg Private Bag X10046, Randburg, 2125, South Africa

Thieme ML, Abell R, Stiassny MLJ, Skelton P (2005). Freshwater Ecoregions of Africa and Madagascar: A Conservation Assessment. *World Wildlife Fund*.

Thirion CA, Mocke A, Woest R (1995). Biological monitoring of streams and rivers using SASS4. A Users Manual. Internal Report No. N 000/00REQ/1195. Institute for Water Quality Studies. Department of Water Affairs and Forestry. 46.

Turkmen, A., Turkmen,M., Tepe, Y., & Akyurt, I. (2005).Heavymetals inthree Commercially valuable fish species from Iskenderun Bay, North-ern East Mediterranean Sea, Turkey.Food Chemistry,91, 167–172.

Treatment Wetlands (2004), Robert H. Kadlec and Robert L. Knight, Lewis Publishers, Boca Raton, Fl.

TWP.2012 – 3D design of the proposed thickener

United States Environmental Protection Agency (2000). Guiding Principles for Constructed Treatment Wetlands: Providing for Water Quality and Wildlife Habitat (2000), United States Environmental Protection Agency, EPA 843-B-00-003. Available online at www.epa.gov/owow/wetlands/constructed/guide.html

United States Environmental Protection Agency (2000). Constructed Wetlands Handbooks (Volumes 1-5): A Guide to Creating Wetlands for Agricultural Wastewater, DomesticWastewater, Coal Mine Drainage and Stormwater in the Mid-Atlantic Region (1993-2000), Available online at www.epa.gov/owow/wetlands/pdf/hand.pdf

United States Food and Drug Administration (1993). Guidance document for nickel in shell fish. DHHS/PHS/FDA/CFSAN/Office of seafood, Washington D.C.

United States Environmental Protection Agency (USEPA) (2006). Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates, and Fish, Second Edition

US Army Corps of Engineers - Hydrologic Engineering Centers River Analysis System (HEC-RAS). Department of The Army Corps of Engineers Institute for Water Resources Hydrologic Engineering Center 609 Second Street Davis, CA 95616-4687

Vymazal and L. Kröpfelová, 2009. Removal of organics in constructed wetlands with horizontal sub-surface flow: A review of the field experience. Science of the Total Environment, 407: 3911-3922.

Wetland International (2003). The Use of Constructed Wetlands for Wastewater Treatment. Malaysia Office. 3A31. Block A, Kelana Center Point. Jalan SS7/19. 47301 Petaling Jaya. Selangor, Malaysia. Email: mp@wiap.nasionet.net – www.wetlands.org

WHO, (1993). 41st Report of the Joint FAO/WHO Expert Committee on Food Additives. WHO Technical Report Series, no. 837. Geneva.

WHO. (1999). Joint FAO/WHO. Expert committee on food additives. In: Summary and conclusions, 53rd meeting, Rome, 1–10 June.

Zhou Q, Zhang J, Fu J, Shi J, Jiang G (2008) Biomonitoring: An appealing tool for assessment of metal pollution in the aquatic ecosystem. *Analytica Chimica Acta* **606:** 135–15.