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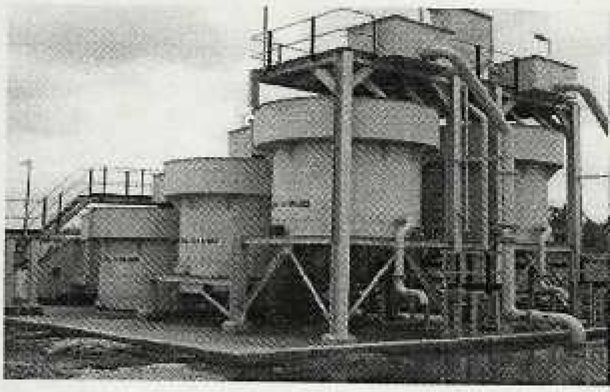
**Kumasi, Ghana.**



# PERFORMANCE EVALUATION OF ANGLOGOLD ASHANTI WASTEWATER TREATMENT PLANT (PWTP) OBUASI MINE ASHANTI REGION

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**Faculty of Civil and Geomatic Engineering**

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Master of Science Thesis

By

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By

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Thesis submitted to

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In Partial Fulfillment of the Requirements for the Degree of

**MASTER OF SCIENCE**

**Faculty of Civil and Geomatic Engineering**

**College of Engineering**

**February 2010**

## CERTIFICATION

I hereby declare that this submission is my own work towards the MSc. and that, to the best of my knowledge; it contains no material previously published by another person or material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the text.

Stephanie A. B. Biney ........................ 23/04/2010.
**(20067605)** Signature Date

Certified by:

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**(Second Supervisor)** Signature Date

Professor S.I.K. Ampadu ........................ 04/05/2010
**(Head of Department)** Signature Date

# DEDICATION

I dedicate this project work to God Almighty, my dear husband Mr Albert Biney , lovely daughter Claudia Efuah Mensimah Biney, my late mother and my siblings for their support to my education.

## ACKNOWLEDGEMENT

I owe my deepest gratitude to the Almighty God for his immense grace and help in accomplishing this project.

Secondly, I wish to express my profound gratitude to my supervisors Dr. Richard Buamah and Prof Mrs. Esi Awuah for their effort they put into guiding this study. Their time sacrifice in the numerous scientific deductions and technical discussions and especially their interest and encouragement, were essential for the completion of this work.

Thirdly, I would also wish to sincerely thank the management of AngloGold Ashanti, Obuasi mine (AGA) for all their necessary support in financially and technically rendered to me towards the success of this project.

In addition many people helped during the field work and laboratory analysis, for such assistance I am particularly grateful to Mr. Peter Owusu Yeboah, Mr Nyazu Quarson Agyabu, Mr. Theophilus Nicolas Bruce, Mr. Victor Nsafor and all the staff of the Environmental Dept, AGA. Mr Ebenezer Asare, Eric Sarkodia and Osei Kwadede all of Projects department AGA, and all my colleagues for their support.

Finally, am thankful to my family, especially my husband for his contribution both in cash and kind as well as encouragement during the period of the execution of the project.

May God bless each and every one abundantly.

## ABSTRACT

The study focused on the evaluation of the AngloGold wastewater treatment plant for the removal of Arsenic and Cyanide located at Sulphide Treatment Plant, (STP). The company's Tailings waste generated and discharged annually is estimated to be about 2,483,815 tons, they constitute about 80% of As and CN. In a bid to mitigate the pollution of the environment by these contaminants (cyanide and arsenic), (AGA ) installed a treatment plant (PWTP).The main objective of this study was to evaluate the performance of the treatment plant. To achieve such objective some quality parameters analysed included: pH, Temperature, Turbidity, Dissolved Oxygen, Fe, As and CN. The physical water quality parameters analysed fell within the recommended ranges given in the operating manual. The efficiency of the settlers is low and therefore they must be disludged to improve their performance. The current performance of the RBC indicates high cyanide degradation efficiency (99%). Current performance of the Actiflo unit indicates high (98%) arsenic removal efficiency. Operating the Actiflo unit at pH 7 – 7.5 can give a recommendable arsenic removal of about 96%. The effluent arsenic concentration of 0.01 to 0.3 ppm fall within the EPA guideline range for mine Currently, treated water for reuse is about 170m$^3$/h. To maximize water reuse, another Actiflo unit should be installed. Further studies and research should be carried out to determine the settling capacity of the settlers which affects the activities of the bacteria in the RBC. Two or more RBC's should be installed to increase the flow capacity. Research should be carried out for the local sand used as an adsorbent to verify it adsorbing capacity for the removal of arsenic in the Actiflo unit.

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## List of Acronyms, Abbreviations and Glossary

### Acronyms

| | |
|---|---|
| AGA | AngloGold Ashanti |
| CIL | Carbon In Leach |
| CIS | Carbon In Solution |
| EPA | Environmental Protection Agency |
| NTU | Nephelometric Turbidity Unit |
| RBC | Rotating Biological Contactor |
| STP | Sulphide Treatment Plant |

### Abbreviations

| | |
|---|---|
| As | Arsenic |
| CN | Cyanide |
| DO | Dissolved Oxygen |
| Fe | Iron |
| $KMnO_4$ | Potassium per manganate |
| PWTP | Processed Water Treatment Plant |
| ppm | Parts per milliom |
| TDS | Total Dissolved Solids |

### Glossary

| | |
|---|---|
| *Processed water* | Is the technical term used for wastewater generated from the processing of the gold ore. |

# CHAPTER ONE

## 1 Introduction

### 1.1 Background

The mining sector has made a significant impact on Ghana's economy as it has led to increased production of minerals like gold, diamonds, bauxite and manganese resulting in increased foreign exchange earnings since 1985, generation of internal revenue, provision of raw materials for the local industries, increased employment avenues and significant improvements in the socio- economic lives of Ghanaians particularly in the rural areas. (Mireku-Gyimah and Suglo, 1993).

Mining activities are operated by huge multinational companies' e.g AngloGold Ashanti, Gold fields Ghana Ltd, Tarkwa mine, Newmont Ghana Ltd, etc. as well as illegal operators referred to as galamsey miners. These mines have long been the target of complaints from local communities of the adverse environmental effects that are generated by their activities. Environmental groups have for several years accused mining companies in Ghana of destroying the environment (Banks et al 1997, Pulles et al 2005).

Mining in Ghana has been the subject of environmental discussion for a very long time. Cyanide and other harmful chemical residues have been detected in many water bodies associated with mining areas, as cited from Kokutse (2008).

## 1.2 Pollution of water bodies

Water pollution is the modification of the nature of a water body through introduction of contaminants. The modification may affect the physical, chemical and microbiological quality of the water body.

Three main sources of water pollution include:

- Industrial wastes e.g. mining waste
- Domestic sewage
- Agricultural waste

## 1.3 Pollution by Mining industries in Ghana

In Ghana there have been cases in which contamination of water bodies with domestic and industrial waste has resulted in many health issues such as Cholera, Dysentery etc. In the mining communities', pollution of water bodies as a result of the chemical contamination (eg. Cyanide contamination) has been reported.

On October 8, 2009, the Newmont Gold Mine, a multinational gold mining company in Ghana operating at Ahafo in the Brong Ahafo Region of Ghana experience an overflow of cyanide containing process solution. This overflow gave rise to a spillage into the environment resulting in contamination of the nearby surface water bodies and eventually caused fish mortality (Daily Graphic October 8, 2009 edition.)

Another incident was at River Pra, the main source of water supply for the communities living around the river, was polluted with chemicals that the illegal miners use to extract minerals, said Mac-Doe Hanyabui, regional manager of the Ghana Water Company (Kokutse, 2008)

AngloGold Ashanti, Obuasi mine started operating in Ghana as an underground mining comapany on April 2004, after taking over from Ashanti Gold Fields Company. The company's Tailings waste generated 2,483,815 tons in 2006 and -2,487,106 tons in 2007 (Environmental Dept report, 2006and 2007) which contain cyanide and Arsenic.

The mine is about a century old and is now operating about 500m deep underground. As a result of urbanization the community has integrated itself with the mine and is encountering environmental issue within the community.

## 1.4 Pollution incident at Anglogold Ashanti (Obuasi mine)

On the 8th of March, 2008, spillage caused by illegal miners, resulted in cyanide and arsenic contaminated tailings entering the environment from the South Processing Plants of the AngloGold mine.

## 1.5 Arsenic Health Effects

Arsenic is a human carcinogen when ingested, inhaled or contacted. It is a drinking water toxicant of great public concern, as exposure to it gives rise to a variety of cancers ( IRIS-(USEPA, 2002; Armienta et al.; 2000; Ballatori et al., Archer et al., 1979,1995; Borum and Abernathy, 1994;). Over 500,000 people die yearly of arsenic-related cancer and more than 1,200,000 people suffer from arsenic poisoning in Asia ( eg Bangladesh) and other part of the world (Harun-Ar-Rashid, 2002). The clinical manifestations due to chronic arsenic toxicity develop very insidiously after six months to tens of years. Arsenic affects all the organs and systems; skin, nervous system, liver, cardiovascular system, endocrine and respiratory systems. The most common skin manifestations are melanosis (blackening/darkening of skin, diffuse or spotted due to deposition of melanin), leucomelanosis (depigmentation in hyperpigmented area characterized by whitish/pall or patch in rain drop manner), and keratosis (rough, dry, hard, and thickened epithelium due to increased keratinization). Cancerous lesions, increased infant mortality, and birth defects are related to arsenic levels less than 100 µg/L. Non-cancer health problems include respiratory, cardiovascular, gastrointestinal, hematological, hepatic, neurological and genotoxic effects (Chen, 2001; Rahman et al., 1998). Diabetes is also linked to arsenic exposure. A recent report (Kaltreider et al., 2001) indicates arsenic interference with hormones, thus making arsenic a potent endocrine disrupter. January, 2006.

### 1.5 Problem Statement

Since the start of operations of the AngloGold Ashanti(AGA) Obuasi mine, formally Ashanti Gold fields Company (AGC) about a century ago, the company has been using the method of Bacteria oxidation(BIOX) and neutralisation principles to reduce the arsenic levels of the waste generated from the Arsenopyrite gold processing and purification. According to the Processing Project Dept, AGA (2002) report, the arsenic concentration of the wastewater normally recorded is about 3000ppm. Through the BIOX and Neutralisation activities, this high arsenic concentration is generally reduced to levels ranging from 10-15ppm of arsenic from the arsenopyrite gold ore from underground mining. Although these principles are able to remove up to 90% of arsenic, the concentration remaining (between 10-15ppm) could not meet Ghana EPA mine effluent discharge guide line. The Cyanide used for the leaching of gold at the mine leave about 50 ppm cyanide residue which add to arsenic contaminants. Eventually this contaminated wastewater is channelled to the tailings holding dam. Upon exceeding the holding capacity of the tailings dam, its content (Cyanide and arsenic) are eventually discharged into the environment (specifically Oda and Sansu streams).

These discharges have been found to be having arsenic and cyanide concentrations above the Ghana EPA guide line (0.1ppm and 0.2ppm) respectively for mine effluent discharge. To mitigate this problem, AngloGold Ashanti installed the Actiflo unit in 2009 to treat further the waste water (Processed water) against arsenic. The Actiflo is supposed to have an added advantage of treating waste water for reuse.

Since the installation of the Actiflo plant, the operations have been encountering some challenges (e.g. frequent shut down due to shortage of chemicals) and therefore not been operating optimally. The performance of the Actiflo plant has not been assessed since its installation for arsenic removal and purification of wastewater for reuse.

### 1.6 Justification of the study

Arsenic released into the environment can penetrate through the sub soil and contaminate groundwater. In Ghana, there is limited information on the presence of arsenic in groundwater used for drinking water; most of groundwater sources used for drinking water production is without any treatment. At the same time there are indications that, in some parts of the country symptoms like arsenicoses have been identified (Buamah 2009). This situation justifies the proposed study which focused on evaluating the effectiveness of the wastewater from gold processing (Processed Water) Treatment Plant (PWTP) which treats arsenic and also clarifies wastewater for reuse. Information on performance of the PWTP will shed light on the activities of the mine with respect to pollution of the environment and specifically the groundwater with arsenic and cyanide.

The treatment plant would be evaluated using water quality performance indicators such as CN, TDS, As, pH, Temperature, Dissolve Oxygen and Turbidity and Fe.

This situation justifies the proposed study which focuses on evaluating the effectiveness of the wastewater treatment plant (also known as processed water treatment plant-PWTP) in removing arsenic.

## 1.7 Objective

To evaluate the performance of waste water treatment plant also known as Processed Water Treatment Plant (PWTP).

### 1.7.1 Specific Objectives

- To determine the quality of influent and effluent of the PWTP.
- To determine the performance of the various treatment units by analyzing for specified water quality parameters. ( pH , Temperature, Dissolved Oxygen, Total Dissolved Solids, Total Dissolved Solids, CN, Turbidity, As and Fe)
- To verify efficiency of As removal in the Actiflo unit within a pH range of 4 to 11

# CHAPTER TWO

## 2 Literature Review

Processed water is the term used for all wastewater generated in the processing of gold and other minerals. Waste water can be characterized as municipal waste, domestic waste, industrial waste or mine effluent.

The Actiflo treatment plant operates with a treatment technology that removes heavy metals such as arsenic, zinc, iron etc and also clarifies waste water for reuse and other purposes. It has been used in many countries e.g, Australia, Canada etc. in the treatment of mine effluent to drinking water standards. The technology is currently being employed in the Bendigo mines in Australia to treat mine effluent to drinking water standards for water supply to the community in which they operate. It has also been used to treat irrigated water to drinking water standards. (http//www.veoliawater.com,2008).

The table below indicates the treatment levels of quality parameter that the Actiflo was used for in treatment of mine effluent in Australia.

Table 2-1: The table below indicates the quality levels attained for various parameters using the Actiflo treatment system in Australia.

| **Parameter** | **Units** | **Minimum** | **Average** | **Maximum** |
|---|---|---|---|---|
| Arsenic | Mg/l | 0.21 | 3.05 | 5.53 |
| pH | | 6.2 | 7 | 8. 2 |
| Turbidity | NTU | 2 | 126 | 442 |
| TDS | Mg/l | 1950 | 4251 | 5020 |

The table below indicates the specification of the Actiflo unit as recommended from pilot project studies and the operating manual.

Table 2-1: Specification of the existing Actiflo unit in Obuasi

| Unit | Capacity/$m^3$ | Flow/$m^3$/h | Retention time/mins |
|---|---|---|---|
| Aeration tank | 28 | 272-320 | 5 |
| Oxidation tank | 160-180 | 320 | 32 |
| Coagulation tank | 1 | 320 | 2 |
| Unit | | Chemical used | |
| Oxidation chamber/ pH adjustment | | Potassium permanganate/ Caustic soda (45% Sodium hydroxide) | |
| Coagulant chamber | | 41% liquid Ferric Sulphate | |
| Flocculant chamber | | Anionic polymer | |

## 2.1 Arsenic occurrence, speciation and mobilization

Arsenic may occur as a semi metallic element ($As^0$), Arsenate ($As^{5+}$), Arsenite ($As^{3+}$), or Arsine ($As^{3-}$). The toxicity of $As^{3+}$ is 10times higher than that of $As^{5+}$ (Castro de Esparza 2006).The chemical character of arsenic is dominated by the fact that it is labile, readily changing oxidation state or chemical form through chemical or biological reactions that are common in the environment (Talanta, 1985,). Therefore rather than solubility equilibrium controlling the mobility of arsenic, it is usually controlled by reduction and oxidation (redox) conditions, pH, biological activity, and adsorption/desorption reactions. The valence states of -3 and 0 occur only rarely in nature. In aqueous environment arsenic normally exist in the +III or +V states.

The molecular structures of some arsenic compounds are shown below:

$$HO-\overset{\overset{\displaystyle O}{||}}{\underset{\underset{\displaystyle OH}{||}}{As}}-OH \qquad HO-\underset{\underset{\displaystyle OH}{||}}{As}-OH$$

**Molecular structures of Arsenate (AsV) and Arsenite (AsIII)**

Arsenic readily changes its valence state and chemical form in the environment.

Some conditions that may affect arsenic valence and speciation include:

- pH :- in the pH range of 4 to 10, arsenic may occur as either $HAsO_4^{2-}$, $H2AsO_4^-$ and $HAsO3^{2-}$ . As(V) species are negatively charged in water, and the predominant As(III) species is neutral in charge .
- Redox potential; The prevailing redox conditions have a remarkable influence on the species of arsenic that will be predominant in aqueous solution. For instance, from Fig 1, it is seen that under oxidizing conditions, arsenic occur predominantly as $H_2AsO_4^-$ and $HAsO_4^-$ within the pH of 4-10. In water, the dominant As is a function of pH and the redox potential. $As^{5+}$ predominates in oxic water (especially surface water) and depending upon the pH value can exist as $H_3AsO_4$. $H_2AsO_4^-$ $HAsO42^-$ and/or $AsO_4^{3-}$. (Fig 1). The Fig 1 shows the control of redox potential (Eh) on the arsenate/arsenite transition.In the pH range 6-9, $HAsO_4^{2-}$ and $H_2AsO_4^-$ dominate with relatively low concentration of $AsO_4^{2-}$. Below pH 6 $H_2AsO_4$ , $H_2AsO_4^-$ and $H_3AsO_4$ dominates whiles above pH 9, only $AsO_4^{3}$- mostly occur.

As(III) is the dominant species under reducing conditions. Under reducing conditions the arsenic can exist as $H_3AsO_3^-$ and/or $H_2AsO_3^-$. Below pH 9, $H_3AsO_3$ is the dominant species where as $H_2AsO3^-$ nad $HAsO_3^{2-}$ dominate above pH 9 (Fergurson and Gavis, 1972).

- The presence of complexing ions: - Complexing ion such as ions of sulfur, iron, and calcium has the potential of adsorbing and interacting with As in the environment. In the presence of high concentrations of reduced sulphur, dissolved arsenic sulphide species are found to be formed. Under acidic and reducing conditions, the arsenic sulphide species found include $As_2S_3$ (corpiment) and $As_2S_3$ (regular). Ferric iron oxides and ferrioxyhydroxides have been reported to have a high potential of adsorbing arsenic to form arsenopyrites (FeAsS).
- Adsorption-desorption reactions can also affect the mobility of arsenic in the environment, clays, carbonaceous materials, and oxides of iron, aluminum, and manganese are soil components that may participate in adsorptive reactions with Arsenic. The unstable nature of arsenic species may make it difficult to treat or result in treated wastes whose toxicity and mobility can change under some environmental conditions. Therefore, the successful treatment and long-term disposal of Arsenic requires an understanding of arsenic chemistry and the disposal into the environment.

In the presence of extremely high contractions of reduced sulphur, dissolved As-sulphide species are found to be more regular. Reducing acidic conditions are more favorable for precipitation of orpiment ($As_2S_3$), regular (AsS) or other sulphides minerals containing coprecipitated Arsenic. Therefore high arsenic contaminated waters are not expected wherever there is a high concentration of free sulphides. The existence of $H_3AsO_3$ within a reducing environment and in mixed pH conditions in the context of arsenic-rich mine effluent is more prominent.

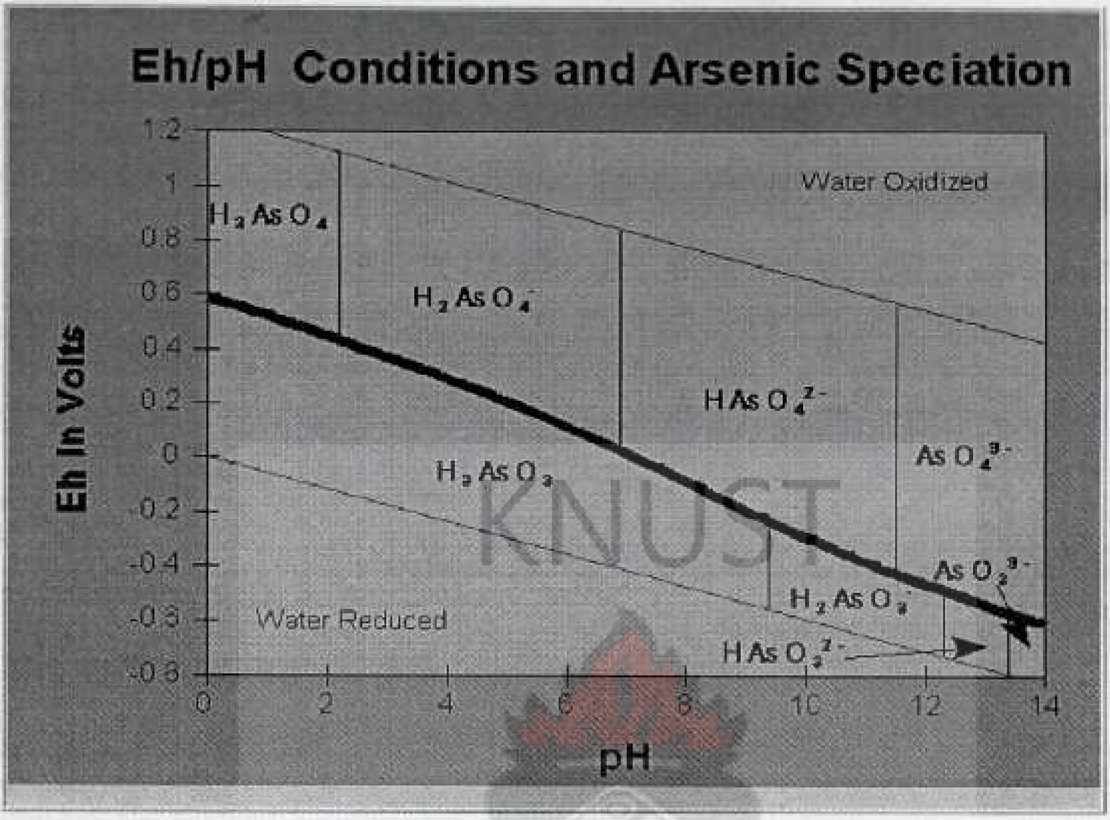


Figure 2-1 Control of arsenic speciation by Eh/pH conditions

## 2.2 Wastewater processes for Cyanide and Arsenic at AngloGold Ashanti

### 2.2.1 Detoxification of Cyanide in waste water (processed water)

Certain microorganisms, such as fungi, bacteria and some micromes, can metabolize and use cyanide, thiocyanate, and cyanamide in their cellular metabolism to synthesize amino acids. These compounds can also be used as nitrogen and carbon sources. For example, *Bacillus Ipeeaterium* converts potassium cyanide (KCN) to asparagine, aspartic acid, and carbon ~~dioxide~~ oxidiz~~es. It~~ oxidizes free and complexed cyanide to carbonate and ammonia. Several biological processes have been studied for cyanide decomposition from waste waters including trickling filters, activated sludge, fluidized bed reactors, and rotating biological contactors (RBCs).

### 2.2.2 Cyanide treatment at Anglogold Ashanti (Obuasi mine)

Experiments that were carried out with chemicals in methods of cyanide destruction such as Ferrous sulphate, Potassium Hypocchlorate, Alkaline chlorination and Hydrogen Peroxide technologies failed to yield concrete consistent residues devoid of cyanide, thiocyanate and other toxic chemicals and compounds ( Processing projects Dept AGA report,2004).

Biological cyanide destruction process have demonstrated the capacity to remove cyanide, thiocyanate and toxic heavy metals to the degree that mining effluent can be discharged to aquatic environment or to the Actiflo unit for treatment of arsenic to pproduce water that can be re-used.

The Sulphide treatment plant located at the South Processing unit consumes about 500m$^3$/hr and the strains of bacteria used in the Bio-oxidation step cannot tolerate cyanide concentrations above 0.03ppm and 0.5 ppm of thiocyanate concentrations. Bacteria ( *pseudomona sp*) have been found to use carbon and nitrogen from degraded cyanide for growth and cell formation. Cyanide is mineralised to carbonate and ammonia. Some strains such as Pseudomanas sp, which degrades cyanide, may convert ammonia to nitrate. Thiocyanate is degraded quite rapidly in aerobic biological systems.

#### 2.2.2.1 The detoxification process

The Bacteria degrades cyanide and thiocyanate to ammonia and convert the ammonia to nitrate.

#### 2.2.2.2 Detoxification reaction chemistry

**CYANIDE**

$$2NaCN + 4H_2O + 2O_2 \xrightarrow{\text{BACTERIA}} 2NaHCO_3 + NH_3 \quad (1)$$

**THIOCYANATE**

$$2NaSCN + 4H_2O + 2NaOH + 4O_2 \longrightarrow NaHSO_4 + 2NaHCO_3 + 2NH_3 \quad (2)$$

**NITRITE & NITRATE FORMATION**

$$NH_3 + H_2O \longrightarrow NH_4^+ + OH^- \quad (3)$$

$$2NH_4^+ + 3O_2 \rightarrow 4H^+ + 2H_20 + 2NO_2^- \quad (4)$$

$$2NO_2- + O_2 \rightarrow 2NO_3^- \quad (5)$$

**ALKALINITY CONSUMPTION**

$$2NH_4HCO_3 + 4O_2 + Ca(HCO_3)_2 \rightarrow Ca(NO_3)_2 + 4CO_2 + 6H_2O \quad (6)$$

**NITRATE REDUCTION**

$$6NO_3^- + 5CH_3OH \rightarrow 5CO_2 + 3N_2 + 7H_2O + 6OH^- \quad (7)$$

### 2.3 Treatment of Arsenic from mine effluent at AngloGold Ashanti (Obuasi mine)

Broad categories of treatment relating to the removal of heavy metals such as aresnic from mine effluent involve aeration and oxidation. The relatively soluble $Fe^{2+}$ is oxidised to $Fe^{3+}$ Oxidation can be achieved by aeration or by oxidation agents such as sodium hypochlorite or potassium permanganate and chlorine.

Sodium hypochlorite is usually the oxidant of choice, as it is in expensive and readily available. Unlike chlorine, the reaction of potassium permanganate with organic compounds will not produce trihalomethane. The following shows the reaction that occurs during the oxidation of iron with permanganate.

$KMnO_4 + 3Fe(HCO_3)_2 + 7H_20 \longrightarrow MnO_2 + 3Fe(OH)_3 + KHCO_3 + 5CO_2 + 5H_2O$ (8)

The stoichiometric amount of potassium permanganate needed to oxidise 1 mg/l of iron is 0.91 mg/l. In practice, however, the actual amount of potassium permanganate can be much greater, as there are normally other compounds in the wastewater that also react with the oxidant. The reaction time required to oxidise the iron is largely dependent on the pH and temperature of the wastewater. Short reaction times are usually sufficient at high pH (8-11) and high temperatures ($30\text{-}33^0C$). The reaction time is inversely proportional to pH and temperature of the wastewater to be treated.

### 2.3.1 Removal of Arsenic by the Actiflo unit

Removal of arsenic from wastewater by the Actiflo is done by oxidising the wastewater with an oxidising agent, coagulating and flocculating with coagulant and flocculants respectively followed by an adsorption and subsequent precipitation and removal.

#### 2.3.1.1 Oxidising with KMnO4

Arsenite can be easily oxidised to arsenate with $KMnO_{4m,}$ and therefore the more favoured predominant form of arsenic will be arsenate in solution. The arsenates mostly form a stable precipitate or compound than arsenite, which can then be filtted and removed from the water.

The following equation shows the reaction that occurs during the oxidation of arsenite with potassium permanganate:

$3AsO_2^- + 2KMO_4 + 4OH^- \longrightarrow 3AsO_4^{3-} + 2MnO_2 + 2K^+ + 2H_2O$ (9)

The stiochiometric amount of potassium permangate needed to oxidise 1mg/l of arsenite is 1.41mg/l. Once again, the permanganate requirement will generally be much higher due to the consumption of permanganate by other agents.

Under oxidising conditions, $H_2AsO_4^-$ is dominant at low pH (less than pH 6.9), whilst at higher pH, $HAsO_4^{-2}$ becomes dominant ($H_3AsO_4$ and $AsO4^{3-}$ may be present in extremely acidic and alkaline conditions respectively). Under reducing conditions at pH less than about pH 9.2, the unchanged arsenite species $H_3ASO_3$ will predominate (Brookins, 1988, Yen et al, 2000).

### 2.3.1.2 Coagulation with Ferric Sulphate

Coagulation-flocculation process facilitates the removal of suspended solids and colloids. This occurs in final stage of solids-liquid separation namely settling.

Coagulation is the destabilization of colloidal particles brought about by the addition of a chemical reagent known as the coagulant. The suspended solids include precipitated impurities from the oxidation process. The time required for coagulation and flocculation reactions to take place are an essential factor. Coagulation action depends on the valence of the metals involved. The higher the valence, the more effective the coagulating action (Schultz-Hardy theory: a trivalent ion is ten times more effective than a divalent ion). pH is also a prominent factor in the removal of colloids. The optimum pH is compromised between the pH necessary for coagulation (according to the type of colloids) and the pH necessary for flocculation (relating to the build up of iron hydroxide floc). Usually it corresponds to the minimum solubility of the hydroxide in question. The optimum pH for coagulation-flocculation using Ferric sulphate is pH>5 (Degremont, 1991).

The basic reaction when the $Fe^{3+}$ ion is added to water is the formation of a precipitate of ferric hydroxide with the release of some acidity:

$$Fe2\ (SO_4) + 6HCO_3^- \rightarrow 2Fe\ (OH)_3 + 6SO4^{2-} + 6CO_2 \qquad (10)$$

Edwards (1994) defines arsenic removal from water by coagulation as the conversion of dissolved arsenic to insoluble products by the combined mechanisms of precipitation, co-precipitation and adsorption.

## 2.4 Waste water Quality parameters

Performance of treatment plants is assessed by analyzing the influent and effluent qualities of waste water in terms of physical, chemical biological and design parameters

### 2.4.1 Physical Parameters

#### 2.4.1.1 Temperature

Temperature has important effect on the survival and growth of bacteria for biological activity in wastewater and the amount of gases dissolved in the wastewater.

In general, optimal growth occurs within fairly narrow range of temperature, although the bacteria may be able to survive within much broader limits.

Temperatures below the optimum typically have a more significant effect on growth rate rather than temperatures above the optimum, it has been observed that growth rate double with approximately every $1^0C$ increase in temperature until optimum temperature is achieved.

According to the temperature ranges in which they function best, bacteria may be classified as psychrophilic, mesophylic and thermophilic.

Table 2-2: Typical temperature range for various bacteria

| Bacteria type | Temperature $^{0}$C | |
|---|---|---|
| | Range | Optimum |
| psychrophilic, | 10-30 | 12-18 |
| mesophylic | 20-50 | 25-40 |
| thermophilic. | 35-75 | 55-65 |

#### 2.4.1.2 Turbidity

Turbidity is used to indicate the quality of waste discharges and natural waters with respect to colloidal and suspended matter.

The measurement of turbidity is based on comparison of the intensity of light scattered by a sample to the light scattered by a reference suspension under the same conditions (Standard Methods, 1998). Formazin suspensions are the primary reference standard. Colloidal matter will scatter or absorb light and thus prevent its transmission. It should be noted that the presence of air bubbles in the fluid (wastewater) will cause erroneous turbidity readings. In general, there is no relationship between turbidity and the concentration of total suspended solids in untreated wastewater.

### 2.4.2 Chemical Parameters

#### 2.4.2.1 pH

The pH of the environment is a key factor in the growth of organisms. Most bacteria cannot tolerate pH levels above 9.5 0r below 4.0. Generally, the optimum pH for bacteria growth lies between 6.5 and 7.5. pH is an important quality parameter of both water and wastewater (Payne,2000). pH also play a remarkable role in the oxidation of arsenic in wastewater

#### 2.4.2.2 Total Dissolved Solids (TDS)

Total Dissolved Solids (TDS) are solids in water that can pass through a filter (usually with a pore size of 0.45 micrometers). TDS is a measure of the amount of material dissolved in water. This material can include some carbonate, bicarbonate, chloride, sulfate, phosphate, nitrate, calcium, magnesium, sodium, organic ions, and other ions. A certain level of these ions in water is necessary for aquatic life. Changes in TDS concentrations can be harmful because the density of the water determines the flow of water into and out of an organism's cells (Mitchell and Stapp, 1992). However, if TDS concentrations are too high or too low, the growth of much aquatic life can be limited, and death may occur.

#### 2.4.2.3 Dissolved Oxygen (DO)

Numerous scientific studies suggest that 4-5 parts per million (ppm) of DO is the minimum amount that will support a large, diverse fish population. The DO level in good fishing waters generally averages about 9.0 parts per million (ppm).

# CHAPTER THREE

## 3 Study site description and the operating units of the wastewater treatment plant

The Obuasi municipality formally Adansi west district Assembly has a population of 224,102 (2000 Ghana census). The municipality is in the Ashanti region of Ghana about an hour drive from the capital Kumasi and located on $06^{0}$ $12^{0}$ N and longitude $1^{0}$ $40^{0}$W.

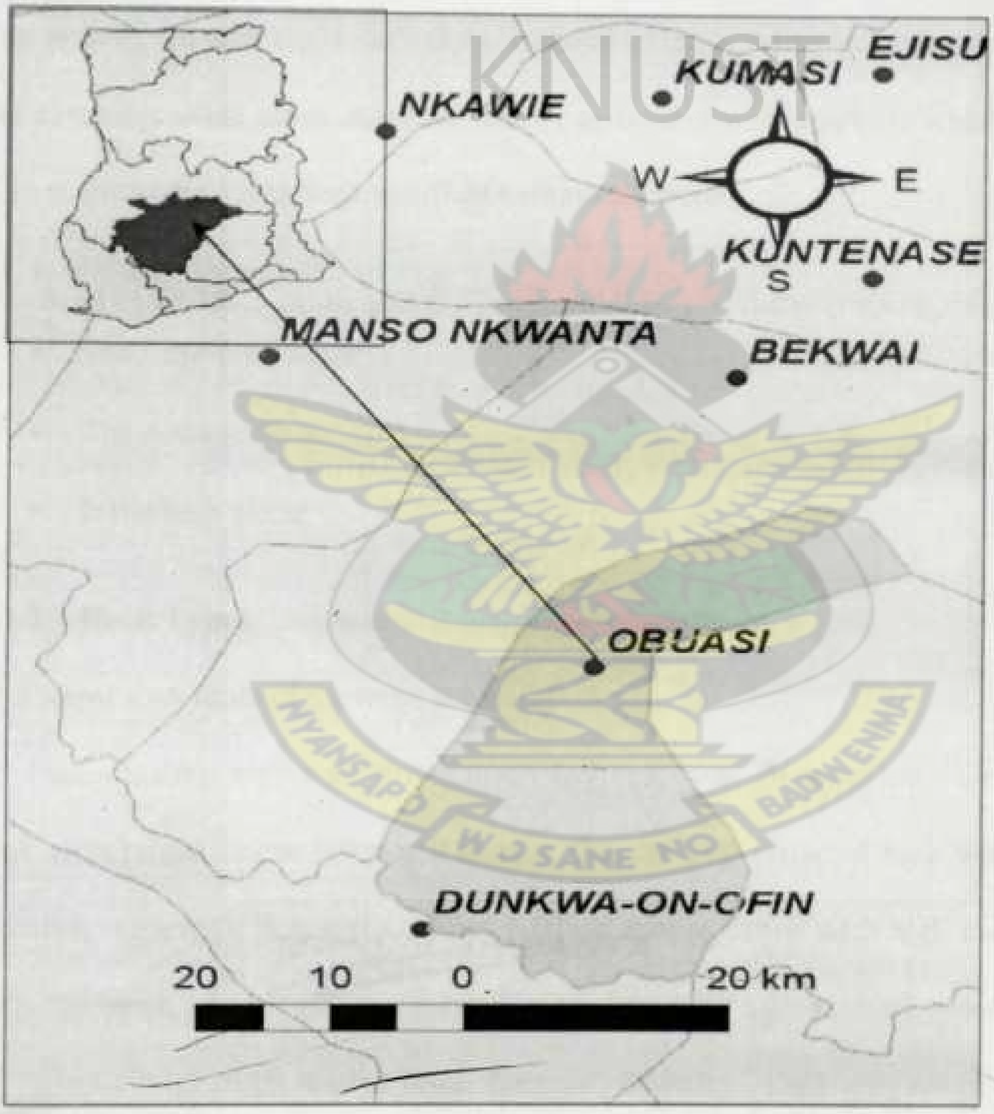


Figure 3-1 Map of Ghana showing the study area

## 3.1 Geology of Obuasi

The Obuasi is located on the most prominent of the five gold belts at the south west section of Ghana, which stretches from south of Prestea to Konongo in the north with mining operations located within a 474 square kilometre concession. The bulk of the gold deposits in Ghana are located on a number of major gold belts in the palaeoproterozoic rocks of the West African craton.

The bulk of the auriferous deposits at Ashanti - Obuasi Mine is located in a trend which has extensive shear zones characteristically associated with graphitic schist.

Five major shear zones are identifiable within the trend.

- Obuasi Shear
- The Côte d'Or Shear
- The Ashanti Shear
- Insintsiam Shear

### 3.1.1 Rock Types

The major rock units of the mine are as follows:

Phylites – Slabby rock with strong linear features; Meta-Greywackes – Graining massive rock with minor linear features; Schist – Sheared and distorted rock with wavy linear features; Graphitic Schist (Graphite) – Black friable Schist with high carbon content – soils the hand; Meta-Volcanics (Dyke)- Grey, greenish grey to dirty green massive rock of igneous origin with limited linear features ; Dolerite – Dark grey massive rock cutting across other rock units (Real Dyke); Ankerite Spotted Schist – Grey Schist with spotted Ankerite (Mg- Carbonate).

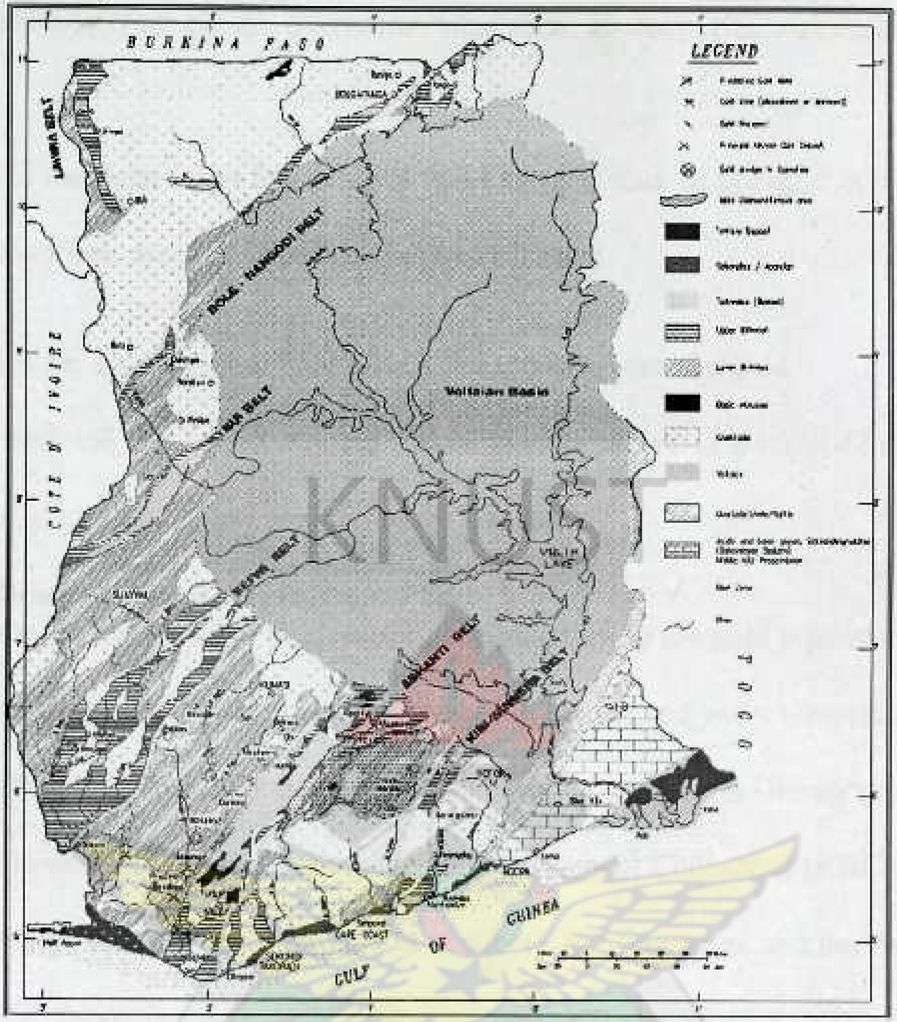


Figure 3-2Geological map of Ghana

#### 3.1.1.1 Ore Types

The Obuasi deposit comprises of four major types of mineralisation:

**QVT** - Quartz Vein Type Mineralisation

**DST** - Disseminated Sulphide Mineralisation

**GNS** - Granitoid Mineralisation (Primary Non-Refractory)

**SOX** - Supergene Oxide & Transition Ore

Quartz - visible gold, galena bournonite, tetrahedrite, sphalerite, chalcopyrite, pyrite and rare arsenopyrite.

Sulphides - arsenopyrite, pyrite, pyrrhotite, marcasite, chalcopyrite, sphalerite and rare gold.

Arsenopyrite is the most important mineral that hosts the bulk of the gold in the sulphide ore with finer crystals associated with higher gold content.

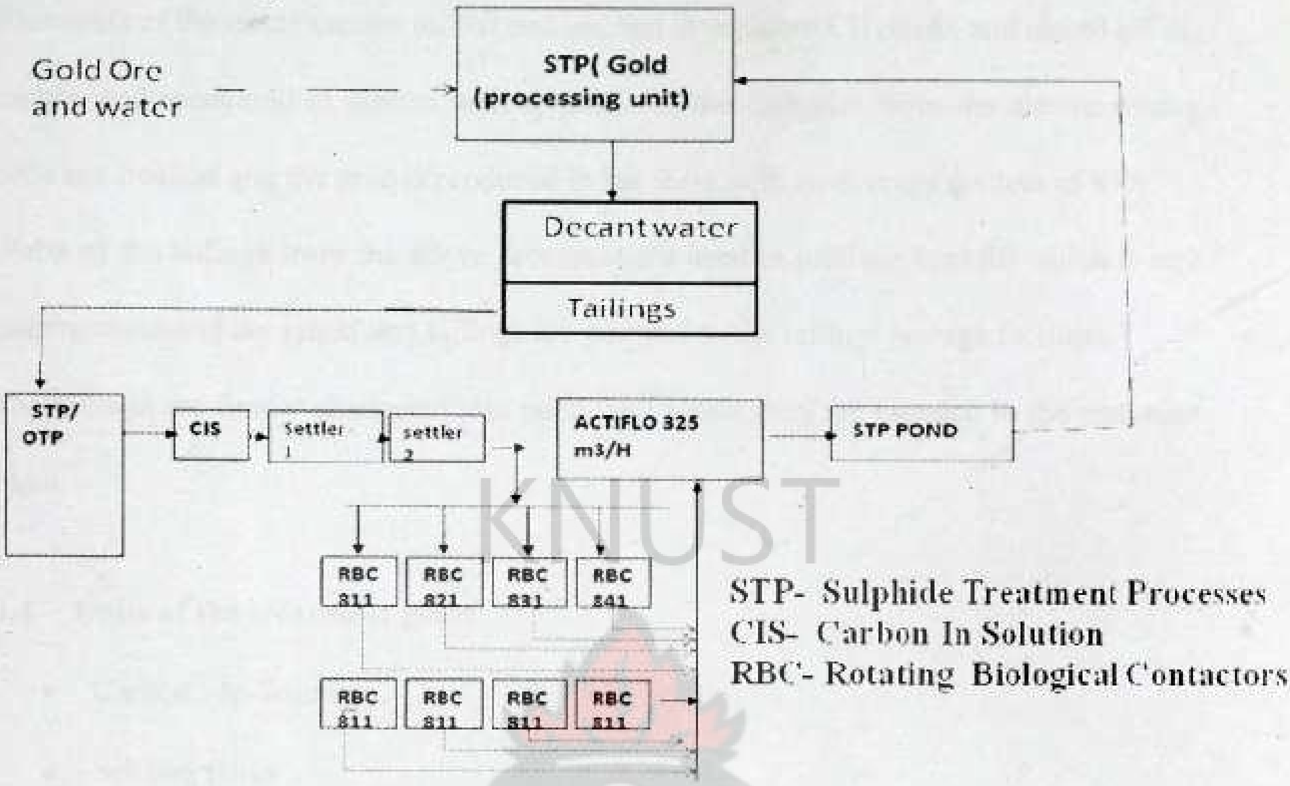
Granitoids - pyrite, arsenopyrite, pyrrhotite, trace chalcopyrite and gold.

Oxide and Transition Ore – decomposed Sulphide or fresh ore as a result of exposure to the weather (e.g. rusting of Iron exposed to the weather).

## 3.2 The Processed water Treatment Plant

The scheme for the treatment of wastewater generated during the gold processing is given in Fig 3-3.The wastewater from the gold processing (processed water) treatment plant is located at the Sulphide treatment plant about ten minutes drive from Obuasi municipality, with the Actiflo unit located close to the Rotating Biological Contactors (RBC). It has the four units namely; the CIS, RBC's (eight in number), Settling tanks and the Actiflo. The Actiflo has the following sub units. Aeration tank, Oxidation tank, coagulation and flocculation dosing tanks and the clarification chamber.

The PWTP has two sources of mine effluent as influent points and currently treat about 500m$^3$/hr of mine effluent (Processed water) (Environmental monitoring report,2009). The source is from the Sulphide Treatment Plant (STP) for recovery of about 85% of gold from the ore.



STP- Sulphide Treatment Processes
CIS- Carbon In Solution
RBC- Rotating Biological Contactors

Figure 3-3 Schematic flow showing the units of the treatment plant

### 3.3 Gold ore processing

The ore body contains arsenopyrite (500m underground mining) which encapsulates the gold particles. The sulphide ore is milled in a combination of SAG (Semi-Autogenous Grinding) and ball mill; this is followed by flotation to concentrate the gold prior to the bacterial oxidation (Biox) of the sulphides. The arsenopyrite is oxidized in the Biox (Bioxidation) process and the arsenic dissolves in the acidic slurry. The arsenic is subsequently precipitated as ferric arsenate in the neutralizing section and this precipitate is pumped away with the final tailings.

The gold bearing slurry is leached in CIL (Carbon In Leach) tanks and the gold is eluted off the activated carbon and recovered in electro wining cells.

Remnants of the oxide ore are milled and leached in separate CIL tanks and eluted off the carbon and recovered in electro wining cells. All the cathodes from the electro wining cells are smelted and the gold is produced in bar form with an average content of 85%.

Parts of the tailings from the above processes are used to produce backfill which is sent underground and the remaining tailings are pumped to the tailings storage facilities.

The tailings are finally channeled into pond 2&3 where they are pumped to the treatment plant.

### 3.4 Units of the treatment plant

- Carbon –In-Solution
- Settling tanks
- Rotating Biological Contactors
- Actiflo

### 3.4.1 Carbon in Solution (CIS)

Carbon-In-Solution is a technique of retrieving gold after cyanidation is applied at CIL plant. The process basically adsorbs the gold in solution from the wastewater (decant water) using activated carbon. The tailings channeled to the Sansu Tailings Dam contain slurry with gold residue. At the dam, the particles in this slurry are able to settle leaving supernatant water above, it is this water that contains gold. The activated carbon adsorbs the gold cyanide complex ~~into it~~ pores. The CIS plant therefore enable the gold available in the decant water to be recovered. It also helps with the removal of some level of cyanide from the decant water prior to the biological cyanide detoxification plant.

There are two CIS tanks each with a holding pond that feeds the CIS with the effluents. The capacity of each of the tank is 200m$^3$ .Each tank is able to take an average of 1.5 tonnes carbon. The unit uses eduction mechanism to drain the loaded carbon from the tanks after adsorption. Copper and calcium have also been known to be adsorbed unto the carbon.

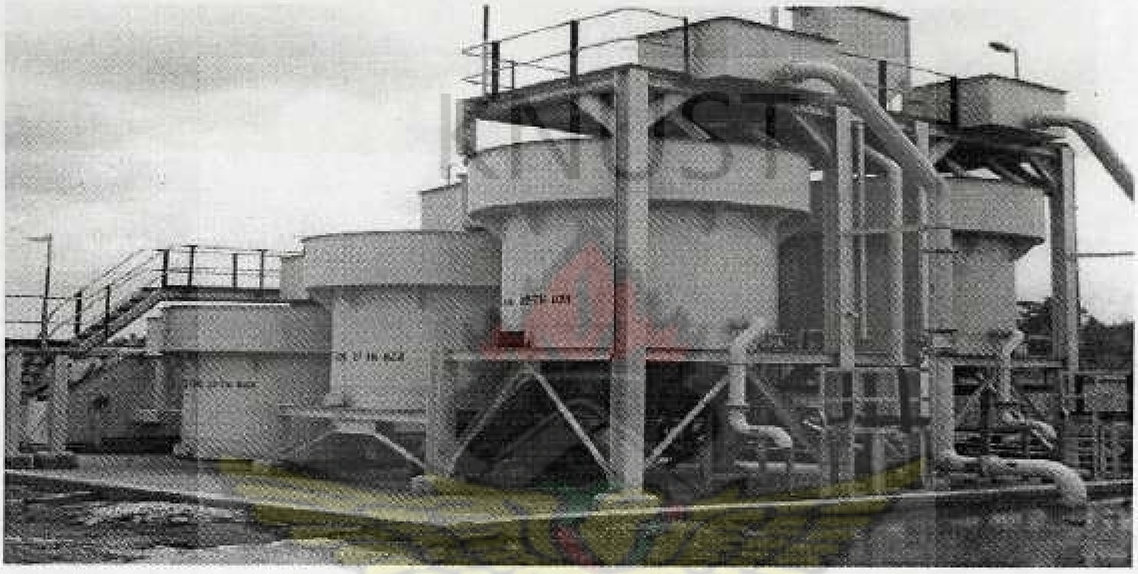


Figure 3-4: CIS holding tanks

### 3.4.2 The Settlers

There are two settling tanks which are sedimentation core clarifier. It serves to collect sediments from the CIS prior to feeding the RBC. They consist of cylindrical tank with conical bottom fitted with a drain valves. Each settler has launder at the top which takes its sources from the overflow pond. On the discharge of the pump are two valves. One feeds the settler at a controlled rate and the other valve serve as a bypass that returns the excess water to the overflow pond in the form of a fountain.

The content of the settler flows into the launder which then feeds the Rotating Biological Contactors, RBC's.

Figure 3-5: Settling tanks

### 3.4.3 The Rotating Biological Contactors

#### 3.4.3.1 Mode of operation

The RBC is made up of large circular plastic sheets corrugated along the diameter and there are installed, eight of them. They are normally operated in parallel. Series operations are necessary when concentrations of cyanide go above 10ppm as tails or to minimize flow for effective degradation by the bacteria because it allows longer retention time and effectiveness. The circular structure is fitted to an axle and made to rotate having 40% of the media surface submerged in the wastewater. The circular plastics are mechanically driven to turn the media sheet in clockwise direction (1.5 rev/min) from the discharge end of the cylinder tank. On the surface of the plastic material are embedded a biomass of bacteria. The bacteria form a thin layer covering the entire rotating surface of the circular structure. This unit biologically degrades cyanide and thiocyanates in the dam decant water using indigenous bacteria before it get to the Actiflo unit. Bacteria type used: Pseudomonas sp. Uses carbon and nitrogen for growth.

Figure 3-6: RBC's in Parallel

### 3.4.4 Operating conditions for the RBC's

Table 3-1 Operating conditions for the RBC unit

| Parameter | Requirement | |
|---|---|---|
| | Range | Ideal |
| Temperature | 14-34 $^{0}$C | 30$^{0}$C |
| pH | 6.0-8.5 | 7.2 |
| D.O | 1.5< 4.5 ppm | 4 ppm |

## 3.5 The Actiflo unit

The following are the sub units of the Actiflo unit:

1. Aeration chamber

2. Oxidation and PH adjustment chamber
3. Coagulation , flocculation and sand chamber
4. Clarification and solid separation chamber
5. Sludge recycle chamber

### 3.5.1 The aeration chamber

Pre-oxidation is accomplished by aeration of the influent feed water from the RBC's. The feed water flow rate is measured by means of a flow meter which in turn controls the chemical dosing flow rates proportionally at a set rate. The initial feed flow rate is 272m$^3$/h increasing to 320m$^3$/h when instantaneous flow is to be maintained. The sectional aeration tank is fitted with an aeration system consisting of a series of membrane diffusers which distributes the air in fine bubbles into the feed water. Air is supplied to the aeration system by an air blower connected by piping to the aeration tank air nozzle. The interconnecting piping between the membrane diffusers in turn connects via the main air supply pipe to the aeration tank air nozzle. The aeration tank has a capacity of 280m$^3$ giving a retention time in the tank of 5 minutes at a flow of 320m$^3$/h into the aeration tank. This reaction time is sufficient to preoxidise arsenic and heavy metals.

### 3.5.2 Oxidation and pH adjustment chamber

Aerated feed water flows from the aeration tank into the sectional oxidation tank under the effect of gravitation. Caustic soda and potassium permanganate (Oxidant) are dosed by means of injection spears into the feed pipeline of the oxidation tank ensuring that the chemicals are mixed with the feed water prior to entering the oxidation tank. Caustic soda is dosed into the aerated water to adjust the pH to 9.5 which cause heavy metals to start precipitating and also enhance chemical oxidation. Potassium permanganate is used as oxidant for the Actiflo feed water and further oxidise all partly oxidised heavy metals and arsenic. A side entry mixer ensures that all precipitated particles and suspended solids in the oxidation tank remain in suspension by slow mixing. The mixer is protected by a low level switch mounted at the required height on the side of the tank. The oxidation tank has a capacity of 180m$^3$ giving a retention time in the tank of 32 minutes with an operating volume of 160m$^3$and at a flow of 320m$^3$/h into the oxidation tank. This reaction time is sufficient to oxidise arsenic and heavy metals.

### 3.5.3 Coagulation, Flocculation and Sand Chamber

Conventionally water clarification processes primarily involve the destabilization and subsequent removal of colloidal suspended solid materials that are not readily removed by gravitation alone. Usually the stability of colloidal suspended materials is attributed to a net negative surface charge that causes individual particles to repel each other and remain in suspension. To counteract these repulsive forces, a chemical coagulant such as alum ($Al_2(SO_4)_3$), ferric chloride ($FeCl_3$), ferric sulphate ($Fe_2(SO_4)_3$), poly-aluminum chloride (PACL), is added to bring about a net reduction in the repulsive force between the suspended materials. This process termed coagulation, results in the destabilization and , or attraction of the suspended solids to form chemical floc. Although destabilized, the chemical floc may remain in solution due to their extremely low mass.

The removal of these particles is most easily achieved by aggregating the smaller particles together into larger, more settleable floc. Floc formation is typically accomplished by forming inter-particle polyelectrolyte bridges by using chemical (flocculant aid) polymer. This process, commonly called flocculation, provides larger more settleable flocs that are more readily removed by gravitational settling. The microsand serves several important roles in the Actiflo process:

The coagulation chamber is equipped with a fast mixer and cross plated for improved mixing and has dimensions 1.45m x 1.19m a water level of 3m deep. The reaction time in the coagulation chamber is 2 minutes at the maximum feed rate of 320m$^3$/h. pH is also measured by a pH probe fixed inside the coagulation tank. From the coagulation chamber the water flows to the injection chamber through an overflow weir. Provision is made for anionic polymer to be dosed into the flocculation section at a set ratio to the influent rate.

Recycled sand from the hydrocyclone underflow is also dosed here. The injection chamber is equipped with a fast mixer and cross plated for improved mixing and has dimensions 1.45m x 1.19m with a water level of 3m deep. The reaction time in the coagulation chamber is 2 minutes at the maximum feed rate of 320m$^3$/h. The maturation chamber retention time is 6 minutes at the maximum flow rate of 320m$^3$/h. The mixers of the Actiflo are protected by level switches that are fixed inside the maturation tank.

The fully formed ballasted flocs leave the maturation tank and enter the settling tank. Here, laminar up flow through the lamellar settling zone provides rapid and effective removal of the sand/sludge floc. Clarified water exits the Actiflo system via a series of collection troughs or weirs for discharge to the receiving stream. The clarification chamber has dimensions 1.73m x 2.39m with a water depth of 3m. The turbidity of the clarified water is monitored in the clear water well with a turbidity meter.

### 3.5.4 Clarification and solid separation chamber

The process is a compact, conventional-type clarification system that utilizes sand (silica) as a seed for floc formation. The sand provides an adsoption surface which help in precipitation and settling capacity of the flocs . The resulting sand ballasted floc displays unique settling characteristics, which allow for clarifier designs with high overflow rates and short retention times. These designs result in system footprints that are between 5 and 50 times smaller than conventional clarification systems of similar capacity. The feed flow to the Actiflo unit is controlled at a set rate by means of the controlled plant inlet feed flow. This feed flow rate is monitored with the feed flow meter at the inlet of the aeration tank. The operating feed flow rate is 272m$^3$/h is increased to 320m$^3$/h when instantaneous flow at maximum capacity is maintained.

### 3.5.5 Sludge Recycle Chamber

The ballasted floc sand-sludge mixture is collected at the bottom of the settling tank and withdrawn using a rubber-lined centrifugal slurry pump .The sand-sludge mixture is then pumped to the hydrocyclone for separation. Energy for pumping is effectively converted to centrifugal forces within the body of the hydrocyclone causing chemical sludge to be separated from the higher density sand. Once separated, the sand is concentrated and discharged from the bottom of the hydrocyclone and re-injected into the Actiflo process for re-use. The lighter density sludge is discharged out of the top of the hydrocyclone and discharged to the concrete sump.

Figure 3-7: Picture of Actiflo Unit

# CHAPTER FOUR

## 4 Methodology

Sampling was done from September 1 to November 18, 2009 and total samples analyzed was 105.

Sampling points were: CIS (inlet and outlet), settler 1and 2, RBC (inlet and outlet), Actiflo (inlet and outlet and at the sludge accumulation sump. Sampling at each unit was taken in duplicate for accuracy. Samples were acidified and kept between $4-5^{0}C$ in an ice chest and taken to the labs( Environmental lab AGA and Eng. lab KNUST). Sample that were not analysed within 24 hrs were kept within the same preserved conditions for subsequent analyses.

Sampling containers for the analysis of total cyanide were wrapped in black polyethene bag to avoid direct incident sun light.

pH, Temperature and Dissolved oxygen( DO) for the Rotating Biological Contactors and the Actiflo unit were measured insitu with Ph meter (Combo by HANNA,H198130) , thermometer and DO meters respectively. Turbidity values were taken by turbidimeters on the field for the Actiflo in line and repeated at the Lab.

Sampling containers for the analyses of total Cyanide were wrapped in black polythene bags, this was done in other to avoid direct incidence of sun light.

## 4.1 Chemical water quality parameter analysed

Wastewater parameters that were analysed for were: TDS free Cyanide, total Arsenic, As ~~and~~ Fe. Analytical methods used for the various parameters are as follows: TDS was measured by conductivity / EC meter (Combo by HANNA,H198130)

## 4.2 Determination of free Cyanide

Determination of free cyanide was done by Chlorometric method. 6mls of the samples were taken and put in a fumigator. With samples in the fumigator, one scoop of CN1 (Chloramine T) crystalline form was added to the samples, this was to dissolve all cyanide species. Granular CN2 (Barbituric acid ) which is then added in order to enable the cyanide species form complexes. Finally, 3 drops of CN3 (Pyridine) were added to develop a colour change.

The colour changes were compared to shades of colour on a colour disc in a colour comparator. The different colours shades correspond to various concentrations of cyanide. Color that could not match with the colour disc were determined by HACH DR 5000.

## 4.3 Determination of dissolved Arsenic

Samples from the Actiflo unit were analysed using the Atomic Absorption Spectrophotometer (Spectr AA220), and also anaysis within pH 4-11.

## 4.4 Monitoring program

The monitoring program was carried out for twelve weeks to determine the rate of flow, variations in pH and how changes in temperature as a result of weather changes affect the treatment processes for each units of the treatment plant.

# CHAPTER FIVE

## 5 RESULTS AND DISCUSSION

### 5.1 Influent and effluent wastewater (processed water) quality

Based on the analytical activities performed over a period of 12 weeks for assessing and monitoring the performance of the processed water treatment plant, data obtained for the quality of influent and effluent of the various units (CIS, Setters, RBC and Actiflo) have been given in detail in appendix 1. Parameters analyzed for include, pH, Temperature, Turbidity, Total Dissolved Solids (TDS), Dissolved Oxygen (DO), As, CN and Fe. Values obtained for the various parameters have been compared with the range of values specified in the operating manual for the various units of the treatment plant (table 5-1 and 5-2) to evaluate the performance of the units.

Table 5-1 : Optimal operating conditions for the RBC and Actiflo unit (operating manual 2002 and 2008 respectively).

| **Parameter** | **Required condition for RBC** | | **Required condition for Actiflo** | |
|---|---|---|---|---|
| | **Range** | **Ideal** | **Range** | **Ideal** |
| Temperature | 14-34 $^{0}$C | 30$^{0}$C | 31-32 | 32 |
| pH | 6.0-8.5 | 7.2 | 9-9.5 | 9.5 |
| D.O | 1.5< 4.5 ppm | 4 ppm | 6.7-7 | 7 |
| CN | 0.1>0.004ppm | 0.004ppm | >50% | |

### 5.1.1 pH

Wastewater (i.e Processed water) entering the first unit of the treatment plant, the Carbon in solution (CIS) was found to have pH ranging from 7.5-7.6 for both influent and effluent wastewater (Fog5-10. In this unit, aerobic conditions prevails so, the dominant species of As is As (V). This can be seen from the Eh-pH diagram in Fig2-1. Within this pH range other species of As e.g. As (III), As (0) etc may be present.

From the CIS, the effluent enter the settler and then to the Rotating Biological Contactors (RBC)(Fig.3.3). In all these subsequent units pH values measured was found to range within the limit of 7.5-7.6. This pH happens to be the ideal range for performance of the bacteria in the RBC for optimum degradation of Cyanide, (Operating manual, 2002). Table 5-1.Within the Actiflo, the unit where effluent from the RBC's enters, the prevailing pH range as observed ranged from 7.5-8.2 (Fig.5.1). The registered increased of 990-2050 in pH was probably due to periodic dosing of the RBC with lime. Lime addition in this unit is to raise the solution's pH to 9.5 for optimum removal of As. This increase in pH , however, did not match up to the recommended pH (Table 5-1) required for optimum removal of As in the Actiflo. In view of this, bench scale analyses was conducted to determine the effect of varying pH on As removal performance (Fig 5-9).The observed pH values however fell within the pH range for oxidation of As(III) to As(V).(Fig.2.1)

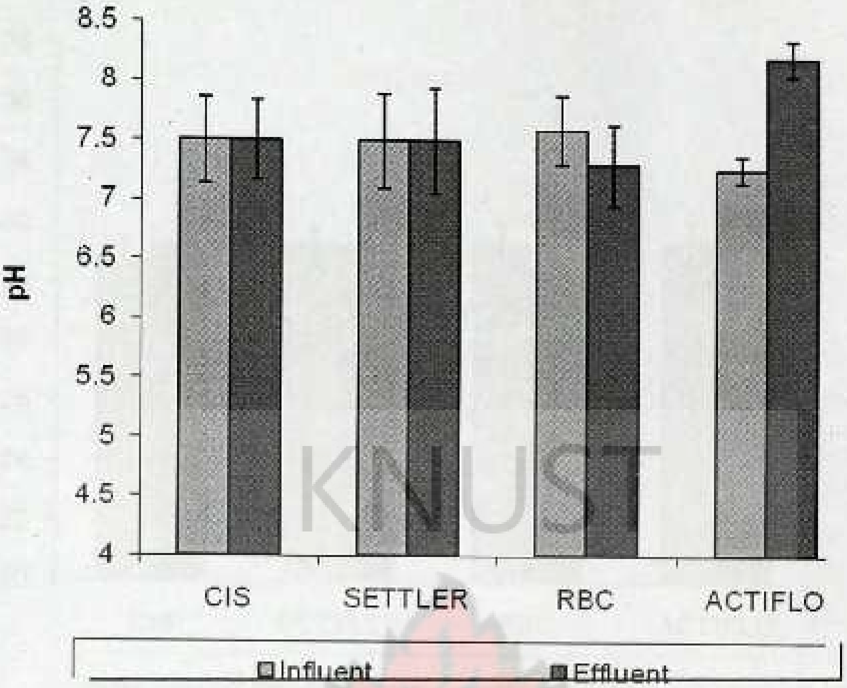


**Figure 5-1: pH of effluent and influent for the various units of PWTP**

### 5.1.2 Temperature

Temperatures recorded for the four units (CIS, Settlers, RBC and Actiflo fell within the recommended range 30-35$^0$C (Table 5-1 and Fig 5-2). This temperature promotes or facilitates the optimal performance of *Psuedomonas* species used in the RBC.

However variation of temperature in the RBC unit might was be due to the activities of the bacteria.

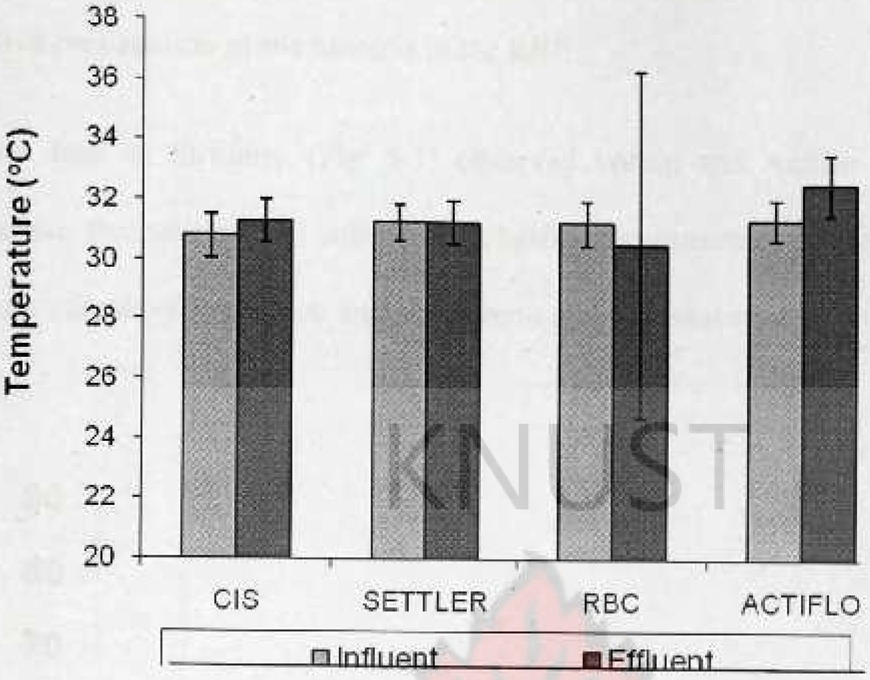


Figure 5-2: Temperatures of effluent and influent for the various units of the PWTP

### 5.1.3 Turbidity

Turbidity values observed in the CIS unit showed a reduction of more than 50% from the original value (Fig 5-3). The decrease in the turbidity in the unit was as a result of adsorption activity of the activated carbon used as an adsorbent for recovering gold particles. Effluent from the CIS enters the settlers which serve as sedimentation tanks.

Contrary to expectation, turbidity increased in the settlers probably due to turbulence and re-suspension as the effluent from CIS enters the setter unit. According to the operators and managers of the plant, the settlers have not been disludged for the past five years; therefore any turbulence could contribute to arousal of already settled solids thereby increasing the turbidity and suspended solids. Another remarkable observation was the increase in turbidity observed in the influent of the RBC. This increase could be due to the intermittent dosing of the solution in the RBC with a substrate (molasses) for vegetative propagation of the bacteria in the RBC.

A sharp drop in turbidity (Fig 5-3) observed within the Actiflo unit was due to coagulation, flocculation and subsequent clarification processes leading to precipitation of arsenic complexed with iron and manganese and eventual separation from the clarified water.

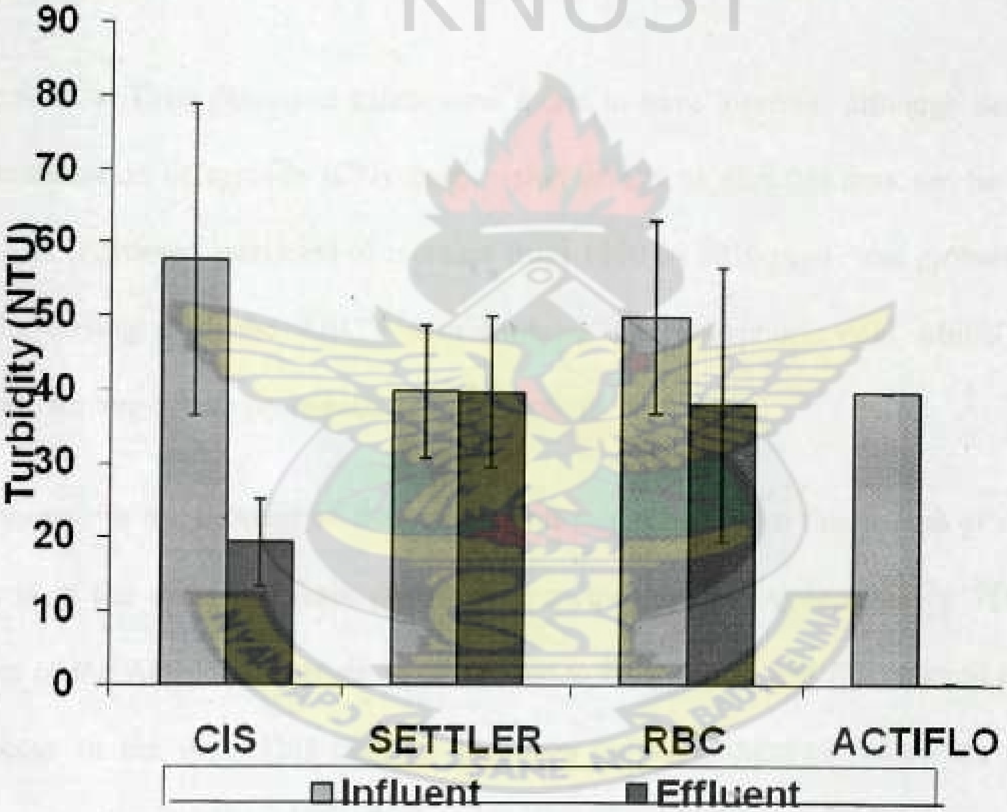


Figure 5-3: Turbidities of effluent and influent for the various units of the PWTP

### 5.1.4 Total Dissolved Solids (TDS)

TDS give information on solids and salts that are in dissolution within the wastewater. Activities in the various units would lead to changes in concentration of these solids. Total dissolved solids observed ranged from 1900-2050 mg/l (Fig 5-4).

In the (CIS), raw wastewater TDS was observed to increase slightly an indication that some (salts) might have reacted with the activated carbon granules (Fig 5-4) forming soluble products.

In the RBC's, Total dissolved solids were found to have increase, although degradation or detoxification of cyanide (CN), (conversion of CN to nitrates) may not be affecting TDS. The registered increased of increase from 1990 to 2050 mg/l was probably due to periodic dosing of the RBC's with Molases and phosphoric acid which serve as substrate for vegetative propagation of the bacteria.

The increase in the influent of the Actiflo unit might be due to the dosage of coagulant which is in the dissolved form contributing to the increase.A decrease in TDS in the influent of the Actiflo unit might possibly due to coagulation and flocculation processes that occur in the unit. This confirm that iron oxide, manganese oxide are removed complexed with arsenic in this unit.

Generally suspended particles may adsorb unto surfaces of Oxides like Ferric oxides. Such oxides are known to have higher adsorption capacity for heavy metals like Pb, Zn and Cd (Buamah et al 2009). Such adsorption processes is therefore expected to decrease TDS indirectly.

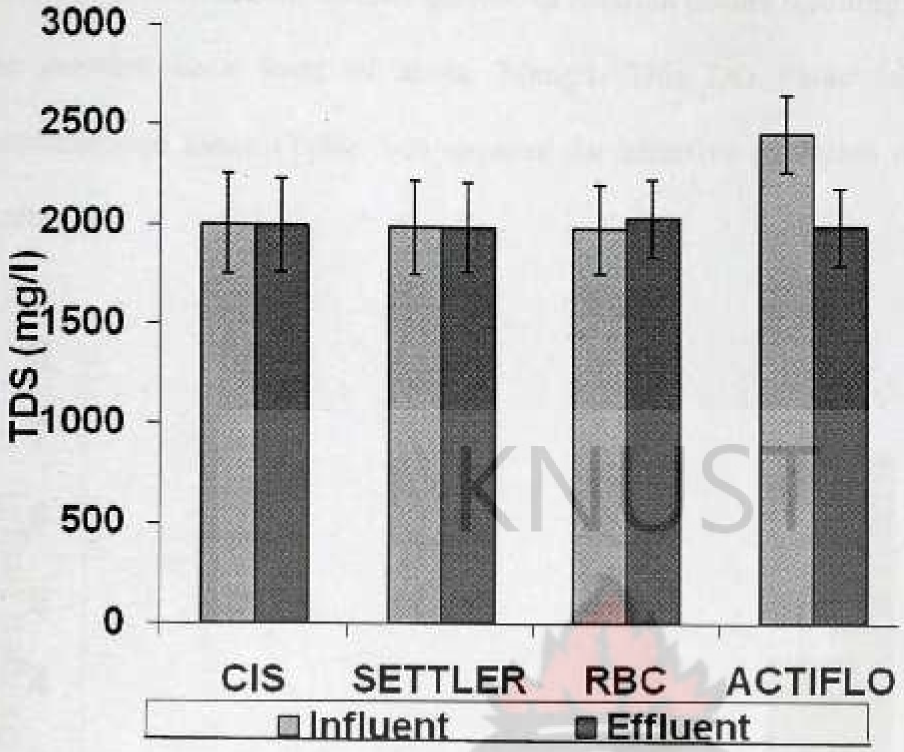


**Figure 5-4: TDS of effluent and influent for the various units of the PWTP**

### 5.1.5 Dissolved Oxygen (DO)

Average Dissolved Oxygen (DO) observed in the CIS and settlers of the treatment plant was 2.5mg/l for both influent and effluent. The increased DO value of 4mg/l observed in the RBC was possibly due to aeration activity accomplished by the aerators installed in the RBC. Operating operations of aerobic micro organisms (Pseudomonas) would therefore be facilitate in the RBC .Increasing DO in wastewater is desirable since it helps prevent the formation of obnoxious odors. For biological treatment processes like the detoxification or degradation of cyanide in the RBC. DO of 0.2mg/l and above has been reported to inhibit denitrification. (Skerman and Mac Rae, 1957: Terai and Mori, 1975).

Within the Actiflo unit, another episode of aeration occurs resulting in further increase in the aeration to a level of about 7.0mg/l. This DO value fall within the range recommended range (Table 5-2) required for effective oxidation of Fe and Mn in the Actiflo.

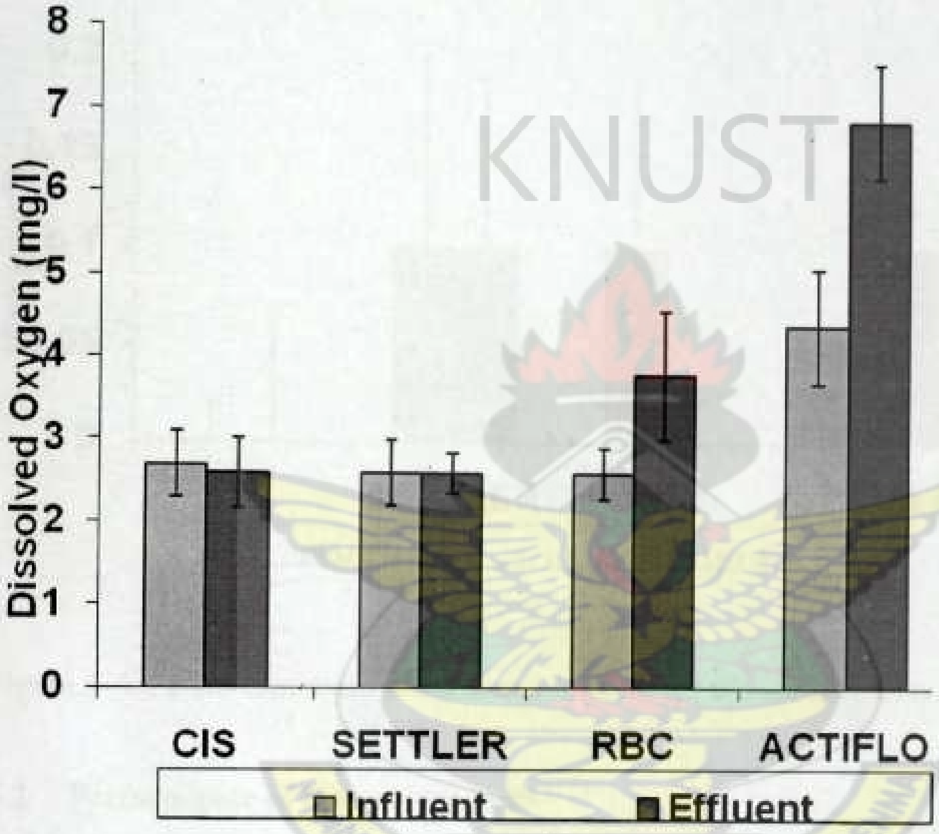


Figure 5-5 DO effluent and influent for the various units of the PWTP

### 5.1.6 Fe occurrence in the various units of the PWTP

Fe play a very important ~~role in the~~ oxidation of As. Concentrations of Fe as observed in the CIS might due to the homogeneous nature of the Fe in the Arsenopyrite gold ore. However, Fe increased in the settler units this might be as a result of the setters not dislodged for a long time. Fe decreases in the RBC because of the absorption of the Fe unto the surfaces of the bacteria. There was a drastic increase in the Actiflo units confirms the effectiveness of the coagulant used (($Fe_2(SO_4)3$). This can be seen from Fig 5-6 below.

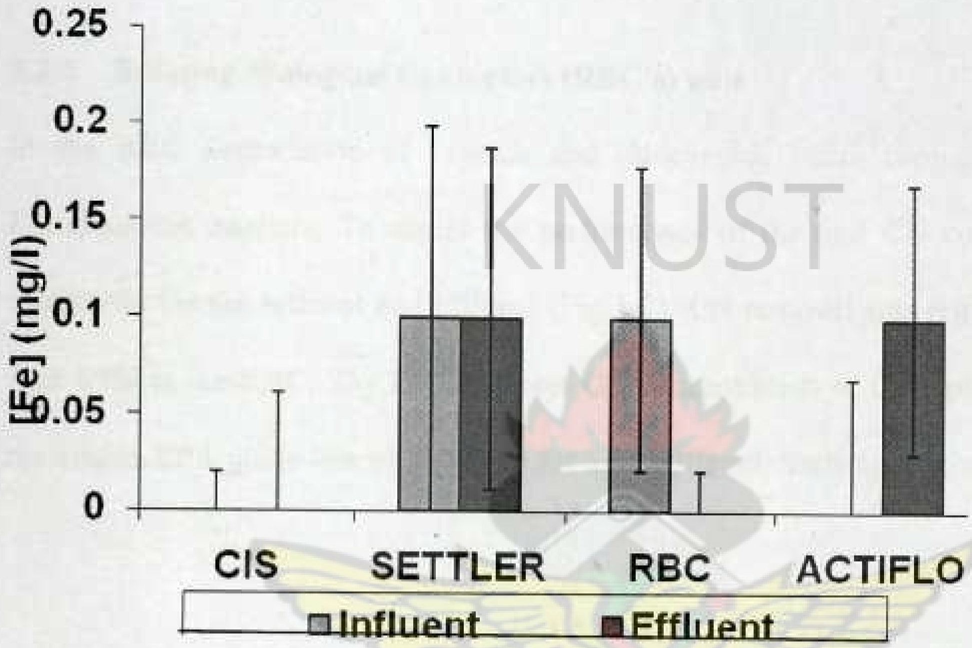


Figure 5-6: Fe concentration effluent and influent for the various units of the PWTP

## 5.2 Performance of the various units

### 5.2.1 Carbon in solution (CIS) unit

There is no chemical or biological process taking place in this unit. Activated carbon is used in the adsorption of gold particles from wastewater.

### 5.2.2 Settlers

The settlers are there as sedimentations tanks separating out settleable particles so thatthey do not interfere with the activities of the bacteria in the Rotating Biological Contactors (RBC). Using turbidity as an indicator for assessing the occurrence of suspended solids; it was expected that, Turbidity levels will drop within the Settlers or at least fall below values recorded for the CIS and RBC. Contrary to expectation the turbidity levels increased (Fig 5-3) possibly due to re-suspension of settled material. The Settlers have not been disluged for the past five years and need to be disludged.

### 5.2.3 Rotating Biological Contactors (RBC's) unit

In the RBC degradation of cyanide and thiocyanide occur through the activity of Pseudomonas bacteria. To assess the performance of the unit CN concentrations were monitored for the influent and effluent (Fig 5-7). CN removal was registered to be more than 99% in the RBC. The RBC effluent CN concentration of 0.004ppm is far less than the Ghana EPA guide line of (0.2ppm) for mine effluent discharged in surface waters.

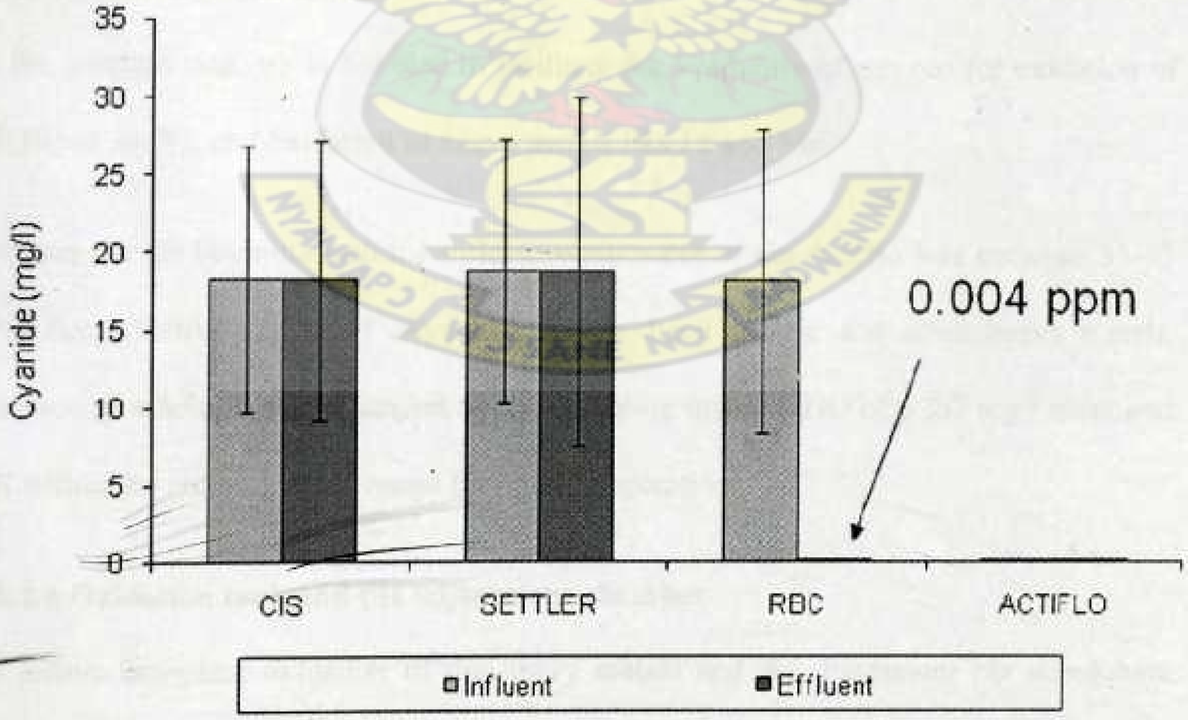


Figure 5-7: Cyanide concentration effluent and influent for the various units of the PWTP

### 5.2.4 Actiflo unit

This unit is for removal of arsenic (As) and other heavy metals using mechanisms of aeration, coagulation, flocculation and adsorption. Temperature and pH are very important influencing parameters for the performance of this unit. Measured temperatures of 30-33$^0$C fell within the recommended temperatures for effective removal of As. The pH values recorded were between 8.0-8.2. These pH recorded were below the recommended pH of 9.5. In view of this low prevailing pH in the Actiflo , a laboratory scale experiment was performed to monitor the removal of As at varying pH ( i.e 4-11) to verify the effect of pH on the removal efficiency of As. This can be seen in Fig 5-10.

The Actiflo units have five sub units: Aeration tank, Oxidation tank and pH adjustment chamber and Coagulation, flocculation and sand addition chamber

### 5.2.5 The aeration tank

In the aeration tank, air is bubbled to facilitate the availabity of oxygen for oxidation of As(III) to As(V), and oxidation of heavy metals like Fe and Mn.

Pressure for air bubbling into the influent wastewater of the Actiflo was between 33-35 kPa. For effective supply of oxygen to pre-oxidized arsenic and other heavy metals, pressure of 40kPa is recommended by the operating manual. DO of 6 to7 mg/l measured fell within the recommended range for optimal operations.

### 5.2.6 Oxidation tank and pH adjustment chamber

To ensure complete oxidation of the heavy metals and As, Potassium per manganate ($KMnO_4$) is dosed in a separate tank and pH adjusted to 9.5.The oxygenated water will cause the predominate form of Arsenic to be arsenate in solution. The arsenates mostly form a stable precipitate which can then be filtered and removed. The concentrations measured in the study for potassium permanganate and caustic soda (lime) were 9.1mg/l and 7.0mg/l respectively. The concentration of potassium permanganate to be dosed as recommended by the operating manual is 9.0mg/l. Caustic soda concentration recommended by the operating manual is 3.0mg/l for oxidation of arsenic, but higher value are necessary for oxidation of other heavy metals.

### 5.2.7 Coagulation, flocculation and sand addition chamber

Coagulation is done by the addition of Iron sulphate ($Fe_2(SO_4)3$) as coagulant to the wastewater in the coagulation-floculation chamber. The concentration observed was 105mg/l and floculant used was a polymer. The coagulant and flocculation were able to form Fe flocs complexed with arsenic that were able to precipitate out. This is the reason why lower Turbidity values were recorded in the Actiflo unit and water clear enough to be reused.

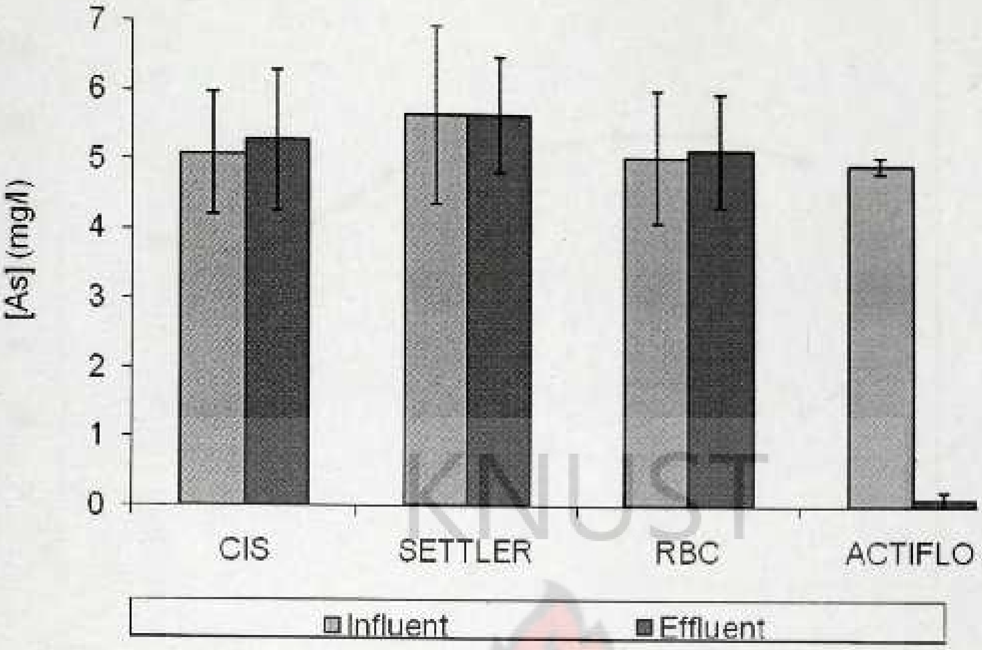


Figure 5-8 : Arsenic concentration effluent and influent for the various units of the PWTP

### 5.3 Effect of pH on As removal

pH play a remarkable rule in the oxidation and subsequent removal of arsenic. pH of 9.5 is recommended by the operating manual for higher removal efficiency. However pH values measured by the inbuilt pH meter of the Actiflo units varied from pH 8-8.2. In view of this, a lab scale experiment was designed and conducted to determine the effect of varying pH on arsenic removal. Fig 5-9 showed the percentage arsenic removals corresponding to the various pH values from 4-11.

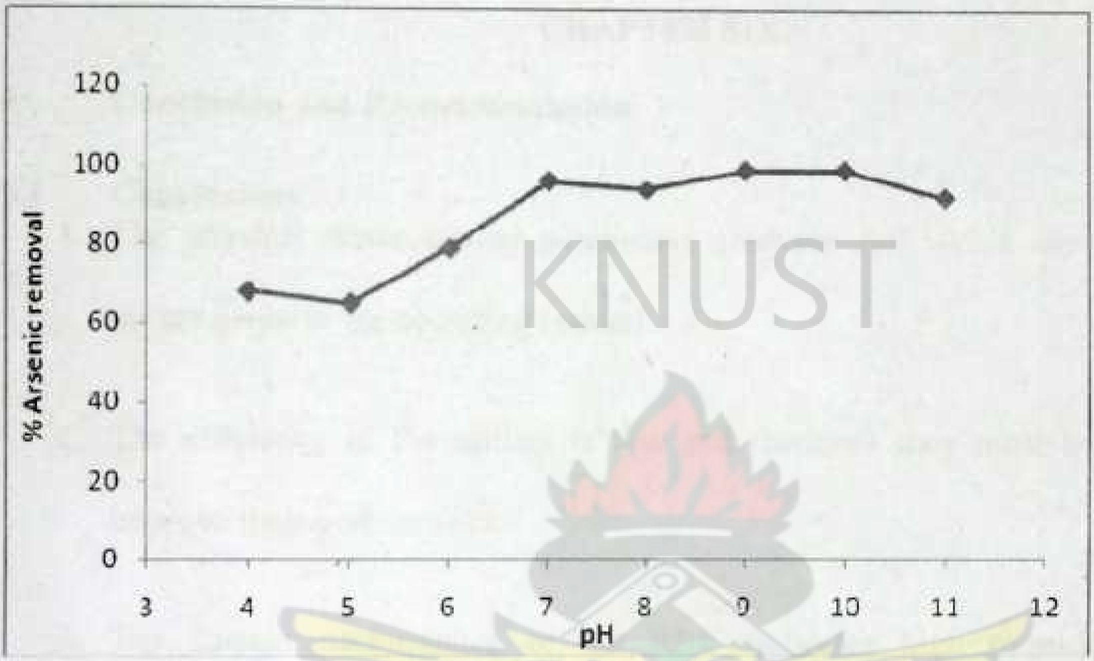


Figure 5-9 : Variation of pH with the corresponding percentage removal of As

# CHAPTER SIX

## 6 Conclusion and Recommendation

### 6.1 Conclusions

1. The physical water quality parameters analysed fell within the recommended ranges given in the operating manual.
2. The efficiency of the settlers is low and therefore they must be disludged to improve their performance.
3. The current performance of the RBC indicates high cyanide degradation efficiency (99%).
4. Current performance of the Actiflo unit indicates high (98%) arsenic removal efficiency.
5. Operating the Actiflo unit at pH 7 – 7.5 can give a recommendable arsenic removal of about 96%. The effluent arsenic concentration of 0.01 to 0.3 ppm fall within the EPA guideline range for mine effluent discharge

### 6.2 Recommendations

- Further studies and research should be carried out to determine the settling capacity and the appropriate retention time of the settlers.
- pH for operations of the Actiflo can be fixed at pH 7 – 7.5 for arsenic removal can help reduce cost.
- Research should be carried out with the locally produced sand used as an adsorbent to verify it adsorbing capacity for the removal of arsenic in the Actiflo unit.

- Long term performance evaluations need to be undertaken for the various units.

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# APPENDICES

APPENDIX 1: (Laboratory analysis of water quality for both influent and effluent for all the unit of the treatment plant)

| | Influent Sample | pH | Temp | TDS | Turb | DO | CN | AS | Fe |
|---|---|---|---|---|---|---|---|---|---|
| CIS | 1 | 7.8 | 30 | 1950 | 83 | 3 | 3.5 | 4.998 | 0.015 |
| | 2 | 7.8 | 30.2 | 1870 | 162 | 2.8 | 15 | 5.01 | 0.003 |
| | 3 | 7.0 | 30.2 | 1930 | 76 | 2.3 | 17 | 6.074 | 0.004 |
| | 4 | 7.7 | 31.3 | 1890 | 32 | 2.5 | 25 | 5.841 | 0.054 |
| | 5 | 7.6 | 31.9 | 1870 | 49 | 2.2 | 25 | 5.327 | 0.004 |
| | 6 | 7.1 | 31 | 2510 | 49 | 3.2 | 25 | 3.573 | 0.01 |
| | Average | 7.5 | 30.8 | 2003.3 | 75.2 | 2.7 | 18.4 | 5.1 | 0.0 |
| | Standard deviation | 0.364783 | 0.75542483 | 250.3331 | 46.55069 | 0.39833 | 8.558135 | 0.882183 | 0.019657 |

| | Efluent Sample | pH | Temp | TDS | Turb | DO | CN | AS | Fe |
|---|---|---|---|---|---|---|---|---|---|
| CIS | 1 | 7.8 | 31 | 1960 | 30 | 2.1 | 2 | 5.028 | 0.162 |
| | 2 | 7.8 | 30 | 1870 | 90 | 2.1 | 15 | 6.04 | 0.023 |
| | 3 | 7.7 | 31.4 | 1940 | 17.1 | 2.7 | 17.5 | 6.053 | 0.018 |
| | 4 | 7.6 | 32.1 | 1870 | 16.6 | 3 | 25 | 5.908 | 0.004 |
| | 5 | 7.5 | 31.6 | 1880 | 16.6 | 3 | 25 | 5.577 | 0.018 |
| | 6 | 6.9 | 31.5 | 2480 | 16.6 | 2.8 | 25 | 3.406 | 0.004 |
| | Average | 7.5 | 31.3 | 2000.0 | 31.2 | 2.6 | 18.3 | 5.3 | 0.0 |
| | Standard deviation | 0.337189 | 0.71460945 | 238.2436 | 29.31605 | 0.416733 | 9.076067 | 1.021247 | 0.061177 |

|  | Tank 1 | pH | Temp | TDS | Turb | DO | CN | AS | Fe |
|---|---|---|---|---|---|---|---|---|---|
| Settler | 1 | 7.8 | 31 | 1980 | 42 | 2.3 | 17 | 4.913 | 0.154 |
|  | 2 |  |  |  |  |  |  |  |  |
|  | 3 | 7.7 | 32 | 2000 | 50 | 2.8 | 23 | 7.061 | 0.04 |
|  | 4 | 7.7 | 31.8 | 1970 | 35 | 2.5 | 15 | 7.146 | 0.045 |
|  | 5 | 7.5 | 31.2 | 1985 | 38 | 2.7 | 23 | 5.785 | 0.136 |
|  | 6 | 6.7 | 31 | 2040 | 35 | 2.5 | 18 | 3.651 | 0.015 |
|  | Average | 7.5 | 31.3 | 1995 | 40.0 | 2.6 | 18.9 | 5.7 | 0.1 |
|  | Standard deviation | 0.4 | 0.6 | 237.3 | 9.1 | 0.4 | 8.6 | 1.3 | 0.1 |

|  | Tank 2 | pH | Temp | TDS | Turb | DO | CN | AS | Fe |
|---|---|---|---|---|---|---|---|---|---|
| Settler | 1 | 7.6 | 30.5 | 1990 | 36 | 2.3 | 15 | 5.311 | 0.023 |
|  |  |  |  |  |  |  |  |  |  |
|  | 3 | 7.7 | 32.0 | 1960 | 45 | 2.8 | 18 | 4.925 | 0.108 |
|  | 4 | 6.9 | 31.4 | 1970 | 47 | 2.4 | 20 | 5.655 | 0.004 |
|  | 5 | 7.5 | 31.5 | 2018 | 38 | 2.8 | 22 | 5.855 | 0.234 |
|  | 6 | 7.7 | 31.2 | 2035 | 33 | 2.7 | 20 | 5.529 | 0.004 |
|  | Average | 7.5 | 31.3 | 1995 | 40.0 | 2.6 | 18.9 | 5.7 | 0.1 |
|  | Standard deviation | 0.4 | 0.7 | 224.8 | 10.3 | 0.2 | 11.2 | 0.8 | 0.01 |

| | Influent Sample | pH | Temp | TDS | Turb | DO | CN | AS | Fe |
|---|---|---|---|---|---|---|---|---|---|
| **RBC** | 1 | 7.8 | 30.5 | 1920 | 42 | 2.4 | 3.5 | 4.919 | 0.193 |
| | 2 | 7.8 | 30.5 | 1900 | 46 | 2.3 | 3.5 | 4.856 | 0.137 |
| | 3 | 7.8 | 30.5 | 1910 | 57 | 2.3 | 3.5 | 4.378 | 0.169 |
| | 4 | 7.7 | 30.5 | 1840 | 107 | 2.3 | 15 | 5.83 | 0.027 |
| | 5 | 7.8 | 30.7 | 1850 | 114 | 2.3 | 15 | 6.03 | 0.04 |
| | 6 | 7.8 | 30 | 1880 | 153 | 2.4 | 15 | 5.03 | 0.03 |
| | 7 | 7.7 | 31.3 | 1940 | 83 | 2.8 | 17.5 | 5.93 | 0.03 |
| | 8 | 7.8 | 31.7 | 1930 | 66 | 3 | 16 | 6.114 | 0.03 |
| | 9 | 7.7 | 31 | 1940 | 48 | 2.5 | 20 | 6 | 0.034 |
| | 10 | 7.7 | 31.9 | 1890 | 32 | 2.9 | 15 | 5.724 | 0.004 |
| | 11 | 7.7 | 31.6 | 1880 | 55 | 2.3 | 15 | 5.802 | 0.004 |
| | 12 | 7.7 | 31.5 | 1900 | 66 | 1.9 | 15 | 4.856 | 0.004 |
| | 13 | 7.5 | 32.3 | 1860 | 45 | 2.5 | 37.5 | 5.466 | 0.089 |
| | 14 | 7.5 | 32.8 | 1890 | 39 | 2.7 | 37.5 | 5.537 | 0.272 |
| | 15 | 7.6 | 31.4 | 1900 | 46 | 3 | 25 | 4.78 | 0.08 |
| | 16 | 7.0 | 31.5 | 2490 | 45 | 2.8 | 25 | 3.28 | 0.004 |
| | 17 | 7.7 | 31.2 | 2480 | 39 | 2.9 | 25 | 3.353 | 0.004 |
| | 18 | 6.7 | 32 | 2470 | 46 | 2.8 | 25 | 3.257 | 0.004 |
| | Average | 7.6 | 31.3 | 1992.8 | 62.7 | 2.6 | 18.3 | 5.1 | 0.1 |
| | Standard Deviation | 0.291545 | 0.73308819 | 225.9309 | 32.03639 | 0.31086 | 9.846203 | 0.959455 | 0.07861 |

| | Efluent Sample | pH | Temp | TDS | Turb | DO | CN | AS | Fe |
|---|---|---|---|---|---|---|---|---|---|
| RBC | 1 | 7.1 | 30.5 | 1970 | 49 | 2.3 | 0.007 | 4.705 | 0.093 |
| | 2 | 7.3 | 31.3 | 1950 | 28 | 4.1 | 0.01 | 4.804 | 0.06 |
| | 3 | 7.4 | 30.4 | 1960 | 30 | 3.6 | 0.011 | 4.804 | 0.069 |
| | 4 | 7.4 | 31.6 | 1980 | 26 | 3.6 | 0.014 | 4.834 | 0.033 |
| | 5 | 7.2 | 30.6 | 1990 | 81 | 3.8 | 0.012 | 4.834 | 0.03 |
| | 6 | 6.8 | 30.8 | 1980 | 86 | 3.8 | 0.013 | 5.004 | 0.059 |
| | 7 | 7.1 | 31.1 | 2000 | 25 | 3.8 | 0.012 | 4.791 | 0.018 |
| | 8 | 7.3 | 30.5 | 1990 | 24 | 3.4 | 0.013 | 4.513 | 0.043 |
| | 9 | 7.6 | 33.3 | 1960 | 33 | 2.3 | 0.004 | 6.21 | 0.041 |
| | 10 | 7.5 | 30.8 | 1950 | 49 | 3.5 | 0.004 | 6 | 0.021 |
| | 11 | 7.5 | 31.7 | 1960 | 50 | 3.4 | 0.004 | 5.9 | 0.041 |
| | 12 | 7.4 | 31.5 | 1920 | 35 | 3.5 | 0.004 | 6.03 | 0.032 |
| | 13 | 7.3 | 31.8 | 1930 | 32 | 3.5 | 0.004 | 5.68 | 0.004 |
| | 14 | 7.2 | 32.4 | 1910 | 30 | 3 | 0.004 | 6.12 | 0.034 |
| | 15 | 7.3 | 32.5 | 1930 | 32 | 3.6 | 0.004 | 5.84 | 0.004 |
| | 16 | 7.4 | 32.2 | 1980 | 31 | 3.6 | 0.004 | 6.02 | 0.003 |
| | 17 | 7.7 | 32 | 2010 | 34 | 4.1 | 0.004 | 5.799 | 0.004 |
| | 18 | 7.7 | 0 | 2050 | 29 | 3.6 | 0.025 | 5.917 | 0.004 |
| | 19 | 7.7 | 32 | 2010 | 21 | 3.9 | 0.8 | 6.122 | 0.004 |
| | 20 | 7.8 | 31.9 | 1990 | 57 | 3.5 | 0.004 | 5.953 | 0.004 |
| | 21 | 7.7 | 31.8 | 1990 | 69 | 4 | 0.004 | 5.706 | 0.004 |
| | 22 | 7.7 | 32 | 1960 | 39 | 3.8 | 0.004 | 6.047 | 0.004 |
| | 23 | 7.8 | 32 | 1990 | 47 | 3.9 | 0.004 | 5.978 | 0.004 |
| | 24 | 7.8 | 31 | 2050 | 29 | 4 | 0.004 | 5.124 | 0.004 |
| | 25 | 7.6 | 32.4 | 1920 | 103 | 3.3 | 0.004 | 5.773 | 0.015 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 26 | 7.5 | 32.3 | 1950 | 69 | 3.1 | 0.004 | 5.826 | 0.004 |
| | 27 | 7.4 | 32.8 | 1970 | 75 | 3.5 | 0.004 | 5.564 | 0.004 |
| | 28 | 7.4 | 32.2 | 1950 | 52 | 3.9 | 0.004 | 5.446 | 0.004 |
| | 29 | 7.4 | 32.3 | 1940 | 53 | 3.7 | 0.004 | 5.535 | 0.004 |
| | 30 | 7.3 | 32.4 | 1960 | 58 | 3.6 | 0.004 | 5.435 | 0.004 |
| | 31 | 7.4 | 32.4 | 1960 | 72 | 3.2 | 0.004 | 5.515 | 0.004 |
| | 32 | 7.4 | 32.2 | 1970 | 68 | 3.6 | 0.004 | 5.212 | 0.004 |
| | 33 | 7.5 | 32.4 | 1960 | 30 | 3.3 | 0.004 | 4.893 | 0.043 |
| | 34 | 7.5 | 32.3 | 1900 | 23 | 3.1 | 0.004 | 5.367 | 0.015 |
| | 35 | 7.4 | 32.8 | 1910 | 32 | 3.5 | 0.004 | 5.328 | 0.043 |
| | 36 | 7.4 | 32.2 | 1920 | 34 | 3.9 | 0.004 | 5.03 | 0.004 |
| | 37 | 7.4 | 32.3 | 1950 | 30 | 3.7 | 0.004 | 4.759 | 0.004 |
| | 38 | 7.3 | 32.4 | 1930 | 19.7 | 3.6 | 0.004 | 5.378 | 0.017 |
| | 39 | 7.3 | 32.4 | 1970 | 18.3 | 3.2 | 0.004 | 5.313 | 0.015 |
| | 40 | 7.3 | 32.2 | 1930 | 19 | 3.6 | 0.004 | 5.445 | 0.004 |
| | 41 | 6.9 | 31.2 | 2470 | 19 | 5.9 | 0.13 | 3.727 | 0.004 |
| | 42 | 6.7 | 31.5 | 2490 | 20 | 5.2 | 0.13 | 3.544 | 0.004 |
| | 43 | 6.5 | 31.4 | 2490 | 23 | 5.2 | 0.13 | 3.553 | 0.004 |
| | 44 | 6.8 | 31.4 | 2489 | 25 | 5.4 | 0.13 | 3.701 | 0.004 |
| | 45 | 6.2 | 31.4 | 2450 | 23 | 5.3 | 0.13 | 3.601 | 0.004 |
| | 46 | 6.7 | 31.5 | 2480 | 26 | 5.3 | 0.13 | 3.751 | 0.004 |
| | 47 | 6.9 | 31.5 | 2490 | 34 | 5.2 | 0.13 | 3.612 | 0.004 |
| | 48 | 7.0 | 6.9 | 2450 | 29 | 5.3 | 0.13 | 3.606 | 0.045 |
| | **Average** | 7.3 | 30.6 | 2048.1 | 40.0 | 3.8 | 0.0 | 5.2 | 0.0 |
| | **Standard deviation** | 0.344375 | 5.8104634 | 196.1029 | 20.40649 | 0.77751 | 0.120947 | 0.819111 | 0.021489 |

| | Influent | pH | Temp | TDS | Turb | DO | CN | AS | Fe |
|---|---|---|---|---|---|---|---|---|---|
| Actiflo | 1 | 7.3 | 32 | 2020 | 47 | 3.5 | 0.01 | 5.799 | 0.004 |
| | 2 | | | | | | | | |
| | 3 | 7.3 | 32.1 | 1980 | 26 | 3.2 | 0.004 | 4.734 | 0.058 |
| | 4 | 7.4 | 30.5 | 1950 | 62 | 3.9 | 0.004 | 5.198 | 0.004 |
| | 5 | 7.2 | 31.2 | 1980 | 34 | 3.1 | 0.004 | 5.704 | 0.004 |
| | 6 | 7.1 | 31 | 2480 | 31 | 8.4 | 0.13 | 3.502 | 0.004 |
| | Average | 7.3 | 31.45 | 1982.5 | 42.25 | 3.425 | 0.0055 | 4.9874 | 0.0148 |
| | Standard Deviation | 0.114018 | 0.68044103 | 223.875 | 14.54304 | 2.246553 | 0.055739 | 0.933701 | 0.02415 |

| | Efluent Sample | pH | Temp | TDS | Turb | DO | CN | AS | Fe |
|---|---|---|---|---|---|---|---|---|---|
| Actiflo | 1 | 8.4 | 32.8 | 2020 | o.645 | 6.7 | 0.004 | 0.031 | 0.167 |
| | 2 | | | | | | | | |
| | 3 | 8.2 | 31.7 | 2030 | 0.093 | 6.8 | 0.004 | 0.105 | 0.012 |
| | 4 | 8.2 | 32.7 | 2031 | 0.065 | 7.1 | 0.004 | 0.33 | 0.11 |
| | 5 | 8.1 | 33 | 1950 | 0.07 | 6.9 | 0.004 | 0.04 | 0.004 |
| | 6 | 8.0 | 30.6 | 2440 | 0.07 | 8.4 | 0.13 | 0.155 | 0.045 |
| | Average | 8.2 | 32.55 | 2007.75 | 0.076 | 6.875 | 0.004 | 0.1265 | 0.0676 |
| | Standard Deviation | 0.148324 | 1.00647901 | 196.2096 | 0.012557 | 0.697854 | 0.056349 | 0.12158 | 0.069508 |

| Unit | Influent Sample | pH | Temp | TDS | Turb | DO | CN | AS | Fe |
|---|---|---|---|---|---|---|---|---|---|
| CIS | | 7.5 | 30.8 | 2003.3 | 75.2 | 2.7 | 18.4 | 5.1 | 0.0 |
| Settler | | 7.5 | 31.3 | 1995.0 | 40.0 | 2.6 | 18.9 | 5.7 | 0.1 |
| RBC | | 7.6 | 31.3 | 1992.8 | 62.7 | 2.6 | 18.3 | 5.1 | 0.1 |
| Actiflo | | 7.3 | 31.45 | 1982.5 | 42.3 | 3.4 | 0.0 | 5.0 | 0.0 |
| | | | | | | | | | |
| | | | | | | | | | |
| Unit | Effluent Sample | pH | Temp | TDS | Turb | DO | CN | AS | Fe |
| CIS | | 7.5 | 31.3 | 2000.0 | 31.2 | 2.6 | 18.3 | 5.3 | 0.0 |
| Settler | | 7.5 | 31.3 | 1995.0 | 40.0 | 2.6 | 18.9 | 5.7 | 0.1 |
| RBC | | 7.3 | 30.6 | 2048.1 | 40.0 | 3.8 | 0.0 | 5.2 | 0.0 |
| Actiflo | | 8.2 | 32.6 | 2007.8 | 0.1 | 6.9 | 0.0 | 0.1 | 0.1 |

## APPENDIX 2: Averages and standard deviations of influent and effluent wastewater for the units

| Operating Unit | | Influent pH | Stdev | | Effluent pH | Stdev |
|---|---|---|---|---|---|---|
| CIS | | 7.5 | 0.365 | | 7.5 | 0.337 |
| SETTLER | | 7.5 | 0.4 | | 7.5 | 0.439 |
| RBC | | 7.6 | 0.292 | | 7.3 | 0.344 |
| ACTIFLO | | 7.26 | 0.114 | | 8.2 | 0.148 |

| Operating Unit | | Influent Temp | Stdev | | Effluent Temp | Stdev |
|---|---|---|---|---|---|---|
| CIS | | 30.8 | 0.755 | | 31.3 | 0.715 |
| SETTLER | | 31.3 | 0.6 | | 31.3 | 0.717 |
| RBC | | 31.3 | 0.733 | | 30.6 | 5.81 |
| ACTIFLO | | 31.4 | 0.68 | | 32.6 | 1.006 |

| Operating Unit | | Influent TDS | Stdev | | Effluent TDS | Stdev |
|---|---|---|---|---|---|---|
| CIS | | 2003.3 | 250.33 | | 2000 | 238.24 |
| SETTLER | | 1995 | 237.3 | | 1995 | 224.85 |
| RBC | | 1992.8 | 225.93 | | 2048.1 | 196.1 |
| ACTIFLO | | 2480 | 196.21 | | 2007.8 | 196.21 |

| Operating Unit | | Influent Turb | Stdev | | Effluent Turb | Stdev |
|---|---|---|---|---|---|---|
| CIS | | 57.8 | 21.135 | | 19.4 | 5.94 |
| SETTLER | | 40 | 9.1 | | 40 | 10.291 |
| RBC | | 50.3 | 13.1 | | 38.4 | 18.747 |
| ACTIFLO | | 40 | 0.013 | | 0.1 | 0.013 |

| Operating Unit | | Influent DO | Stdev | | Effluent DO | Stdev |
|---|---|---|---|---|---|---|
| CIS | | 2.7 | 0.398 | | 2.6 | 0.417 |
| SETTLER | | 2.6 | 0.4 | | 2.6 | 0.248 |
| RBC | | 2.6 | 0.311 | | 3.8 | 0.778 |
| ACTIFLO | | 4.4 | 0.698 | | 6.9 | 0.698 |
| | | | | | | |

| Operating Unit | | Influent Cyanide | Stdev | | Effluent Cyanide | Stdev |
|---|---|---|---|---|---|---|
| CIS | | 18.4 | 8.558 | | 18.3 | 9.076 |
| SETTLER | | 18.9 | 8.5 | | 18.9 | 11.225 |
| RBC | | 18.3 | 9.846 | | 0 | 0.121 |
| ACTIFLO | | 0 | 0.056 | | 0 | 0.056 |

| Operating Unit | | Influent Arsenic | Stdev | | Effluent Arsenic | Stdev |
|---|---|---|---|---|---|---|
| CIS | | 5.1 | 0.882 | | 5.3 | 1.021 |
| SETTLER | | 5.7 | 1.3 | | 5.7 | 0.844 |
| RBC | | 5.1 | 0.959 | | 5.2 | 0.819 |
| ACTIFLO | | 5 | 0.122 | | 0.1 | 0.121 |

| Operating Unit | | Influent Fe | Stdev | | Effluent Fe | Stdev |
|---|---|---|---|---|---|---|
| CIS | | 0 | 0.02 | | 0 | 0.061 |
| SETTLER | | 0.1 | 0.1 | | 0.1 | 0.089 |
| RBC | | 0.1 | 0.079 | | 0 | 0.021 |
| ACTIFLO | | 0 | 0.069 | | 0.1 | 0.07 |

**APPENDIX 3: pH variation with the corresponding percentage removals**

| pH | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|
| Influent | 5.13 | 4.91 | 4.72 | 5.61 | 5.63 | 4.12 | 4.34 | 5.13 |
| Effluent | 1.62 | 1.72 | 1 | 0.2 | 0.031 | 0.033 | 0.029 | 0.42 |
| % removal of arsenic | 68 | 65 | 79 | 96 | 94 | 99 | 99 | 92 |