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DISSOLVED AIR FLOTATION PROCESS FOR ALGAE REMOVAL IN SURFACE WATER TREATMENT IN KENYA

BY

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BY

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DECLARATION

This Thesis is my original work and has not been submitted for a degree in any other university.

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This Thesis has been submitted for examination with my approval as University Supervisor.

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DEDICATION

To my Mum, Dad, my brother, sisters and Pam, for their support and encouragement during the entire challenging research study period.

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To all may God bless you with his unlimited bountifulness.

ABSTRACT

DISSOLVED AIR FLOTATION PROCESS FOR ALGAE REMOVAL IN SURFACE WATER TREATMENT IN KENYA

Sedimentation is the most widely used primary clarification stage before rapid gravity sand filtration for the production of potable water in most water supplies in Kenya. Algae form low density particles which exist in a colloidal state and have a tendency to float, hence cause solid-liquid separation problems in the sedimentation stage. Raw water which is algal laden is difficult to clarify by sedimentation because gravitational forces are largely ineffective due to algal stability. There is therefore an inherent need to look for a suitable unit process to solve the algae removal problem.

This study has investigated the performance of the Dissolved Air Flotation (DAF) process as a suitable alternative to sedimentation for algae removal in surface water treatment in Kenya. Batch DAF experiments were carried out in the laboratory using algal laden surface water samples collected from the Athi river and other sources in addition to laboratory cultured algae water samples. The performance and effectiveness of the process have been assessed for algae and turbidity removal and colour improvement.

Experimental results show that clarification of surface water laden with blue-green, green, diatom and dinoflagellate algae types in the batch bench scale DAF model is effective. The results suggest that at optimum coagulant dose, algae removal of between 70%- 90%, turbidity reduction by over 80% and colour improvement of above 75% can be achieved with the batch DAF system.

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ABBREVIATIONS AND SYMBOLS

DAF Dissolved Air Flotation

EOM Extracellular Organic Matter

Rr Recycle ratio = $\left(\dfrac{\text{Recycle stream volume}}{\text{Raw water influent volume}}\right) x\,100\%$

NTU Nephelometric Turbidity Units

MOWD Ministry of Water Development

mV Millivolts

TARDA Tana River Development Authority

EOM Extra cellular Organic Matter

kPa Kilo Pascals

Psig Pounds per square inch

μm Micrometre

JKUAT Jomo Kenyatta University of Agriculture and Technology

nm Nanometre

1 INTRODUCTION

1.1 General

Today in water treatment practice, engineers and water treatment experts are being forced to evaluate and consider non-conventional water treatment processes. This has been brought about as a result of the changing nature of raw water characteristics due to the influence of humankind on the environment. Additionally, the implementation of new and more stringent drinking water regulations, increasing public concern and awareness over the safety of drinking water, the ever increasing treatment plant construction costs and the emergence of new water treatment technologies increase the likelihood of such scenarios. Dissolved air flotation is one such technology that is fast gaining a foothold in water clarification because of its attractive advantages [Gregory, 1997].

Prior to the 1900's flotation was much regarded as an art. However, in the foregoing years and particularly after 1976, a lot of research and development has been carried out on the flotation process, with plenty of experience being gained from existing operational plants. Most of the research findings have been published and experience from existing plants has confirmed that flotation is actually a science [Gregory, 1997].

Flotation is a solid-liquid or a liquid-liquid separation procedure which is applied to particles whose density is lower or has been made lower than that of the liquid in which they are dispersed. Flotation separation can be defined as the transfer of solids from the body of the liquid to the surface by means of attachment to bubbles. It is based on the capacity of certain solids or liquid particles to link up with air bubbles to form "particle-gas bubble" composites with a density less than that of the liquid in which they form the dispersed phase [Degremont, 1991].

Flotation can generally be classified into three types [Flotation Information Forum, 1999]:-

1. Natural flotation which occurs if the difference in density is naturally sufficient for separation.
2. Aided flotation which occurs when external means are used to promote the separation of the particles that are naturally floatable.

3. Induced flotation which occurs when the density of a particle which is originally higher than that of the liquid is artificially lowered through formation of a less dense particle-gas bubble composite and thus leading to separation.

In the field of water treatment, induced flotation has found wide usage especially utilizing very fine air bubbles or microbubbles akin to those found in water running from a tap on a high pressure main, to aid in the formation of the particle-gas bubble composites. This process is commonly referred to as Dissolved Air Flotation (DAF) [Degremont, 1991].

Dissolved air flotation has been used successfully over the years in the clarification of algae laden waters all over the world [Gregory, 1997]. Research carried out on the process has demonstrated the effectiveness of DAF in the removal of algae in water treatment. Van Vuuren and Botes [1991] when carrying out a study on the application of DAF in the treatment of eutrophic water from lake Nsese in South Africa, concluded that DAF was the most efficient unit process to deal with algae related problems. Edzwald and Wingler [1990] when looking at the chemical and physical aspects of DAF flotation for the removal of algae, observed that the turbidity and algae count data indicated lower turbidities and better removals of algae using DAF than with conventional treatment. Vlaski *et al* [1997] when studying algae laden water treatment by DAF, concluded that optimal coagulant dose for DAF was in the range of two to three times lower than that for full scale sedimentation. Algae removal was found to be very effective and appropriate even at these low coagulant doses. DAF has thus proved to be an efficient process for particulate removal and this has led to its wide use all over the world.

There is however no recorded use of DAF for water treatment in Kenya. The research study hopes to investigate DAF viability in Kenya, particularly in the clarification of problematic algal laden waters.

1.2 Research Interest

During a recent seminar on *Floc Blanket Clarifiers and Dissolved Air Flotation Process in Water Treatment* held at the University of Nairobi on 30th July 1999, it became clear that a number of water works in Kenya are experiencing problems with algae in their treatment process . This was due to the fact that algae cannot be effectively removed by the conventional sedimentation process owing to their floating characteristics. Of particular interest was Wamunyu water supply where the algae problem had got out of hand rendering the treatment process at the works difficult. In addition several other key water treatment works including Kisumu Water works, Mbuhuni water supply and Kabaa water supply are reported to be experiencing similar problems.

In Kenya, sedimentation is the most widely used primary clarification stage before rapid gravity filtration in the production of potable water. Algae form low-density particles which have a tendency to float and hence are bound to cause problems in the sedimentation stage. Raw water which is algal laden is thus difficult to clarify by conventional means because gravitational sedimentation forces which are important for the sedimentation process will be ineffective. Additionally, algae form very light flocs which settle very slowly.

There is therefore the need to find a suitable alternative to sedimentation for use in the clarification of algae laden surface waters in Kenya. The search for a suitable method for the removal of algae in water was the driving force behind this research.

1.3 Research Approach

A Bench scale model was set up at the University of Nairobi, Department of Civil Engineering, Environmental Health Engineering laboratory to simulate the DAF process and experiments carried out on laboratory cultured algae water samples and surface water samples collected from several sources. Data generated from the above experiments was then analysed for algae removal, turbidity removal and colour improvement.

2 LITERATURE REVIEW

2.1 Algae and its Properties

2.1.1 General

All surface water supplies support the growth of minute aquatic organisms. The free swimming and floating organisms are called plankton and are of great importance in water treatment technology. The plankton are composed of floating animals or zooplankton and floating plants or phytoplankton. The latter are predominantly algae and cyanobacteria and since they are chlorophyll-bearing organisms their growth is influenced greatly by the amounts of fertilising elements in water.

Algae are by definition unicellular or multicellular autotrophic photosynthetic protists. The term "algae" derived from the Latin name for sea wrack has come to be applied to all relatively simple marine and fresh water vegetation [Prescott, 1977].

Included under algae are the smallest and most simple of chlorophyll bearing organisms. The entire plant may be comprising of only a single cell, which could be less than 1 micron in diameter. However, on the other extreme some brown algae are known to be some of the longest plants in the world [Prescott, 1977].

2.1.2 Fresh water algae

Though minute, fresh water algae generate a lot of interest because they have many economic importance's and biological significance. Algae play important roles in reservoirs and lakes in the cycling of nutrients and other constituents as part of a food chain. Some algae types are pathogenic to man, producing endotoxins that can cause gastro-enteritis while others interfere with treatment plant operations. These constitute just a few of the many reasons which lead to a study of them.

The primary classification of fresh water algae is based on five main criteria [Morris,1976] :-

(i) Photosynthetic pigments

(ii) Nature of food reserves

(iii) Nature of cell wall components

(iv) The types of flagella

(v) Certain details of the cell structure

After consideration of the above algae are classified into various phyla. Generally the phyla of fresh water algae are recognised as follows [Prescott,1977]:-

a) Chlorophyta - Green algae
b) Cyanophyta - Blue green algae
c) Chrysophyta - Yellow-green algae
d) Euglenophyta - Euglenoids
e) Cryptophyta - Cryptomonads
f) Pyrrophyta - Dinoflagellates
g) Rhodophyta - Red algae
h) Chloromonadophyta- Chloromonads
i) Phaeophyta - Brown algae

Algae from the various phyla show striking differences in colour and these often afford a quick guide to preliminary classification of alga. However, the colour frequently varies with changes in environmental conditions and an accurate classification depends on chemical analyses of the photosynthetic pigments.

There are three kinds of photosynthetic pigments in algae. Chlorophylls, carotenoids and biloproteins and the distribution of these is important in algal classification.

Chlorophylls extracted from different algae show different spectral properties. On this basis a number of different chlorophylls have been recognised and have been termed chlorophylls a,b,c,d and e.

The distribution of these chlorophylls amongst various algal groups is as shown in Table 2.1:-

TABLE 2.1 The Distribution of Photosynthetic Pigments in Algae [Morris, 1976].

	Cyanophyta	Cholorophyta	Xanthophyta	Chrysophyta	Bacillariophyta	Pyrrophyta	Crytophyta	Euglenophyta	Phaeophyta	Rhodophyta
Chlorophylls										
Chlorophyll a	+	+	+	+	+	+	+	+	+	+
Chlorophyll b	+	-	-	-	-	-	-	+	-	-
Chlorophyll c	-	-	?	+	+	+	-	+	-	-
Chlorophyll d	-	-	?	-	-	-	-	-	-	+
Chlorophyll e	-	+	-	-	-	-	-	-	-	-

\- Absent

\+ Present ? No scientific evidence has been found

The three chlorophylls commonly found in planktonic algae are chlorophylls a, b and c. Chlorophyll a is present in all algae, constitutes approximately 1 to 2 % of the dry weight of organic material in all planktonic algae and is, therefore, the preferred indicator for algal biomass estimates [Morris, 1976].

The molecular structure of chlorophyll a is as shown in Figure 2.1 below and the major components are carbon and hydrogen although magnesium, oxygen and nitrogen are also present :-

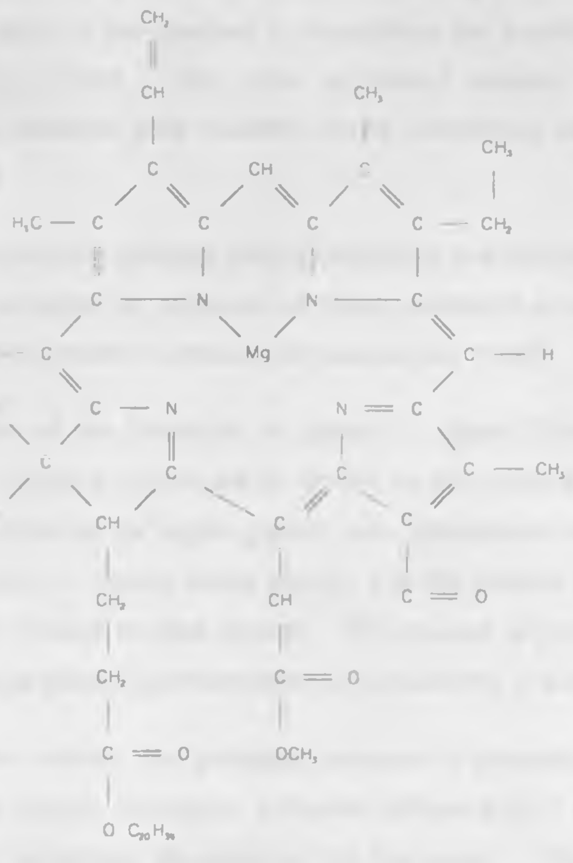


FIGURE 2.1 The Molecular Structure of Chlorophyll-a [Dust and Shindala, 1970]

2.1.3 Conditions suitable for algae to thrive

Various species of algae are reported to grow in different conditions. However, algae basically requires air, water and sunlight for its growth. Algae reproduce through four different methods [Morris,1976] :-

1) Vegetative reproduction
2) Asexual reproduction

3) Sexual reproduction
4) Germination of the zygote.

In nature, rarely a single algae species exists alone in a given habitat. A mixture of algae species compete and survive within the limits set by the environment. All algae require high temperatures, optimum pH and alkalinities, adequate macronutrients such as Carbon, Nitrogen, Phosphorus, low turbidities, large surface area, shallow depths and sunlight for their metabolism. For algae to grow these macronutrients must be available in sufficient quantities, lack of any one nutrient will limit total algal population. However, different species of algae thrive best under different habitats.

The relative success of a pair of species competing for the same substrate is a function of the ability of the species to metabolise the available food nutrients and adapt to a given habitat. The more successful species will be the one that metabolises the available food nutrients more completely and adapts best to the particular habitat.

Research has shown that nitrogen and phosphorous are both essential for the growth of algae. The limitation in amounts of these elements is usually the factor that controls their rate of growth [Cornwell and Mackenzie, 1998].

When *Liebigs law of the minimum* is applied to algae [Cornwell and Mackenzie, 1998], it means that algal growth will be limited by the nutrient that is least available. Of the nutrients required for algae growth, only phosphorus is not readily available from the atmosphere or natural water supply. For this reason phosphorus is deemed to be the limiting nutrient in algal growth. The amount of phosphorus thus controls the quantity of algal growth and therefore the productivity in surface water.

For many surface waters, the principal sources of phosphorus are the result of human activity including municipal, industrial effluents and agricultural runoff that carries fertilisers containing phosphorus into the water. Where both nitrogen and phosphorous are readily available algal blooms occur.

2.1.4 Effects of algae on surface water pH

In many surface waters that support extensive algae blooms and where algae exhibit rapid growth, pH values as high as 10 have been observed [Sawyer *et al.*, 1994]. Algae use carbon dioxide in their photosynthetic activity and this removal is responsible for such high pH conditions.

Algae can reduce the free carbon dioxide concentration to below its equilibrium concentration with air and consequently can cause an even greater increase in pH. As the pH increases the alkalinity forms change with the result that carbon dioxide can also be extracted for algal growth from bicarbonates and carbonates present in the water [Sawyer *et al.*, 1994].

Algae will continue to extract carbon dioxide from the water until an inhibitory pH is reached which is usually in the range of pH 10 to 11.

During the dark hours of the day algae produce rather than consume carbon dioxide. This is because their respiratory process in the darkness exceeds their photosynthetic processes. This carbon dioxide production has the opposite effect and tends to reduce the pH. Diurnal variations in pH due to algal photosynthesis and respiration is common in surface waters [Sawyer *et al.*, 1994].

2.1.5 Effects of algae on surface water Treatment

Research has shown that algal laden water can impact in many ways on treatment works processes, treated water quality and may result in the following [Schofield *et al*, 1997]:-

- High associated zooplankton populations.
- Increased available organic carbon in supply.
- Requirement for pH correction.
- Increased coagulant usage.
- A potential to shield bacteria from disinfection.
- Increased chlorine demand.
- Taste and odours.
- Filter penetration or binding hence clogging.

As a result the amount of algae entering any treatment process has to be controlled if not outrightly eliminated.

2.1.6 Techniques of algae control and removal

Due to the undesirability of prolific algal blooms, methods aimed at either removal or control of algae have been investigated. Apart from the chemical destruction of algae several other removal methods have been studied and proposed including centrifugation, microstraining, dissolved air flotation and filtration.

Algae exist as low-density particles which have a tendency to float. The floating and colloidal properties of algae and subsequent light nature of flocs produced after coagulation render algae laden water suitable for flotation. This together with the desire to minimise disinfection by-products and reduce chlorine usage have led to consideration of Dissolved Air Flotation as an alternative to sedimentation in the clarification of such waters.

Janssens and Buekens [1993] presented a selection diagram which could be used as a guide for the selection of a floc separation method based on the raw water quality (Figure 2.2). The diagram is based on suspended solids and algae to define the different possible treatment configurations. Raw water suspended solids is expressed in turbidity units (NTU) and the trophic state or the amount of algae in the water characterized as algal biomass, expressed as chlorophyll-a concentration.

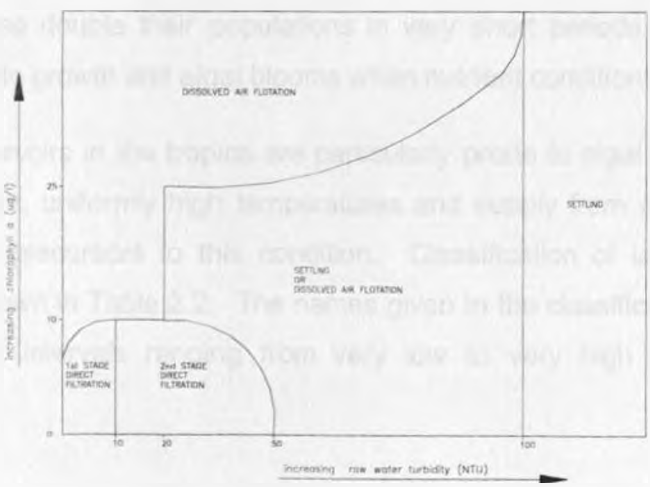


FIGURE 2.2 Floc separation processes selection diagram [Janssens and Buekens, 1993].

2.2 The Kenyan experience

In the recent years a number of researchers have reported that surface waters in Kenya have been experiencing a lot of pollution and this has led to eutrophication in receiving water bodies. This is thought to be as a result of untreated industrial effluent discharges to rivers and streams, effluents from ill operated Sewerage treatment works and the more common non-point sources from extensive agricultural activity which is the backbone of the Kenyan economy.

This presents a worrying trend for our surface waters if the situation is not checked and rectified. In rivers and lakes, eutrophication promotes phytoplankton growth leading to algal blooms.

The tropical climate also facilitates the rapid growth of algae in our surface waters. Plenty of sunlight and resultant high temperatures affects the physical and biological processes in water bodies and therefore the concentration of many variables. The metabolic rate of aquatic organisms is also related to the temperatures. As the temperature increases, respiration rates increase leading to increased oxygen consumption and increased decomposition of organic matter [Chapman and Hall, 1992]. Temperature also increases growth rates particularly of bacteria and phytoplankton, these double their populations in very short periods increasing the turbidity, macrophyte growth and algal blooms when nutrient conditions are suitable.

Surface water reservoirs in the tropics are particularly prone to algal blooms. Long exposure to sunlight, uniformly high temperatures and supply from eutrophic rivers are thought to be precursors to this condition. Classification of lakes based on trophic levels is shown in Table 2.2. The names given in the classification represent empirically defined intervals ranging from very low to very high productivity of biomass.

TABLE 2.2 Trophic states of surface water lakes [Chapman, 1992]

Trophic Category	Annual mean Chlorophyll (mg/m^3)	Chlorophyll Maxima (mg/m^3)	Remarks
Ultra- oligotrophic	1 [1]	2.5 [1]	
Oligotrophic	2.5	8.0	Lakes of low primary productivity and low biomass associated with low concentrations of Nutrients (N and P).[1]
Mesotrophic	2.5 - 8	8 - 25	Less well defined than either Oligotriphic or Eutrophic lakes and are generally thought to be lakes in transition between the two conditions.[1]
Eutrophic	8 - 25	25 - 75	Lakes which display high concentrations of nutrients and associated high biomass production, usually with a low transparency.[1]
Hypertrophic	25	75	Lakes at the extreme end of the euthrophic range with exceedingly high nutrient concentrations and associated biomass production.[1]
Lake Victoria in East Africa.	16.7	25.4	This lake is of critical importance since it supplies water works in Kampala City, Uganda and Kisumu and Mwanza which are important Comercial centres in Kenya and Tanzania respectively with raw water for treatment.[2]

Source 1 : Chapman [1992]
Source 2: Republic of Kenya [1988]

Lake Victoria is the second largest fresh water lake in the world and is of critical importance to the East African region. Kampala City and other smaller towns in Uganda and Kisumu in Kenya depend on this lake for their water supplies. A comparison of the various trophic states of the surface water reservoirs and Lake Victoria shows that it borders to the eutrophic stage. The raw water from Lake Victoria has moderate to high chlorophyll levels and is bound to present problems at the treatment stage if appropriate unit processes are not utilised.

Given these conditions in our rivers and surface reservoirs, it is therefore not suprising to encounter problems related to algal blooms in a number of water treatment works. In Kenya for example, most water treatment works use conventional sedimentation to clarify raw water. And thus in the event of appreciable algal concentrations, are unable to cope with the problem of algae removal in the clarification stage.

A number of Water treatment works now face problems caused by the presence of algae . Algae is reported to cause nuisance both in the water treatment and the distribution systems. Furthermore production of toxins by specific algae and secondary effects of high zooplankton growth have posed a potential danger for public health in these areas. The following are some of the documented cases.

2.2.1 Wamunyu Water Supply

Wamunyu Water Supply Treatment Works was built by the Ministry of Water Resources in 1974 and is situated in Machakos District north of Wamunyu Trading Centre. The area around Wamunyu town is relatively dry and prior to construction of the waterworks people had to trek for many kilometres in search of drinking water.

Wamunyu Water Works draws its raw water from the Athi river. Raw water from the Athi River is characterised by both high levels of sediment and an increasingly high industrial and municipal wastewater effluent load which is dependant on climatic conditions.

During the wet season (April-June and October-November) the raw water is very turbid, has a lot of suspended material and is characterised by a reddish brown colour. This is because of the heavy silt load carried upstream from the broad catchment area.

Whilst the available data is somewhat limited, it is sufficient to confirm that the Machakos region probably represents the major source of sediment with significant but unquantified contributions from the Kiboko and lower catchment. On the basis of a gauging programme instigated by Tana River Development Authourity (TARDA), the sediment load in the middle reaches of the Athi immediately below the Thwake confluence has been estimated to be at least 8.5 million tonnes/year. Clearly sediment loads of this magnitude are highly consequential to the design of any river developments on the Athi [Tana,1981].

With regard to bio-chemical water quality the dominant factor is the discharge of effluents in the upper catchment. The primary source of the effluents is the Nairobi City Sewerage Works, but there are also a number of other contributors including various industrial and agricultural processing plants in the Nairobi/Thika area. It is considered that fertilizer wash-out from farms may also be a significant contributor to the high effluent loads in the river.

Under drought conditions it is already not uncommon for these effluent discharges to make up the major part of the river flow in the upper catchment and with the continuing development of the Nairobi/Thika region. This bio-chemical pollution can be expected to steadily increase [Tana, 1981]. During the dry season therefore, the raw water from the Athi River becomes relatively less turbid. However it is characterized by having high concentrations of dissolved salts particularly of nitrites and phosphates from effluents and wash-out from agricultural activities as mentioned earlier. Evidence of this can be seen from results of the Wamunyu samples tested during the study in Table 2.2. Because of this phenomenon the water in the river is characterized by algal blooms in the dry spell months of the year (plates in Appendix 4).

Wamunyu Water Works employs the conventional treatment plant process i.e. Coagulation/Flocculation, Sedimentation, Filtration and finally Disinfection.

The water works experiences a lot of problems with algae removal particularly in the dry spell months of the year as it cannot be effectively removed through sedimentation. The result has been frequent shocks to the pumping plant as well as shorter filter runs because of frequent filter clogging. There is also heavy usage of chlorine to try and suppress algae growth in the treatment units.

This problem has been further worsened by the present *la-nina* phenomenon where the extended dry spell and drought conditions led to algae thriving to reach uncontrollable levels. During these periods the treatment works operators were forced to work long tedious hours to manually skim the algae scum from the treatment units but this had little or no appreciable effect. Shorter filter runs due to clogging in addition to production of unwholesome water with distinct green colour were a common occurrence. [Ministry of Water Development, 1999].

These prevailing conditions have made water treatment at Wamunyu Waterworks quite difficult and very expensive as a lot of chemicals are used in order to produce water of reasonable quality.

2.2.2 Kisumu Water Supply

Kisumu water works is located in Kisumu town about 500 km north-west of Nairobi. The treatment works gets water from Lake Victoria and employs conventional treatment process with vertical upward flow clarifiers.

During the refurbishment of Kisumu water treatment works in 1986/87, the existing vertical flow clarifier tanks were modified through three different configurations (with dispersion cone and lamella plates, without dispersion cone and lamella plates, and with dispersion cone but no lamella plates) [Republic of Kenya, 1988].

Refurbishment works were meant to improve the flow distribution at the inlet of the clarifiers. One was by converting the clarifier base from square to circular and installation of the dispersion cones and secondly by installation of lamella plates aimed at controlling the density currents. However, the clarifiers are still prone to the regular floc carryover to the filters during similar periods before the refurbishment. This may be attributed to among other things the raw water characteristics which the floc blanket clarifiers have some deficiencies in achieving the expected effluent quality especially during long bright sunshine hours.

The raw water quality characteristics can be described in general terms as a moderately conductive, very soft, alkaline with low alkalinity, moderately turbid (a mean of 15.2 NTU and standard deviation of 6.0), pH mean of 7.9 and temperature of 26.2°C. The chlorophyll content of the water has a mean minimum of 11.5 mg/m^3 to a mean maximum of 25.4 mg/m^3 with an average of 16.7 mg/m^3 [Nyangeri, 1998]. The algae-laden waters has total algae lower in the wet season (green algae) than in the dry season while the reverse is indicated for zooplankton [Republic of Kenya, 1988].

Algae-laden lake supplies cause sun floc to rise in the clarifier during the bright sunlight hours. The sunrays activate the algae-infested floc producing gas bubbles, which cause floc particles to rise and overflow at the surface. More gas produced by photosynthesis, attaches to flocs at higher temperatures causing algae flotation and thus impairing settling. A possible immediate option which is recommended to reduce the problem of floc carryover include covering the top of the clarifier to avoid direct sunlight rays penetrating deep into the clear surface water and activate the algae-infested flocs [Nyangeri, 1998]. Recent researchers have however proved that floc blanket clarification is not an effective treatment process for algae-laden waters with low turbidity. In these cases dissolved air flotation has proven to be the best available technology [Gregory, 1997; Finlayson and Huijbregsen, 1997; Adkins, 1997].

2.3 Theory of dissolved air flotation

2.3.1 General

Dissolved air flotation also referred to as the "Sveen-Perdersen" process was patented and first introduced in the 1920's as a process for recovery of fibres and to treat "white water" in the pulp and paper industry. Since then the process has become well established in water treatment [Flotation Information Forum, 1999].

Dissolved air flotation is a unit operation used to separate solid or liquid particles from a liquid phase. Separation is brought about by introducing fine gas (usually air) into the liquid phase. This is normally accomplished by introducing pressurised recycle water, saturated with air, to atmospheric pressure, thereby releasing the dissolved-air and producing fine air bubbles. The bubbles generated attach to the particulate matter reducing their specific gravity and the buoyant force of the combined particle-gas bubbles composite is great enough to cause the particle to rise to the surface, enhancing flotation separation.

At present applications of DAF in water treatment include:-

- Separation of flocculated matter in clarification of surface water.
- Separation and recovery of fibres in pulp and paper mill effluents.
- Separation of flocculated or non-flocculated oils in waste waters from refineries, airports and steelworks.
- Thickening of sludge from biological waste water treatment or from drinking water clarification.

DAF process is generating a lot of interest and is currently receiving much attention as an effective process for solid-liquid separation in water technology.

Zabel [1985] reported that in the United Kingdom 20 plants were in use or under construction. In Sweden DAF has gained widespread acceptance and in Finland there were 36 plants which use the process within their treatment chain [Klute *et al*, 1995]. According to Janssens [1992], DAF is receiving attention in Belgium, France, Netherlands and Europe as a whole. Cases of successful use of the process in the Americas, the Far East and Australia have also been reported. On the African continent [Haarhoff and Van Vuuren, 1995] reported that dissolved air flotation had been used successfully in South Africa for more than 25 years in the field of water and wastewater treatment. In fact they have had such notable success in South Africa that a South African Design Guide for Dissolved Air Flotation Plants had been published.

DAF provides an alternative clarification technique to sedimentation and is particularly attractive for relatively small particles and for particles with a density close to that of water. With flotation the loading rates are not directly related to the suspension characteristics so it is usually possible to provide short retention periods whilst still obtaining good clarification [Tebbutt, 1983]. The principle advantage of flotation over sedimentation is that small, light and colloidal particles that settle slowly can be removed more completely and in a shorter period.

2.3.2 Stability of Colloids and Colloidal particles

Colloidal dispersions consist of discrete particles that are separated by the dispersion medium. The particles maybe aggregates of atoms, molecules or mixed materials that are considered larger than individual atoms or molecules but are small enough to possess properties greatly different from coarse dispersions [Sawyer *et al.*, 1994]. Colloidal particles normally range in size from about 0.001 to about 1 micrometer (μm). Due to their size, the surface area in relation to mass of colloidal particles is so large that surface phenomenon predominate and control the behaviour of colloidal suspensions. The mass of colloidal particles is so small that gravitational effects are negligible. This is why settling is ineffective with colloidal dispersions [Sawyer *et al.*, 1994].

All colloidal particles are electrically charged. The charge varies considerably in its magnitude with the colloidal material and may be positive or negative. Many colloidal dispersions are dependent upon the electrical charge for their stability. Like charges repel, similarly charged colloidal particles cannot come close enough together to agglomerate into larger particles. And thus stay dispersed in solution [Unit Processes Lecture notes, 1999].

Colloids have large surface area and also great adsorptive powers. Adsorption is normally preferential in nature some ions being chosen and others excluded. The selective action yields charged particles and is the fundamental basis of the stability of colloids.

Colloidal dispersions of solids in liquids, often referred to as suspensoids are generally of two types. Those that bind strongly with the liquid are generally more stable and difficult to separate from the liquid than those that do not. Colloids that bind strongly with water are termed hydrophilic or water loving and those that do not are termed hydrophobic or water hating [Sawyer *et al.*, 1994].

Hydrophobic colloids are all electrically charged and the primary or surface charge may be developed in several ways. The sign and magnitude of the primary charge is a function of the character of the colloid, the pH and general ionic characteristics of the water. A lower water pH tends to make colloids more positive or less negative.

The natural colloids in water and wastewater are not always well defined hydrophobic sols but they do lend themselves to separation when treatment plant designed to remove hydrophobic suspensoids is used. The natural colouring matter of surface waters and the colloidally suspended matter of domestic wastewaters are examples of quasi-hydrophobic hydrophilic negatively charged colloids encountered in our day to day life [Sawyer *et al.*, 1994].

The stability of hydrophobic colloids depends upon the electrical charge that they possess. The primary charge results from charged groups within the particle surface in combination with that gained by adsorption of a layer of ions from surrounding medium as seen in Figure 2.3.

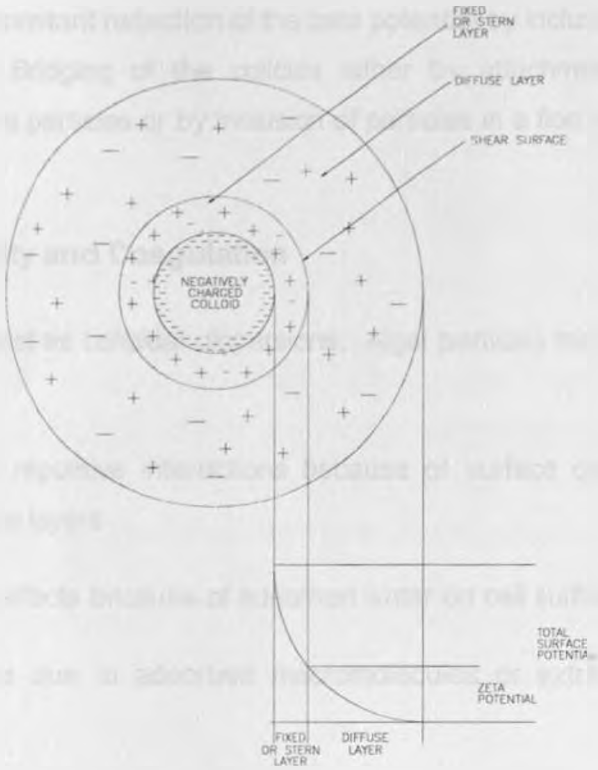


FIGURE 2.3 Electrical Double Layer of a Negatively Charged Colloid [Sawyer *et al.*, 1994]

Due to the primary charge on the particle an electric potential exists between the surface of the particle and the bulk of the solution. The charge is a maximum at the particle surface and decreases with distance from the surface. When two colloidal particles, of similar primary charge approach each other, their electrical double layers begin to interact. As they come closer the similar primary charges they possess results in repulsive forces. The closer the particles the stronger the repulsive forces.

The above repulsive forces which keep particle from aggregating are counteracted to some degree by an attractive force termed Van der waals force. All colloidal particles possess this attractive force regardless of charge and composition. The magnitude of this force is a function of the composition and density of the colloid but is independent of the composition of the aqueous phase. The Van der waals force decreases rapidly with increasing distance between particles [Sawyer *et al.*, 1994].

When in aqueous solution, colloidal particles develop electrical charges at the water-particle interface [Committee report, 1971] thus the particles remain dispersed indefinitely when the forces of repulsion exceed the attraction forces and the particles cannot coalesce [Hammer, 1986]. Destabilization of the colloids can be enhanced by one of the three primary physio-chemical phenomena or by some combination thereof. These include:- (1) Specific ion adsorption; (2) Compression of the diffuse double layer and concomitant reduction of the zeta potential by inclusion of indifferent electrolytes; and (3) Bridging of the colloids either by attachment of polymeric species on two or more particles or by inclusion of particles in a floc mass [Posselt *et al.*, 1968].

2.3.3 Algal stability and Coagulation

Algae laden waters exist as colloidal dispersions. Algal particles may be stable from [Edzwald, 1993]:-

- Electrostatic repulsive interactions because of surface charge producing diffuse double layers
- Hydrophillic effects because of adsorbed water on cell surfaces and
- Steric effects due to adsorbed macromolecules or extracellular organic matter.

Ives [1959] described the electrokinetic properties of algae, and the significance of algae surface charge in coagulation and flocculation. He showed that algae are electronegative for all pH conditions investigated of pH 2.5 to 11.5. Thus algae carry a negative surface charge contributing to practical stability and hindering flocculation. While surface charge is an important property of algae affecting its stability as a particulate suspension, other factors were also found to be important.

One such important parameter is the extracellular organic matter (EOM). Algae during growth excrete polysaccharides, pectins, lipoproteins and polyamino acids. The amount and structure of EOM adsorbed on algal surfaces or released to bulk solution depend on algal type and growth phase [Lusse *et al.*,1985; Bernhardt *et al.*,1986; Bernhardt and Clasen, 1991]. The EOM may cause stability because of steric effects or may aid flocculation through interparticle bridging depending on the ionic strength and Calcium concentration.

Edzwald *et al.*, [1990] have developed a conceptual model describing particle removal by DAF for water treatment. It is based on the single collector particle-deposition modelling approaches used in air and water filtration.

In the model the removal of particles by rising air bubbles in a DAF process is modelled as a two-step process i.e. particle transport to the bubble surface and attachment to the bubble. The removal efficiency of particles by a single bubble is expressed by [Edzwald *et al.*, 1990]:-

$$R = \alpha_{pb} \times \eta_T \ (100\%) \qquad \text{equation 2.1}$$

Where α_{pb} is the attachment efficiency of particle-bubble collisions and η_T is the total single collector (bubble) collision efficiency due to transport of particles to the bubble surface by brownian diffusion, interception and gravity sedimentation. Due to particle-bubble interactions involving small bubbles and small particles, the attachment efficiency is the resultant of two causes: electrical-charge interactions between particles and bubbles and a displacement of the water layer surrounding the particles from successful collisions between particles and bubbles.

A performance equation for batch condition as recommended by Edzwald *et al.*, [1990] is:-

$$dN_p/dh = -3/2\ (\alpha_{pb}\ \eta_T\ N_p\ \phi_b/d_b) \qquad \text{equation 2.2}$$

where N_p is the number concentration of particles, h is the unit depth of the flotation unit, ϕ_b is the bubble volume concentration and d_b is the mean bubble diameter. The effects of recycle ratio and saturator pressure are combined into one term , ϕ_b , which is the quantity of air supplied expressed in terms of the air supplied per volume of water treated. ϕ_b has two effects on flotation.

First, it represents the total volume of bubbles available for collection of particles and is analogous to filter-bed volume in filtration.

Secondly, the bubble volume concentration should exceed the particle volume concentration in order to lower floc density.

The right hand side (RHS) of equation 2.2 is a measure of flotation performance:

$$\alpha_{pb}\ \eta_T\ N_p\ \phi_b/d_b$$

This product shows that flotation is affected by chemical parameters (pH and coagulation effects on α_{pb}) and various physical variables including flocculation period (effects on N_p and particle size and thus η_T) and bubble concentration (ϕ_b) and size (d_b) [Edzwald *et al.*, 1990].

This model demonstrates the need for optimum conditions to treat the sample water prior to DAF treatment so that one is able to optimize α_{pb}, η_T, N_p. The bubble volume concentration, ϕ_b and bubble size, d_b are controlled at the flotation stage.

The model prescribes that good particle bubble attachment and hence effective flotation requires conditions in which particles (algae) have been destabilized; i.e. particles that are hydrophobic and that have low or no surface charge. These requirements are the same as destablization of particles for flocculation, settling and for filtration. Hence chemical coagulation is not only critical but important for success in algae removal by dissolved air flotation.

2.4 Mechanisms of removal by Dissolved Air Flotation (DAF)

The objective of Dissolved Air Flotation is to separate delicate hydrophobic solids or solids with hydrophobic spots, from the liquid phase of water or wastewater by the help of microbubbles.

The microbubbles act as nuclei for the attachment of the suspended solids and some of the colloidal hydrophobic solids or solids with hydrophobic spots, providing a transport mechanism for the movement of the agglomerates of the solid to the surface. Bubbles of 40 – 70 μm in size have rise rates from 3 - 10 m/h [Degremont, 1991]. The rise rate is slow enough not to destroy the fragile flocs, forming an agglomeration of particles with weak mutual bonding and high enough to allow time for separation of the agglomeration. With the attachment of the particles to bubbles, the floc-gas bubble composite size grows and rise velocities grows simultaneously.

In water treatment solids are flocculated using biological and chemical processes to form suspended solids called flocs. Suspended solids > 0.1 mm are called settleable suspended solids. The number of suspended solids < 0.1 mm which include plankton, colloidal particles is normally high and these are often non-settleable. Flotation can be used as one method to separate the non-settleable suspended solids from the liquid phase [Tebbutt, 1993].

Success in DAF depends on the quality of floc and this is why flotation is often combined with preliminary flocculation. The flocculated form of the particles is an indispensable condition for an efficient floc-bubble adhering process. By incorporating a flocculant, the floc can be enlarged if necessary and particle area increased. This leads to improved adhesion of the bubbles and an increase in the rising velocity.

Pre-treatment by coagulant addition and flocculation prepares particles for flotation. Effective flotation requires destabilised particles i.e. low or no electrical charge and hydrophobic particles [Vrablick,1959; Hyde , 1977; Jassens, 1992].

Destabilisation is as important for flotation as sedimentation. However, the floc size can be smaller and consequently also the coagulant dosage. This is because the coagulant is required for destabilisation but not for increasing the floc size [Edzwald *et al.*, 1992].

Destabilization means the compensation of the negative charge of the colloid, the zeta potential (ZP). Measurement of the zeta potential can give an indication of the effectiveness of added electrolytes in lowering the energy barrier between colloids (that is reducing the surface potential and electrical double layer thickness) and thus can serve to guide the selection of optimum conditions for coagulation.

The air bubbles have a negative charge [Vrablik, 1959; Tambo *et al.*, 1985]. Hence flocs with a positive or a zero charge can attract air bubbles better than negatively charged flocs. In practice however, it is not necessary to strive for a complete neutralization of charge because the flocculation process works well enough even if the ZP is slightly negative as stated by Bean *et al* [1964]. Heinänen *et al.*, [1995] have shown that DAF can work well when the ZP is slightly negative (0 to –10 mV).

The ZP of air bubbles is negative and its numerical value increases with pH. It is –50 to –100 mV in the normal coagulation pH range [Tambo *et al.*, 1985]. In practice, the ZP of air bubbles can hardly be affected by any reasonable means.

The ZP of flocs can be affected in two different ways; increasing the coagulant dosage and decreasing the pH. According to Heinänen *et al.*, [1995] it has been shown experimentally that ZP increases with increasing coagulant dosage . The pH has the opposite effect on ZP i.e. it decreases with increasing pH value.

When air under pressure is introduced in a colloidal suspension the destabilized solid colloidal particles adhere to the air bubbles to form particle – gas bubble composites which have a density less than that of the liquid in which they form the dispersed phase. The phenomenon involved is of the three phase type (usually gas-liquid-solid) and depends on the physical-chemical properties of the three phases especially their interfaces.

The particle-gas bubble composite can be illustrated by the Figure 2.4:-

Microbubbles in floc
Floc 1 mm dia.
Bubbles 50µm dia.

Equivalent floc
With air distributed over a spherical layer

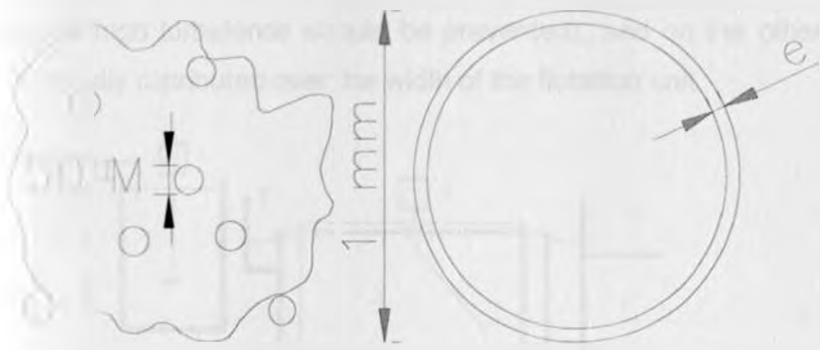


FIGURE 2.4 Diagrammatic Representation of a Particle – Gas bubble Composite [Degremont, 1991] .

Buoyant forces act on the particle-gas bubble composite moving it to the surface of the liquid leading to solid-liquid separation.

2.5 Design of dissolved air flotation systems

A typical dissolved-air flotation plant (Figure 2.5) conventionally consists of a facility to mix chemicals (for pH adjustment and coagulation) with the raw water, a mechanical flocculation stage, followed by the flotation tank [Degremont,1991]. Part of the treated water is recycled, pressurized and saturated with air in a packed tower. The recycled water is introduced to the flocculated water stream via air injection nozzles. Across the nozzles the pressure is reduced to atmospheric pressure, releasing the air in the form of fine bubbles, with diameter 40-70 µm.

The air bubbles attach themselves to the floc and the floc-bubble agglomerates rise to the surface of the flotation tank and are removed as floated sludge either by flooding or mechanical scraping.

The flotation compartment itself is composed of an influent part, the space where the liquid-solid separation occurs, the effluent construction for the flotation treated water and the equipment for removal of the sludge layer.

After the flocculation chambers, the water flows via a baffle to the entrance at the bottom of the flotation tank and past the nozzles. The flotation tank itself is generally provided with an inclined baffle (approx. under an angle of 60). In this way the formed floc-air bubble agglomerates are “sent” to the free water surface. The flotation tank must be covered because both rain and wind can lead to a break-up of the floated sludge.

The inlet to the flotation tank must be designed so that on the one hand there is good mixing between the influent and the air bubbles generated by the nozzles (floc destruction by a high turbulence should be prevented), and on the other hand the water flow is equally distributed over the width of the flotation unit.

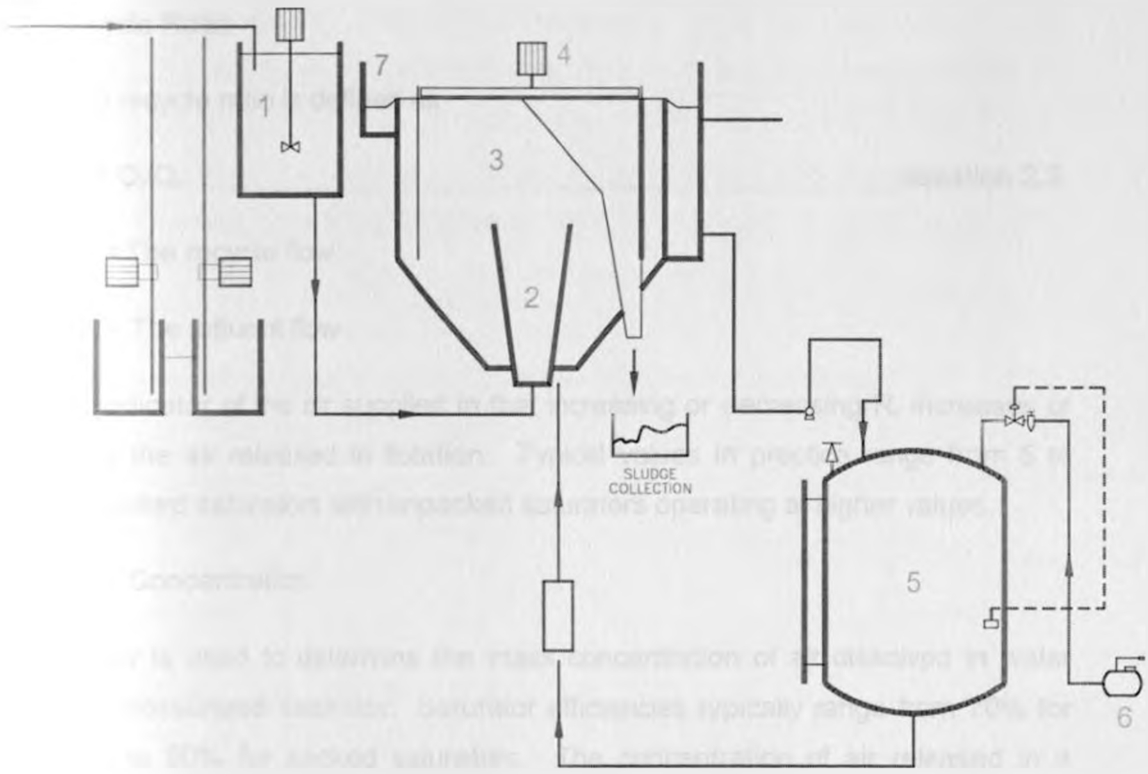


FIGURE 2.5 Typical Diagram of a Flotation Plant [Degremont, 1991].

1) *Flocculation Compartment.*

2) *Mixing Chamber. (Reaction zone : where raw water mixes with air saturated pressurized water)*

3) *Separation Zone.*

4) *Surface Sludge Scraper.*

5) *Saturation Vessel.*

6) *Compressor.*

7) *Clarified water outlet*

2.5.1 Bubbles and their effects

The concentration of air supplied and the air bubble diameter affect the design and operation of DAF. In principle, the air supplied can be controlled and changed by changing either the recycle ratio (R_r) or by changing the saturator pressure. The DAF process is a small bubble flotation process with bubbles ranging in size from 10 to 100 μm (mean about 40 μm). To ensure small bubbles, the saturator pressure needs to operate at several atmospheres above atmospheric pressure so in practice the saturator pressure is not normally varied and operates between 483-585 kPa (70-85 psig). Thus, the saturator pressure is fixed and the plant designer and operator varies the air supplied to DAF by changing the recycle flow.

There are four ways to describe the air supplied in DAF [Edzwald,1993]:-

(i) Recycle Ratio

The recycle ratio is defined as

$R_r = Q_r/Q_o$ .... equation 2.3

Q_r = The recycle flow

Q_o = The influent flow

R_r is an indicator of the air supplied in that increasing or decreasing R_r increases or decreases the air released in flotation. Typical values in practice range from 5 to 12% for packed saturators with unpacked saturators operating at higher values.

(ii) Mass Concentration

Henry's law is used to determine the mass concentration of air dissolved in water leaving a pressurized saturator. Saturator efficiencies typically range from 70% for unpacked to 90% for packed saturators. The concentration of air released in a flotation tank in a continuos flow plant is obtained from mass balance at the point of recycle injection from the following equation [Edzwald,1993]:-

$C_r = ((C_s-C_a)\ R_r-k)/(1+R_r)$ .... equation 2.4

C_r = mass concentration of air released in the DAF tank

C_s = mass concentration of air in the saturated recycle flow, computed form Henry's law.

C_a = mass concentration of air remaining in solution at atmospheric pressure, computed from Henry's law

k = influent saturation factor given by (C_s-C) where C is the actual mass concentration of air in the influent flow .

The mass concentration of air supplied per mass of suspended solids treated has been used as design parameter in wastewater and thickening flotation applications. It is not a useful parameter in drinking water treatment due to the low suspended solids concentrations found in water supplies.

(iii) Bubble Volume Concentration

The bubble volume concentration expresses the bubble volume in the flotation tank in cm^3 of the bubbles per volume of water treated in m^3 (or ppm volume when expressed in the same length dimensions). It is a fundamental parameter related to collisions between bubbles and floc particles and to lowering of floc density. It can be computed directly by dividing the mass concentration C_r by the density of air saturated with water vapour (ρ_{sat}) [Edzwald,1993].

$\phi_b = C_r/\rho_{sat}$ .... equation 2.5

ρ_{sat} values at 4 and 20°C are 1.27 and 1.17 mg/cm^3 respectively.

(iv) Bubble Number Concentration

The bubble number concentration is calculated from [Edzwald,1993]:-

$N_b = 6\,\phi_b/(\pi\, d_b^3)$ .... equation 2.6

N_b = bubble number concentration.

d_b = bubble diameter.

N_b is a fundamental parameter related to bubble-particle collisions and is a function of the recycle ratio for saturator efficiencies of 70% and 90 %.

In practise, the recycle ratio, R_r, is normally used to give the concentration of air supplied.

The rising velocity, V, of the particle-gas bubble composite is assumed to follow Stokes Law [Degremont,1991]:-

$$V = g/18\eta\ .(\rho_l-\rho_s).d^2$$

Where

ρ_l	=	Density of the liquid
ρ_s	=	Density of the particle-bubble composite
d	=	Diameter of the particle-bubble composite
η	=	Absolute viscosity of the liquid
g	=	Gravitational acceleration

The shape or the sphericity of the particle-bubble composite also matters and must be taken into account.

The favourable effect of the size (assimilated to the diameter of a sphere) of the particle – bubble composite should not conceal the fact that in the case of flotation of particles heavier than the liquid, the specific area; (i.e. the ratio of area/volume or area/weight) diminishes as the diameter increases. Given the same quantity of air fixed per unit of surface area this will result in reduction of the factor (ρ_l-ρ_s).

Therefore in order to separate flocs (particle-gas bubble composites) it is necessary to use microbubbles because [Degremont,1991]:-

- In case a good distribution of bubbles all over the cross-section is desired, using bubbles that measure several millimetres in diameter would result in airflow rate much greater than with microbubbles. At the same time this increase in air flow would set up disturbing eddy currents.
- Increasing the concentration of microbubbles increases the likelihood of collision between solid particles and the bubbles. Moreover the low rising velocity of microbubbles in comparison to the fluid mass allows them to adhere to the fragile floc particles. This assumes that their diameter is less than the diameter of the suspended solids or flocs.

2.5.2 Nozzles

Although the air bubble formation depends to a great extent on the saturation pressure, the design of the nozzle itself is also of great importance. The function of saturated air injection nozzle is to reduce the pressure in such a way which encourages the rapid generation of small microbubbles (10-100 microns) and avoid the production of larger or macrobubbles (> 150 microns) which do not contribute to efficient flotation [Franklin *et al*, 1997].

Haarhoff and Rykaart [1994] have shown that certain features of nozzle design such as bends, jet impingement and cones, can be beneficial to the production of microbubbles and minimization of macrobubbles numbers. Moreover the residence time of the saturated water within the nozzle was also shown to be important. A residence time in the nozzle of less than 1.5 millisecond is recommended.

There are several types of nozzles. The diameter of the expansion-opening as well as the length and the diameter of the diffuser, have a large influence on the efficiency of the bubble formation and on the turbulence of the water coming out of the nozzle. It is also common practice to use needle or globe valves as nozzles. Both systems have the fundamental two steps pressure release followed by an impignation surface for development of air bubbles. When using valves, there are in many cases distribution arrangements connected to the valve with the aim to give an even distribution output of whitewater. Typical distances between outlets is 30-60 cm for valve application and 10-30 cm with nozzles.

2.5.3 Reaction zone

The inlet zone also referred to as the reaction zone is the region where the air water and solids initially mix. It is considered to be of critical importance to the overall success of dissolved air flotation.

The reaction zone offers the opportunity for flocculated water to mix with the air-laden recycle stream for the first time. This zone is deemed by most researchers to be of utmost importance. The reaction zone can take many shapes, either simply a section of pipe before the flotation tank or a shrouded volume within the flotation tank, where the bubbles and air mix intimately before it is released into the flotation zone. Delineation of the boundary between the reaction and flotation zones is often difficult and arbitrary where zones are not clearly separated by baffles or otherwise.

It is expected that analogous to the two-phase flocculation, the three-phase mixing and the growth of air/floc agglomerates within the reaction zones will be dependent on mixing time and mixing intensity. Mixing time is readily calculated as the mean residence time. The degree of mixing energy or turbulence is dependent upon the complex hydrodynamics within the reaction zone, which are not readily quantifiable.

2.5.4 Flotation zone

Three parameters are considered to be of importance for the flotation or separation zone. The first parameter is the cross-flow velocity from the reaction zone into the flotation zone. Very high cross-flow velocity will induce a circulation pattern within the flotation zone and excessive turbulence may disrupt the floc-bubble agglomerates. The second parameter is the hydraulic loading in the flotation zone. Very high hydraulic loading will result in a downward flow velocity towards the outlets which may exceed the rising velocity of the floc-bubble agglomerates. The third parameter is the side depth of the flotation zone, which must be sufficient to allow for a clear separation between the outlet zone (which is inevitably slightly turbulent) and the float layer zone (which must be quiescent as possible to prevent sludge layer erosion from below).

The efficiency of the flotation zone is largely influenced by the degree of turbulence in the flotation zone which in turn is a function of the total flow (i.e. raw water flow plus recycle flow).

Haarhoff and Van Vuuren [1995] suggested that the cross-flow velocity must be less than or equal to the hydraulic loading of the reaction zone to avoid an increase in turbulence which could lead to floc break-up.

The flotation unit is generally designed based on a critical residence time depending on the surface loading (upflow rate) and depth of the flotation tank. Exact values for these parameters have however to be investigated and defined in bench and pilot plant scale experiments.

In view of the nature of the flotation process, light and small but strong flocs with a high density are required, which can resist the relatively heavy turbulence and shear at the outflow-openings of the nozzles.

There are a number of process variables controlling the suspended solids removal efficiency of the flotation process e.g. air/solids ratio, bubble volume concentration, nozzle design, detention time and hydraulic load. Many studies have investigated the influence these parameters have on clarification.

The air/solid ratio is often discussed as a design parameter and from a theoretical point of view, this ratio might be of interest. However, in practical design, and in drinking water applications, the use of recycle ratio is more appropriate

Due to the attention being paid to the limits for pressure and recycle percentage, the efficiency of the flotation process depends on the amount of air which has to be theoretically added to the recycle flow. The total air requirement for flotation is between approximately 8 to 10 g of air /m^3 (approx. 5 to 12 ml/litre main flow). In practice, however the recycle percentage is often preferred as a process parameter, varying between 7 and 8%. Depending on the specific operating conditions, other values may be selected. Some typical values reported by researchers are as presented in the Table 2.3.

TABLE 2.3 Recycle Parameters for Clarification [Haarhoff and Van Vuuren, 1995].

Country of Survey	Statistic	Air dosing (mg.l^{-1})	Recycle ratio (%)
South Africa	number	14	13
	minimum	4.5	6.4
	median	7.9	11.0
	maximum	9.9	23.0
Finnish	number		30
	minimum		5.6
	median		10.0
	maximum		42.0
Dutch	Number		5
	minimum		7.0
	median		7.5
	maximum		9.0
British	Number	-	12
	Minimum	70	6.0
	maximum	10.0	10.0
Recommendation (authors)	Minimum	6.0	6.0
	maximum	8.0	10.0

Air dosing are the design values, recycle ratios are measured values.

For clarification, the air/water ratio (expressed as mass-air concentration in mg/l) is of importance and is a function of saturator pressure, saturator efficiency and recycle ratio.

2.5.5 Flotation tank design data

Although circular tanks are used primarily for smaller installations, most treatment plants are designed with rectangular flotation tanks. Flotation tanks are normally designed with a depth of approximately 1.5 m and upflow rates between 8 and 12 m/h depending on the tank surface area. The maximum size of the flotation tank is determined by hydraulic conditions and the design of sludge removal device. Tanks with surface areas in excess of 80 m^2 are in operation. The nominal retention time in the flotation tank is between 5 to 15 minutes depending on the loading (upflow rate) and depth of the flotation tank [Zabel, 1985].

Normally in order to determine optimum parameters for a given raw water laboratory investigations are carried out and the results used in the design of the desired DAF plant. Typical design data values are as shown in Table 2.4 below.

TABLE 2.4 Dissolved Air Flotation Design Data [Corbitt , 1990].

Parameter	Typical Value	Remarks
1. Pressure	270-340 (kN/m^2)	Range 170 – 475 kN/m^2
2. Air to Solids Ratio	0.03 – 0.05	Range 0.01 : 0.02
3. Water Depth	1 – 3 m	Commercial Units
4. Surface Loading Rates	20 – 325 m^3/day-m^2	
5. Tank Detention Time	0.5 – 3 min	
6. Float Detention Time	20 – 60 min	
7. Recycle %	5 – 120	When utilized

2.6 Operation and maintenance

Experience on full scale plants has shown that clarification using DAF process generally perform to a high degree of satisfaction and this can be attributed to the fact that the plants are designed with a fairly narrow band of design parameters.

The sludge accumulating on the flotation tank surface can be removed either continuously or intermittently by flooding or mechanical scraping. The flooding method has the advantages of low equipment cost and minimal effect on the treated water quality but at the expense of high water wastage. Selection of the most appropriate sludge removal mechanism however, depends on the water to be treated.

In terms of practical and mechanical problems, by far the most reported complaints have revolved around the float scraping equipment, such as excessive wear on the scraper blades, regular snapping of the scraper chains, high maintenance on the scraper gear boxes and imported replacement parts. Wear on the sludge pumps, clogging and blocking of pipes and instrumentation have also been reported as secondary problems [Haarhoff and Van Vuuren, 1995].

Being a highly mechanised process the energy costs in flotation can be quite substantial. Flotation tends to have lower capital costs but higher operating costs than sedimentation. Any cost comparison, however should take into account additional advantages such as better treated water quality (when treating problematic water), greater flexibility of the plant, shorter start up time, easier sludge handling, the need to build only shallow tanks and the compact size of the plant.

2.7 Advantages and disadvantages of dissolved air flotation

Research and experience have demonstrated comprehensively the Technical viability of DAF. Of particular attraction are the obvious possible technical advantages compared to normal sedimentation method [Gregory, 1997]. :-

(i) High surface loading rates resulting in less space requirement and lower initial capital investment;

(ii) Excellent ability to remove algae;

(iii) Reduced water losses because of sludge production having higher solids content and which is more easily treatable;

(iv) Particularly suitable for intermittent use because of its start-up characteristics; a treated water of steady quality can be reached after minimum of 60 minutes.

Because of its specific process advantages, dissolved-air flotation fits well in the trends of today in clarification, which may be summarized as follows:

- The development of compact installations with high rate surface loadings
- The application of lower dosages of chemicals
- The generation of sludges with higher solids content
- An improved control of the different processes, particularly in relation to control of pH, control of dosages of coagulants, and control of the order of addition of chemicals.

Dissolved air flotation also has some possible disadvantages which may include [Gregory, 1997] :-

i) Difficulty in adjustment to follow rapidly varying raw water quality

ii) Not intended for treating raw waters with high turbidity (i.e. water with fast settling, large or dense solids:- it is generally recommended that raw water with turbidities above 100 NTU is not suitable for Flotation)

iii) Greater energy cost

iv) Need to roof DAF tanks

2.8 Advancements in dissolved air flotation

Extensive world-wide research and development of DAF has been done interalia, the Scandinavian countries, the Netherlands, Belgium, United Kingdom, France, Germany, the USA, the former USSR, China, and more importantly South Africa.

The initial bench scale models and pilot plant investigations focused on establishing whether flotation could be as efficient as sedimentation and if the chemical coagulation conditions should be different. Subsequently, the pilot plant investigations focussed on the importance and optimization of other operating conditions and plant design features, including:-

Prior flocculation, flow through rate,

Recycle rate, recycle pressure, injection nozzle size and saturator design,

Dimensions of a DAF including the deflector plate and

Sludge removal and its rate or frequency of scrapping.

2.8.1 Combined systems

Recently researchers have embarked on developing compact combined systems incorporating DAF. Studies conducted include the development of a combined DAF/filtration (DAFF), a combined DAF/filtration with pre-settling (SEDIDAFF) process and DAF combined with powdered activated carbon (PACDAF). Most of the studies have come up with promising conclusive results in support of the DAF process [Finlayson and Huijbregsen, 1997].

2.8.2 Modifications to existing treatment plants to incorporate DAF

DAF technology offers flexibility such that existing plants using conventional sedimentation tanks for clarification can be modified to incorporate this technology in the treatment process.

In Cantref water works near Merthyr Tydfil in South Wales, two existing concrete clarifiers have been converted into a pair of dissolved air flotation tanks. This was done in an entirely new configuration in which two stages of flocculation are accommodated underneath the flotation section. Traditional operational and design parameters have been retained. The plant design and the modifications to the new configuration was done in a matter of months. The plant has now been operating successfully and preliminary performance data presented show positive results [Stevenson *et al.*, 1997].

In Gothenburg, Sweden, a double bottom sedimentation basin was upgraded to incorporate DAF. The new design shows marked improved results concerning both algae and suspended particles removal compared to the earlier set-up of sedimentation tanks alone. This has also relieved the pressure on the granular activated carbon filter units after the sedimentation stage [Dahlquist, 1997].

Similar upgrading works have been carried out or are under priority consideration in Europe and America. This supports the fact that DAF is not only a viable water treatment process but also one that can be incorporated in existing plants to improve performance. Incorporation of DAF to existing plant structures in Kenya is therefore a possibility.

Nevertheless it is important to note that the production of high quality floated water does not guarantee the production of final good quality potable water. The proper design of the subsequent stages in the treatment process are equally important [Ponton, 1997].

3 THE DISSOLVED AIR FLOTATION MODEL

3.1 Objectives and scope of the study

The DAF process includes liquid, solid and gaseous phases where physical, and chemical reactions take place at both micro and macro levels. Variations in water quality, quantity, temperature and other factors increase the number of variants and hence affect the flotation process. To evaluate the flotation mechanism it is necessary to study the effect of all these variables simultaneously.

3.1.1 Objectives of the study

The primary objective of this research is to investigate the performance of dissolved air flotation process in the clarification of algal laden waters with a view to assess its efficiency especially with respect to removal of algae in the treatment of surface water in Kenya.

Secondary objectives included:-

- to find out the algae-type and species found in the test water samples.
- to study the turbidity removal and color improvement using the DAF process and
- to investigate the effect of coagulant dose and recycle ratio on the DAF process.

3.1.2 Scope of study

To achieve these objectives previous research findings on the DAF process, the basic features and properties of algae to provide a background on the difficulty of removing algae by conventional gravity aided settling was reviewed. Laboratory scale investigations on algae laden water samples was then conducted.

3.1.3 Methodology

A bench scale batch dissolved air flotation model was set-up in the laboratory and DAF experiments carried out on the test water samples. DAF process performance expectations and effectiveness was evaluated through determining the degree of algae removal and monitoring the residual turbidities and colour of the final supernatant after experimentation.

3.2 The bench scale dissolved air flotation model

A batch bench scale model was developed for this study in line with that used by Bare when studying the effectiveness of algae removal from wastewater stabilization ponds effluents using dissolved air flotation [Bare *et al.*, 1975].

3.2.1 Model type and limitations

The batch model simulates steady state DAF process. The dimensions of the model are constant. The influent and effluent characteristics can be determined as that of an existing plant when operating under similar conditions of temperature and pressure.

DAF process variables can be grouped into two categories, operational and design variables. Operational variables include physical and chemical parameters while design variables include hydraulic loading, solids loading and detention time.

The model can be able to predict with reasonable degree of accuracy the following operational variables for a given sample of raw water :-

(i) Physical variables: - optimum recycle rate,
- optimum operating pressure,

(ii) Chemical variables: - optimum coagulant dose for flotation,
- optimum pH required.

Due to the steady state nature of the model the parameters obtained above cannot be directly applied for the practical case. A pilot plant has to be set up to study the practical continuous flow case.

The data from Bench scale tests and subsequent pilot plants studies then enable the plant designer to optimise the DAF process before coming up with adequate accurate data to design a full scale plant.

3.2.2 Model assembly

The assembly basically comprises of a flotation reactor, a needle valve as the inlet nozzle, a pressurisation cylinder as the saturator and a heavy duty compressor to provide the compressed air. The model set-up is as shown in Figure 3.1 and Plate 3.1.

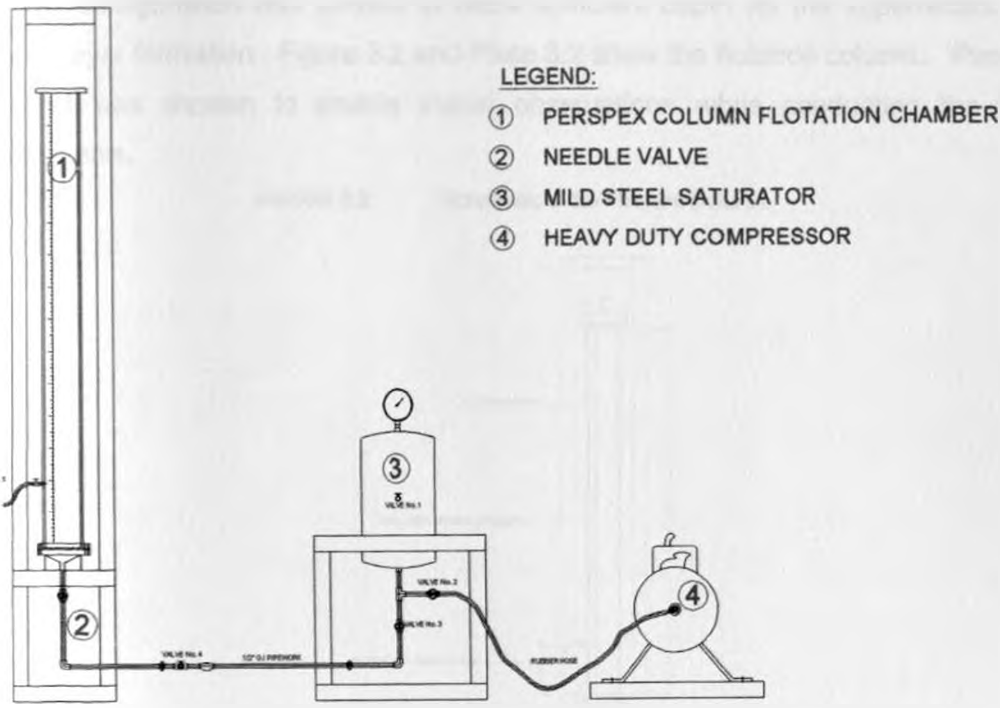


FIGURE 3.1 Bench Scale Batch Dissolved Air Flotation Model

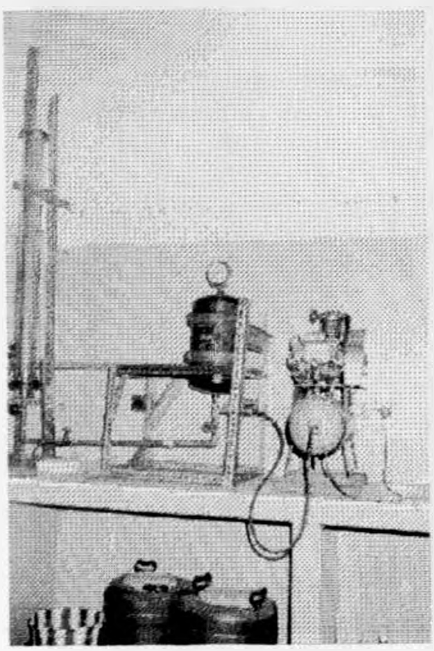
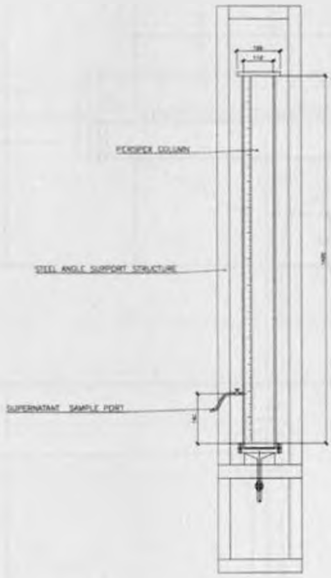


Plate 3.1: Bench Scale Laboratory Dissolved Air Flotation Model.

3.2.3 Flotation reactor

The flotation reactor is a clear perspex column, with an internal diameter of 112 mm and a height of 1400 mm with a capacity of about 14 litres. The column is graduated in litres and has an outlet 180 mm from the bottom for supernatant sampling. The column configuration was chosen to allow sufficient depth for the supernatant and sludge layer formation. Figure 3.2 and Plate 3.2 show the flotation column. Perspex material was chosen to enable visual observations while conducting the DAF experiments.

FIGURE 3.2 Schematic of the Flotation Column.



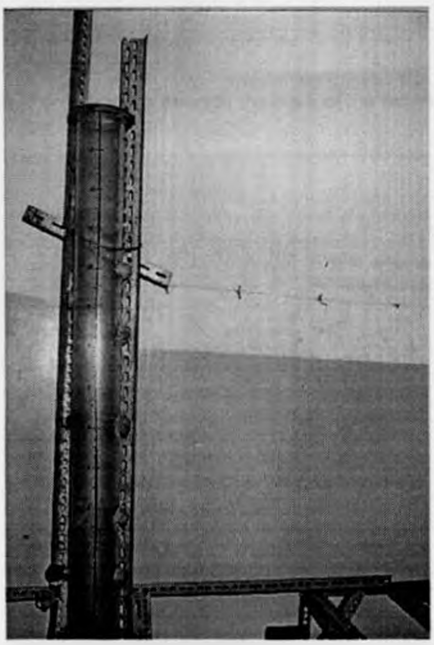


Plate 3.2: Flotation Column.

The column was connected to the base by a flange and a series of 8 number mild steel bolts equally distributed along the flange.

The base was also made of perspex and is shown in Figure 3.3 and Plate 3.3. This provided the inlet of recycle stream into the flotation chamber via a needle valve. Figure 3.4 shows a schematic of the needle valve.

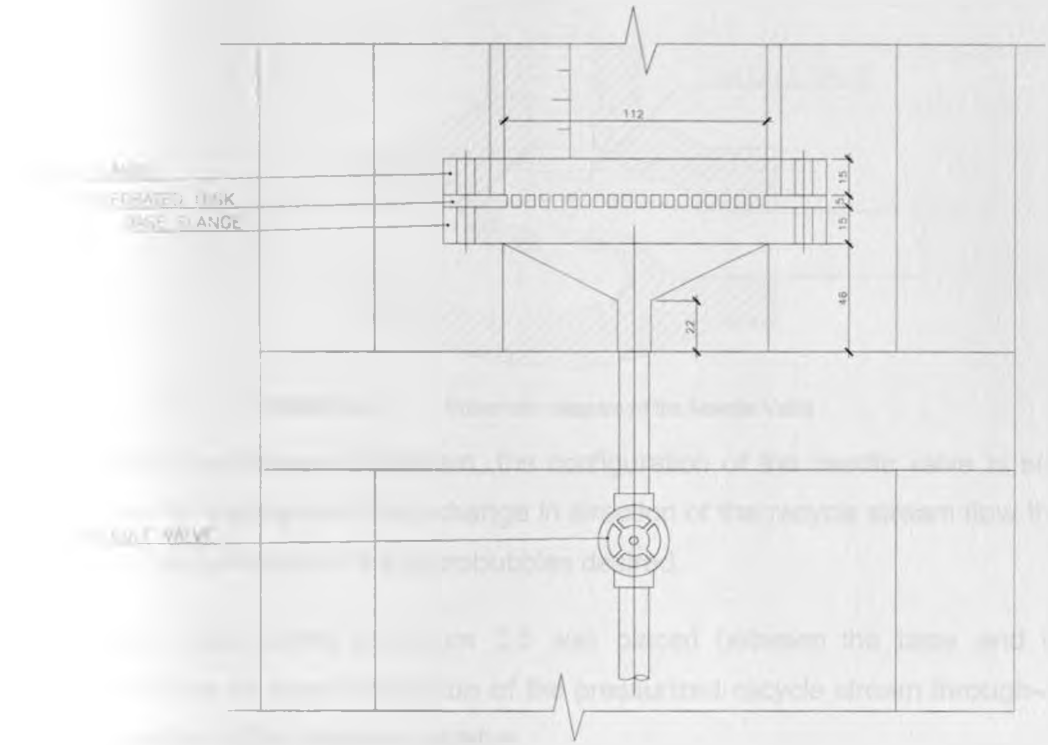


FIGURE 3.3 Section through the base of the flotation column.

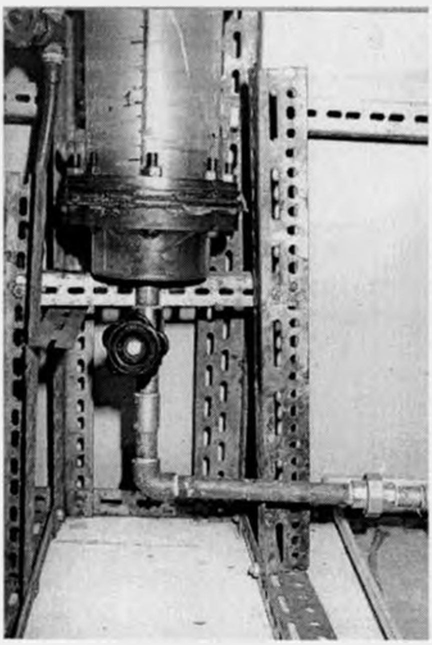


Plate 3.3: Flotation column base.

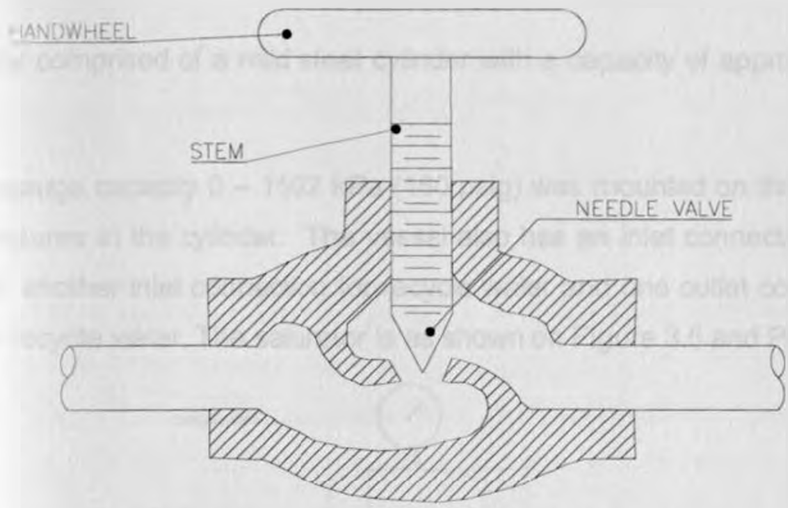


FIGURE 3.4 Schematic diagram of the Needle Valve

As seen from the schematic diagram, the configuration of the needle valve is such that it allows for impingement and change in direction of the recycle stream flow thus allowing for the formation of the microbubbles desired.

A perforated plate shown as Figure 3.5 was placed between the base and the column to ensure an even distribution of the pressurized recycle stream through-out the cross-section of the flotation chamber.

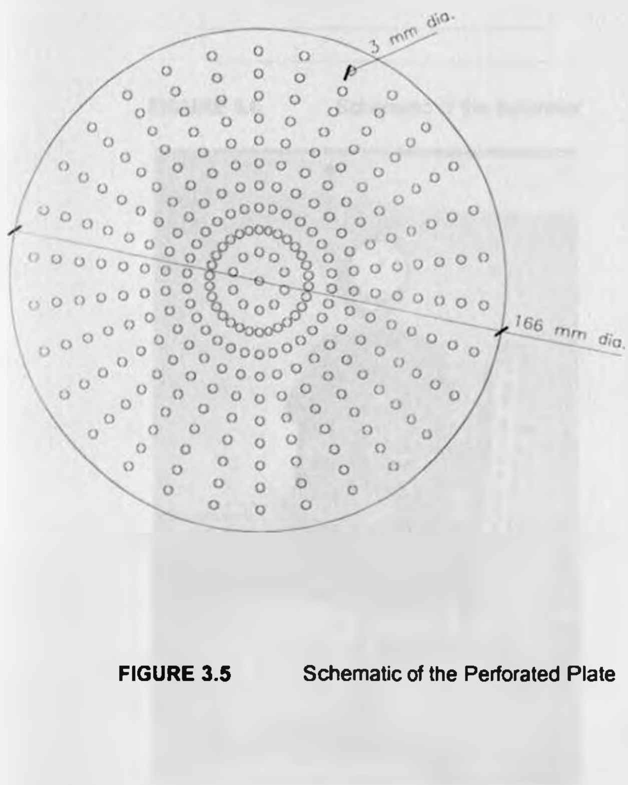


FIGURE 3.5 Schematic of the Perforated Plate

3.2.4 Saturator

The saturator comprised of a mild steel cylinder with a capacity of approximately 15 litres.

A pressure gauge capacity 0 – 1102 kPa (160 psig) was mounted on the cylinder to monitor pressures in the cylinder. The vessel also has an inlet connection from the compressor, another inlet connection for recycle water and one outlet connection for pressurized recycle water. The saturator is as shown on Figure 3.6 and Plate 3.4.

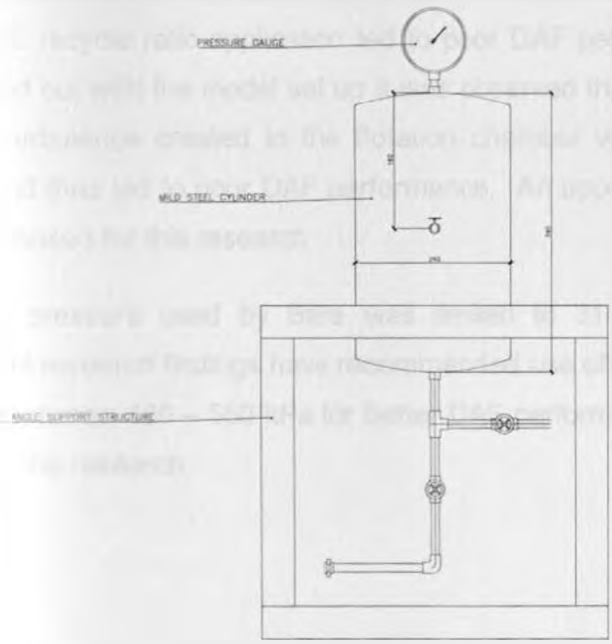


FIGURE 3.6 Schematic of the Saturator

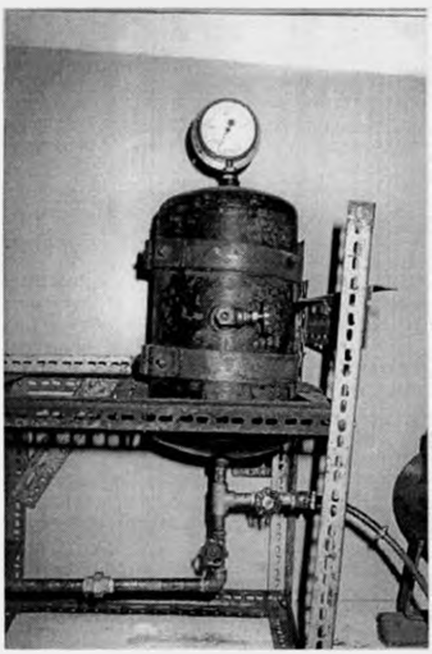


Plate 3.4: The saturator.

3.2.5 Heavy duty compressor

This is to provide a source of compressed air needed to pressurize recycle water. The compressor has a capacity of delivering up to 1100 kPa.

The entire assembly was connected together using 12 mm galvanized iron pipework as shown in Figure 3.1.

Bare *et al.*, [1975] concluded that an increase in the recycle ratio increased the turbulence created in the release valve and subsequently in the flotation chamber. Above 50% recycle ratio application led to poor DAF performance. During the trial runs carried out with the model set up it was observed that with recycle ratios above 50% the turbulence created in the flotation chamber was very high as to impair flotation and thus led to poor DAF performance. An upper limit of 50% recycle ratio was thus chosen for this research.

Saturation pressure used by Bare was limited to 310 kPa [Bare *et al*, 1975]. Subsequent research findings have recommended use of higher saturation pressures generally between 480 – 550 kPa for better DAF performance. This range was thus chosen for the research.

4 EXPERIMENTAL METHODS AND MATERIALS

The research work was conducted at the University of Nairobi, Department of Civil Engineering, Environmental Health Engineering laboratory between November 1999 and August 2000.

4.1 Test water and algae

4.1.1 Culturing algae in the laboratory

Algae cultures used in the batch tests were grown in the laboratory by spiking tap water with algae samples obtained from Muranga sewerage maturation ponds and Wamunyu River.

15 litres of the algae sample was transferred to a perspex culture basin 710 x 310 x 205 mm in dimensions (Plate 4.1). Ultra Heat Treated (UHT) milk rich in nutrients was used as algae feed. 250 ml UHT was added and the mixture diluted to a depth of 180 mm with tap water.

A fluorescent tube was hung directly above the tank at a height of about 1 metre to simulate sunlight. A mechanical fan was set-up in the room to ensure proper air circulation within the room.

The culture was left to grow for four weeks each time monitoring the scum development and removing it to allow free flow of air and light into the culture water. Algae concentration was monitored by observing intensity of the green colour in the culture basin and through measurement of chlorophyll-a levels in the culture water.

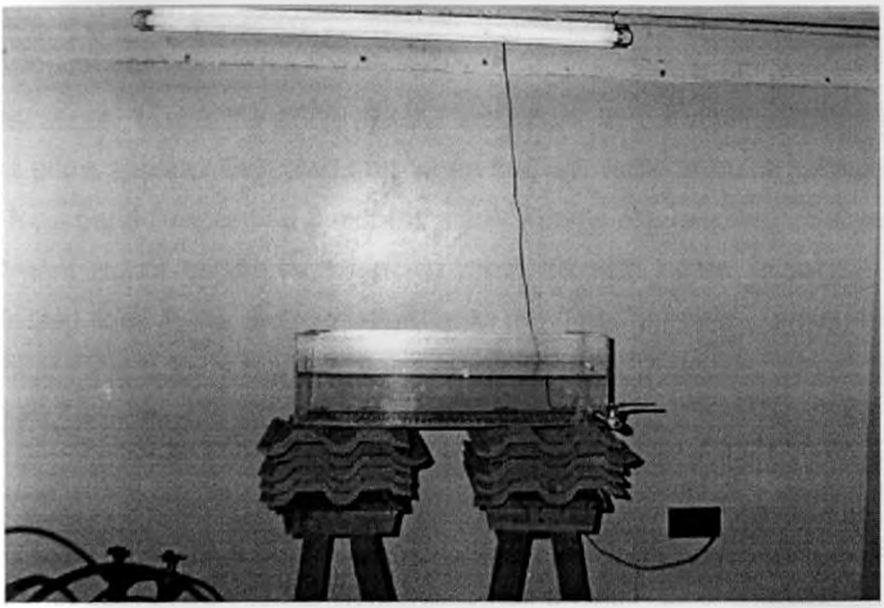


Plate 4.1: Laboratory Algae culture Basin.

When sampling started the culture basin contents were topped up and more nutrients added to replenish used up culture contents.

4.1.2 Surface water samples

Surface water samples were collected from the Athi river at Wamunyu, Ruiru dam, JKUAT reservoir and Dandora. Sampling procedures were undertaken as per the Standard Methods for the Examination of Water and Wastewater Handbook [17th edition, 1989] and Chapman [1992].

4.1.2.1 Wamunyu water works Intake

About 120 litres were obtained from the Athi river at Wamunyu water works intake. The sampling was carried out during the dry spell in early March 2000 when the algae problem is at its worst and on the onset of the rains in April 2000 to compare algae concentrations for the two cases.

The samples were taken very close to the raw water intake pipe at a sampling height of about 300 mm from the surface of the water on both occasions. The water was then transferred to sterilised plastic containers and transported to the laboratory for analysis and DAF test runs.

4.1.2.2 Jomo Kenyatta University of Agriculture and Technology (JKUAT) Surface water Reservoir

This water supply serves the entire JKUAT institution. Information obtained from the treatment plant operator indicated that when the raw water surface reservoir is not cleaned for a period exceeding 3 months algae blooms are reported. Subsequently, the treatment works begins experiencing problems with algae, especially floating algae infested flocs in the sedimentation tanks and frequent filter clogging leading to shorter filter runs. Sampling was carried out in June 2000 one month after the reservoir had been last cleaned.

50 litres was obtained from the 82000 litre capacity surface water reservoir at JKUAT University which is fed by pumping raw water from Ndarugu river. The open reservoir with geo-textile lined embankments has a height of 2 m and at the time of sampling the reservoir height was 0.92 m.

4.1.2.3 Ruiru Dam Water

Samples was obtained from the 400, 300 and 200 mm raw water inlet mains at Kabete Water treatment works. The raw water mains transport water from Ruiru dam 14 Km away to Kabete for treatment. Kabete treatment works produces about 600 m^3/d which is fed into Nairobi city distribution system. Sampling was carried out in August 2000.

4.1.2.4 Dandora Waste water Treatment Works

Dandora Sewerage ponds produce effluents high in phytoplankton and this is thought to be the cause of algae problems downstream of the discharge point along the Athi river where Wamunyu intake is located. This sample was thus important in order to compare the Dandora algae species composition and behaviour with that of Wamunyu. Sampling was carried out in July 2000, at the effluent discharge point from the maturation ponds into Nairobi river.

Details of test runs carried out on the various samples tested can be seen in Appendix 2 of this study report.

4.2 Dissolved air flotation experiments

Batch DAF tests were conducted in the laboratory using the Bench-scale model. The following is a short description of how the model was operated.

4.2.1 Bench scale model operation

Tap water was used for the recycle stream and laboratory grade alum (Aluminium Potassium Sulphate $AlK(SO_4)_2 . 12 H_2O$) used as the coagulant.

5 litres of tap water was introduced into the saturator and pressurised to between 483 and 550 kPa. 4 litres of coagulated sample was then prepared in the laboratory and introduced into the flotation chamber. The needle valve was opened to allow a given percentage of pressurised recycle stream in to the flotation chamber and then shut off. The sample was then allowed a given amount of flotation time ranging from 10 to 60 minutes for the sludge to form and a supernatant sample taken from the sampling port for analysis.

The above procedure was repeated for different amounts of recycle water (i.e. pressurised water from the saturator), coagulant doses and flotation times for the various samples tested. Several runs were also carried out using uncoagulated samples to investigate the effect on DAF performance when coagulant is not added.

Parameters investigated in the batch tests included algae concentrations, turbidity, colour, coagulant doses, recycle ratio and flotation time.

Optimum coagulant dosages for the different test water samples were determined using jar tests. The test water samples were coagulated using laboratory grade alum with a rapid mixing period of 30 sec. at 120 rpm at room temperature, 22°C - 25°C and pH range of 6 - 8. A flocculation period of 15 minutes at 40 rpm was then allowed. The sample was then transferred to the flotation chamber and a given amount of recycle stream introduced. Recycle flow to the flotation unit was varied between 0 and 50 percent. The saturator pressure was maintained at 483 kPa throughout the study inorder to obtain the microbubbles 10 -100 µm in diameter so desired. After allowing suitable flotation time the supernatant was drawn off and taken for analysis

4.2.2 Experimental assumptions

i) The flotation unit operates as a batch reactor i.e. no inflow or outflow

ii) The phytoplankton in the water samples mainly consist of chlorophyll bearing algae. And the algae concentration in the water sample is given by the concentration of chlorophyll-a in the sample.

iii) The flocs quality formed after coagulation/flocculation is reasonably uniform and turbulence introduced by the pressurized water does not break up much of the well formed floc.

iv) Flow is uniform across any horizontal layer in the flotation unit.

v) Optimum coagulation/flocculation conditions will have been achieved during prior treatment of the test water samples and the only variables will be in the flotation stage. This was to be ensured through use of alum at optimum pH range of 6 – 8, at room temperature approximately 22°C - 25°C and ensuring sufficient energy is used in the coagulation flocculation stage.

4.3 Analytical techniques

Standard analysis techniques as stipulated in the Standard Methods for the Examination of Water and Wastewater Handbook [1989] were used and the following are brief descriptions of some of the techniques used.

4.3.1 Algae concentration

This was carried out through Spectrophotometric determination of chlorophyll-a using the Trichromatic method. The pigments were extracted from the plankton concentrate with aqueous acetone and the optical density of the extracts determined with a spectrophotometer. A Unicam SP600 Series2 Spectrophotometer (Plate 4.2) was used and the extracts examined under the red wavelength 625 - 1000 nm.

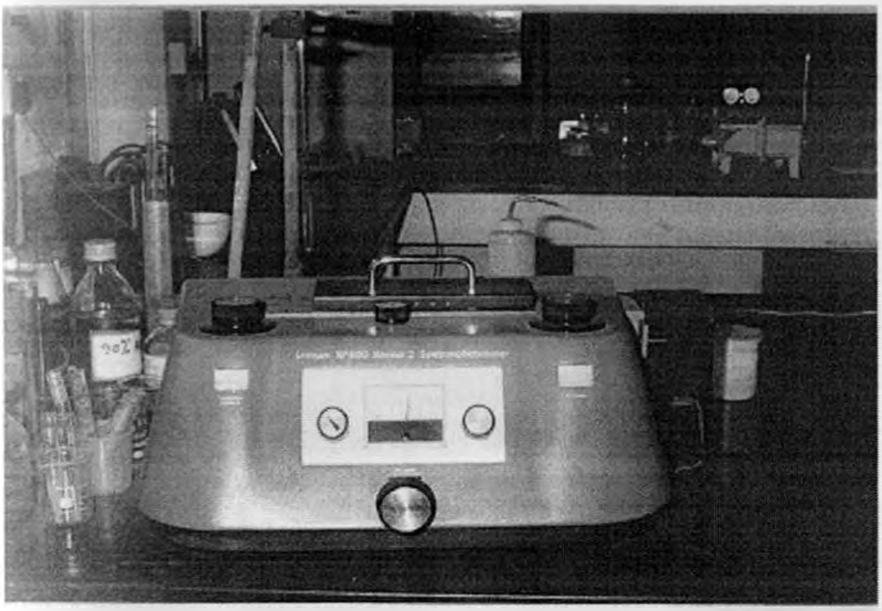


Plate 4.2: Unicam SP600 Series 2 Spectrophotometer.

After Spectrophotometric measurements were done the chlorophyll -a concentration in the samples was determined by use of the following equation [Standard Methods for the Examination of Water and Wastewater Handbook, 1989]:-

Chl-a (μg/l) = $11.64\ D_{663} - 2.16\ D_{645} + 0.10\ D_{630}$ ....equation. 4.1

where D_{663}, D_{645}, and D_{630} are the spectrophotometric absorbances at 663, 645 and 630 nm wavelengths respectively.

$$\text{Chl-a (mg/m}^3) = \frac{\text{chl} - \text{a}(\mu\text{g/l}) \times \text{vol. of extract (l)}}{\text{vol. of sample (m}^3)}$$ ....equation 4.2

4.3.2 Algae species

The algae species in the samples were determined by carrying out phytoplankton analyses at the Department of Botany, University of Nairobi, Chiromo campus. This was done by examining the samples under a compound Watson microscope at low and high power. Determination of the species composition and their abundance in the various samples was carried out. Results for the analyses can be found in Appendix 1 of this report.

4.3.3 Turbidity

Turbidity analysis was carried out using the Nephelometric method. A Hach Model 2100A Turbidimeter was used (Plate 4.3).

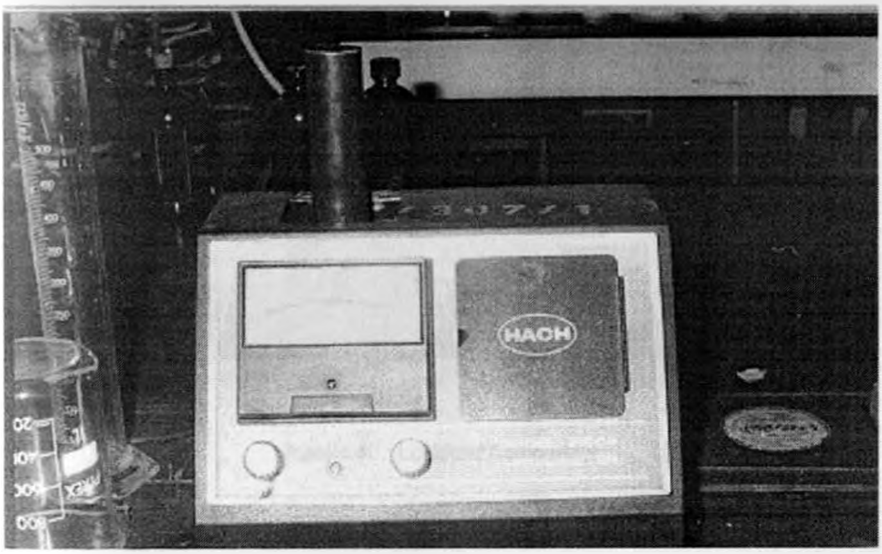


Plate 4.3: Hach Model 2100A Turbidimeter.

Before any measurements were taken the turbidimeter was calibrated using formanzin standards. Samples were then placed in the turbidimeter and turbidity measurements read directly from the turbidimeter scale. Turbidity units were recorded as Nephelometric Turbidity Units (NTU).

At least two readings were obtained for each sample tested and the average of the readings was taken to be the turbidity of the sample.

4.3.4 Colour

Colour measurements were carried out using the Visual Comparison method. A Lovibond 1000 comparator with a Hazen NSA Nessleriser disk calibrated to measure 5 to 70 units was used (Plate 4.4).

The sample was put in a Nessler tube and placed in the comparator. Distilled water was used as the standard. The color was then given by the closest unit to that on the comparator disk when compared under illuminated light in the Lovibond. Colour was given in Hazen units.

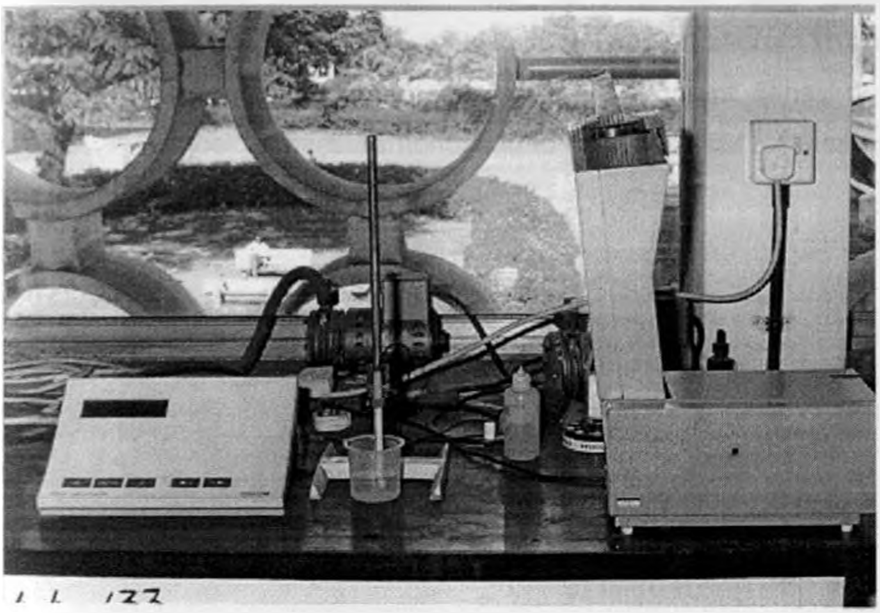


Plate 4.4: Lovibond Comparator.

4.3.5 pH

The pH determination was carried out using a Jennway glass electrode pH meter. The meter was calibrated with pH 7.0 buffer solution before each set of measurements were taken.

The electrode was the rinsed with distilled water and wiped clean before immersion into the samples to be tested. Readings on the meter were then recorded.

At least three readings for each sample were taken. The average of the three readings whose difference did not exceed 0.1 between them was then taken as the pH of the sample.

4.4 Errors in measurements

Biological and chemical measurements can contain measurement errors due to error in biological conservation or loss, reagent preparation and instrument calibration. Adequate care both in the field operations and laboratory operations, through decontamination of sampling containers, laboratory equipment and quality control in the laboratory through continuous instrument calibration, carrying out repeated measurements and checking the consistency of experimental data was ensured to keep these errors to a minimum.

However, difficulties were encountered when carrying out spectrophotometric measurements particularly for samples with low algae concentrations. This could be attributed to the old spectrophotometric cells and instrument sensitivity to low concentrations. A number of measurements had to be carried out for these samples before meaningful results could be obtained.

5 RESULTS, ANALYSIS AND DISCUSSION

5.1 General

The batch DAF experiments carried out in the laboratory allowed for careful control of pH, coagulant dose, coagulation/flocculation time and flotation conditions. Observations showed that flotation is affected by surface water characteristics and chemical pre-treatment. The recycle ratio is also a key operating parameter. Appendix 1 through 3 presents the data collected in this study and only summarised data has been presented in this chapter for discussion.

5.2 Phytoplankton analyses

Detailed Phytoplankton analyses of the water samples using a compound microscope were carried out at the Department of Botany, University of Nairobi and the results are presented in Appendix 1. A summary of the Analyses is presented in Table 5.1 below.

TABLE 5.1 Summary of the Phytoplankton Analyses of the various samples examined.

Water sample	Wamunyu i	Wamunyu ii	JKUAT Reservoir	Ruiru dam	Laboratory Cultured	Dandora Sewerage
Algae Type and Abundance						
Blue Green algae	4.9%	0.0%	0.0%	12.0%	16.2%	91.3%
Green Algae	95.1%	59.6%	0.0%	12.0%	37.6%	8.5%
Diatoms & Dinoflagellates	0.0%	40.4%	100%	76.0%	46.2%	0.2%
Chlorophyll-a Concentration (μg/l)	0.54	0.144	0.038	0.075	0.342	0.83

In the Laboratory cultured algae water sample, there was moderate distribution of species with Diatoms and Dinoflagellates making up bulk of the composition. In Wamunyu I sample taken during algae bloom period there was high distribution of species composition with Green algae being the predominant species. Whereas in the Wamunyu II sample taken on the onset of the rains there was low distribution species composition. Low counts of algae and therefore concentration were also recorded for JKUAT and Ruiru dam samples with Diatoms and Dinoflagellates recorded as the predominant species. The Dandora sample showed high species distribution and diversity. Blue green algae was the predominant species here.

Samples with green and blue-green algae forming the major composition had more concentration of chlorophyll-a than in the ones in which other algae species were predominant. This could be a pointer towards the nutrient composition of the various samples.

In Water supply phytoplankton analyses are of critical importance to obtain direct information on the number, mass or bulk of the different algae species present and on the known effects of these organisms upon the quality of water in which they have their habitat. The examination may also shed some light on the origin and history of the water. Conversely, a knowledge of the nutritional requirement of the different organisms present gives information on the presence of elements that are essential to their growth. Table 5.2 below gives the critical eutrophication nutrient composition for samples analysed during the study.

TABLE 5.2 Summary of Predominant algae types and Critical Eutrophication Nutrient Composition of the various samples tested

Water sample	Wamunyu i	Wamunyu ii	JKUAT Reservoir	Ruiru dam	Dandora Sewerage
Critical Nutrients indicating contamination					
Nitrates as NO_3-N (mg/l)	0.56	0.48	0.03	0.01	0.04
Phosphorus as PO4-P (mg/l)	0.04	0.04	0.03	0.02	0.04
pH	9.97	7.66	7.57	7.16	7.02

It is clear from Table 5.1 and 5.2 that the samples which had high nutrient composition i.e. Nitrogen and Phosphorus contained heavy presence of both green and blue green algae while those with relatively low nutrient composition had heavy presence of diatoms and dinoflagellates. The presence of a particular species of algae in a water sample can thus be used as an indicator of the contamination level in the water.

During discussions with, the head of the Central Testing Laboratories, Nairobi, where water quality tests for most of the water supplies in the country are carried out, it became apparent that tests for algae in the raw water were not a priority. Additionally, tests for the critical eutrophication indicator nutrients for the various surface water samples tested were not carried out unless expressly requested by those concerned due to the cost implications. It is important that tests for Nitrogen, Phosphorus compounds and algal biomass in raw water be given priority particularly in areas prone to algal blooms. This would enable the Treatment works operators to monitor eutrophication levels and algae biomass development in the raw water and thus become better prepared to deal with the algae blooms if and when they occur in the surface water.

The high pH value recorded for Wamunyu I sample is thought to be as a result of the algae bloom at the time of sampling. Algae extracts carbon dioxide from the water during photosynthesis. During algae blooms this activity may cause significant pH changes to occur and rise to as high as 10 or 11 [Sawyer *et al.*, 1994]. Clearly the pH recorded for the Wamunyu I sample is outside the range for effective coagulation/flocculation with alum which has been shown to work best between pH 6 - 8. Measures to lower pH to the optimum range of 6 to 8 for coagulation/flocculation should be instituted in the treatment process if effective destabilisation using alum is to be achieved.

Blue green algae found in a number of the samples tested falls under phyla cyanophyta. They occur as single cells, as filaments or in colonies. They are generally undesirable because of their tendency to aggregate and form large floating mats covering the surfaces of water bodies. Blue green algae when in large concentrations produce toxins that are lethal to fish and can cause illness in animals . Odours imparted are often grassy and may degenerate to pig-pen smells when large growths degenerate [Gordon and John, 1954]. Because of their nitrogen fixing ability bluegreen algae have a competitive advantage over green algae when nitrate and ammonium concentrations are low but other nutrients are sufficiently abundant. Extensive growths of blue green algae are also encouraged by the presence of both calcium and nitrogen in sufficient quantities. Blue green algae do not require direct sunlight for their growth and they thrive well in high salinity environments. The presence of the conditions mentioned above explain why large concentrations of blue green algae were recorded in the effluent from the Dandora Sewerage treatment works compared to other samples tested. Filter clogging species include Anabena species and more importantly Micocystis aeruginosa detected in the Wamunyu sample.

Green algae predominant in the Wamunyu sample belong to phyla chorophyta. Some are found to exist as single celled and while others are many celled. Some are non motile while others are equipped with swimming flagella. Unlike Blue green algae, green algae depend on direct sunlight for their growth and thrive well in low salinity, high pH habitats. Similar conditions exist in the Wamunyu area and thus explain why green algae is predominant in the samples taken from the area. Filter clogging species include Chlorella and Spirogyra species.

Diatoms and Dinoflagellates also common in the samples tested are generally yellow-green and brown organisms in colour and are single celled and less frequently colonial. They normally contain silica impregnated cell walls and are often motile. The essential oils released by diatoms frequently impart an aromatic odour to water. Unlike the other algae species they can grow in cold water and at considerable depths without the aid of light. Diatom blooms are usually associated with reservoir overturns. In the study, Diatoms and Dinoflagellates were found to be predominant in less contaminated clear waters (JKUAT and Ruiru samples). Filter clogging species include Asterionella and Flagillaria species. The Flagilaria species was detected in JKUAT and this could be the reason why they encounter filter clogging problems during algae bloom periods.

Since effluent from Dandora Sewerage works forms a substantial part of the flow into the Athi river particularly during the dry season, it is thought that this could be the cause of the algae problem at Wamunyu. A comparison of species composition and abundance for Wamunyu and Dandora samples showed that blue-green algae was predominant *91.3 percent* in the Dandora effluents particularly the *Spiruilina laxima* species while in Wamunyu I green algae was predominant *95.1 percent* particularly the *Scenedesmus quadricauda* species. The high salinity and calcium concentrations expected in the municipal and industrial waste waters found in Dandora and the low nitrogen content as a result of the purification of the wastes in the ponds favour blue green algae while the low salinity and direct sunshine at Wamunyu could favour green algae blooms.

Whilst it is obvious that the effluent from Dandora contributes to the phytoplankton diversity in the Athi river and therefore Wamunyu which is down stream of the discharge point on the river, we cannot conclusively say that it is the only causative function. From the observations above it is clear that a combination of suitable conditions exist in the Wamunyu region for green algae to thrive.

The species composition of the river water from Wamunyu confirm what many researchers have found in the past i.e. the planktonic flora of tropical rivers is often affected by the annual flood. Floods affect the composition of plankton as well as the overall concentration of algae in rivers. Holden and Green [1960] found that during the flood periods the volume of the water entering the river was so great that both chemical and algal concentrations was reduced. They considered the plankton reduction was due to the dilution together with reduction of nutrients to growth limiting levels.

Imbervore [1970] showed that in the river Niger the water during the major flood was so turbid that photosynthesis was limited to the top metre. The plankton during this period was diatoms whereas in the dry period the planktonic algae were blue-greens and greens. This is well demonstrated by the species composition of Wamunyu I and II taken during the dry and wet seasons respectively. Wamunyu I sample had *95.1 percent* green algae and *4.9 percent* bluegreen algae with no diatoms or dinoflagellates detected while in the Wamunyu II sample green algae formed *59.6 percent* while diatoms and dinoflagellates had significantly risen to *40.4 percent*.

Similarly for algae the ionic composition of the water is of prime importance in determining growth rates and this is especially significant in tropical rivers. Hancocks [1973] showed that as a result of the increase in pH and ionic content there was an increase in algal biomass and also a change in the dominance from diatoms to greens and blue-greens. The Wamunyu I sample had an exceptionally high pH value of 9.97 and this may favour the growth of green algae.

The different algae species composition and distribution recorded between the laboratory cultured sample and field samples tested show that it is difficult to model field conditions in the laboratory. In-situ experiments are thus recommended.

5.3 Batch dissolved air flotation experimental data

5.3.1 Algae removal

Table 5.3 below summarises the algae removal results for the tested water samples. Algae removal was measured in terms of the reduction in chlorophyll-a concentration in the samples after flotation.

TABLE 5.3 Summary of the Algae Removal Results

Water sample	Wamunyu i	Wamunyu ii	JKUAT Reservoir	Ruiru dam	Laboratory Cultured	Dandora Sewerage
Chlorophyll-a in Raw water Sample (µg/l)	0.540	0.144	0.038	0.075	0.342	0.830
Chlorophyll-a after DAF (µg/l)						
10% Recycle Ratio	0.123	0.035	nd	nd	0.083	0.140
20% Recycle Ratio	0.108	0.030	nd	nd	0.047	0.124
50% Recycle Ratio	0.106	0.029	nd	nd	0.061	0.121
Average Chlorophyll-a after DAF (µg/l)	0.112	0.031	-	-	0.064	0.128
Average Chlorophyll-a Removal	*79%*	*78%*	*>90%*	*>90%*	*81%*	*85%*

nd - not detected

The data presented above is for similar experimental conditions, i.e. optimum alum dose (i.e. dose to cause efficient coagulation), 30 seconds rapid mix, 15 minutes coagulation/flocculation, water temperature 22°C - 25°C and allowing 20 minutes flotation time.

The algae removal data obtained from the batch tests show significant chlorophyll-a reduction in all the samples and indicate excellent DAF performance. In samples from JKUAT and Ruiru Dam no chlorophyll-a could be detected using the SP600 Spectrophotometer after flotation. On average Chlorophyll-a removals were above 78 percent in all the samples tested.

In order to model algae removal in the various samples tested the algae removal data was analysed in more detail. Table 5.4 shows the algae removal data for the laboratory sample.

TABLE 5.4 Laboratory Sample Algae Removal Results

Recycle Ratio (%)	Initial algae conc in(μg/l)	Residual algae concentration in(μg/l) Flotation Time (minutes)			
		10 min	20 min	30 min	60 min
0	0.34	0.34	0.341	0.33	0.34
6	0.34	0.241	0.238	0.232	0.188
8	0.34	0.147	0.127	0.121	0.121
10	0.34	0.093	0.083	0.093	0.093
12	0.34	0.073	0.073	0.073	0.073
20	0.34	0.063	0.047	0.047	0.047
50	0.34	0.058	0.061	0.060	0.061

Zabel [1985] reported optimum recycle ratio values of 8 to 10 percent for raw water treatment. In the batch DAF tests for the laboratory sample, data was collected for 6, 8, 10, 12, 20 and 50 percent recycle ratios. Since the range between 20 and 50 percent recycle ratio was large data obtained for 50 percent recycle was treated as outliers. Graphical analysis was performed for the range between 0 and 20 percent recycle ratio which also falls within the normal range of recycle ratios used in practice. The effect of flotation time on algae removal and on recycle ratio was investigated by plotting the algae removal data against recycle ratio for different flotation times. Figure 5.1 shows the results of graphical analysis obtained from DAF data for the laboratory culture.

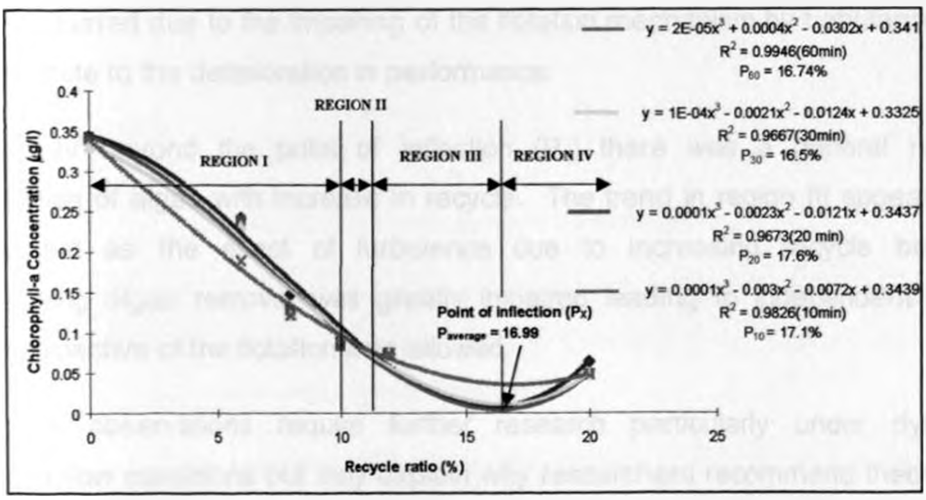


FIGURE 5.1 Graphical analysis of Algae Removal data for Different Flotation Times : Laboratory Sample

From the graphs in Figure 5.1 above it was observed that at any given recycle ratio the algae removal was dependant on the flotation time. Similarly, from the batch tests algae removal formed similar patterns which can be represented by four basic regions with respect to flotation time and recycle ratio.

In region I which covered up to 10 percent recycle rate, there was a general reduction in concentration of algae with increase in recycle ratio. Additionally the best removal was recorded for the graph with the highest flotation time. Algae removal after 60 minutes flotation time was the best followed by 30, 20 and 10 minutes flotation time in that order. This is expected, since more flotation time allows for more attachment of the bubbles to the floating matter and adequate time for floc-bubble composite to rise to the surface and hence better removal ultimately.

Region II between 10 and about 11 percent recycle, can be taken as the transition region between region I and region III.

Region III from 11 percent recycle ratio to the point of inflection of the removal curve (P_x), a reverse of the trend seen in region I was observed. The least removal was recorded for the data on the graph with the highest flotation time. Algae removal after 10 and 20 minutes flotation time was the best followed by 30 and 60 minutes flotation time in that order. The reason for this behaviour could be, as the recycle rate increases the turbulence introduced affected the efficiency of the flotation process. Additionally, as more time is allowed, settling of the heavier agglomerated floc particles occurred due to the impairing of the flotation mechanism by turbulence and thus contribute to the deterioration in performance.

In region IV beyond the point of inflection (P_x) there was a general rise in concentration of algae with increase in recycle. The trend in region III appeared to continue but as the effect of turbulence due to increasing recycle became overwhelming algae removal was greatly impaired leading to independent curve trends irrespective of the flotation time allowed.

The above observations require further research particularly under dynamic continuous flow conditions but may explain why researchers recommend theoretical recycle rates between 8 to 10 percent so that removal is kept within region I where effect of turbulence is minimal and settling of agglomerated flocs is unlikely to occur.

A model equation to show how algae removal (dependent variable) was affected by the recycle ratio an independent variable was then developed. From trend lines in

Figure 5.1, it was generally observed that a third order polynomial equation best fitted this relationship. The model equation can be expressed in a general predictive mathematical terms as:

$$Y = Ax^3 + Bx^2 + Cx + D \quad \text{......... equation 5.1}$$

Where Y is the algae removal, A, B, and C are variables, X is percent recycle ratio and constant D is a y-intercept. The constant D was observed to be dependent on the initial algae concentration. In order to obtain the theoretical points of inflection (P_X) of the removal curves, derivatives of the polynomial equations obtained were computed and equated to zero. The points obtained were taken as optimum level for algae removal as determined by recycle ratio and flotation time.

To obtain a general algae removal equation the laboratory data was combined and the line of best fit obtained. Figure 5.2 gives the equation of the line of best fit.

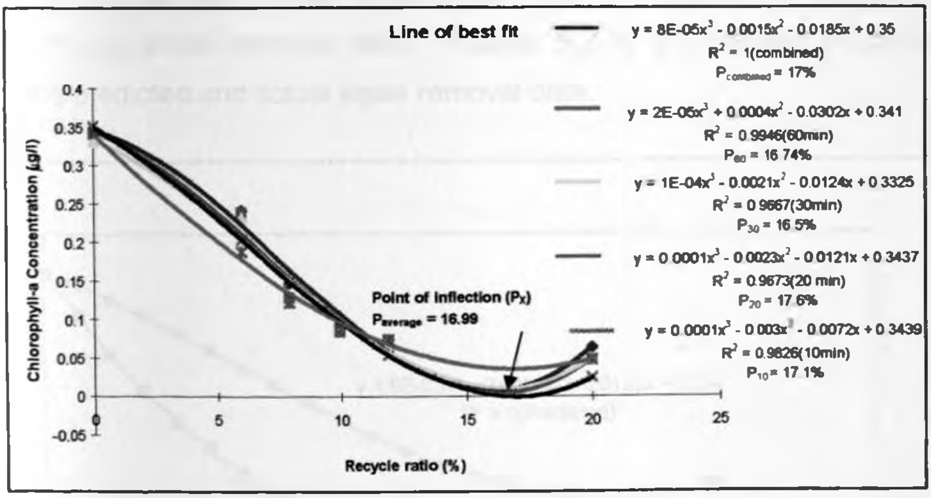


FIGURE 5.2 General Algae Removal Equation : Laboratory Sample

The line fitted the data well and the point of inflection $P_{combined}$ (17%) compared well with the $P_{average}$ (16.99) which is the mean of P_x for the fitted data. This equation was thus adopted as the general algae removal equation.

Similar analysis to obtain general algae removal equations for the other samples was also carried out (Appendix 2). Table 5.5 below shows the values for model constants obtained for the various samples tested and the best removal parameters thereof.

TABLE 5.5 Values for Model Constants For The Various samples Tested

Sample	Initial algae Conc. (µg/l)	Constants for the equation ($Y = AX^3 + BX^2 + CX + D$)				Best Algae Removal	
		A	B	C	D	Recycle Rate (%)	Percentage Removal
Laboratory	0.340	8.00E-05	-0.0015	-0.0185	0.350	17	100
Wamunyu i	0.540	-4.00E-05	0.0031	-0.0689	0.540	16	88
Wamunyu ii	0.144	-1.00E-05	0.0008	-0.0179	0.144	16	85
Dandora	0.830	-7.00E-05	0.0054	-0.1160	0.830	15	92

From Table 5.5, the model constants for the samples tested were different and did not show any similarity apart from the fact that the constant D was closely linked to the initial algae concentration in each case. Since the laboratory sample was prepared under controlled conditions, an attempt to predict algae removal for the other samples using the general equation for the laboratory sample with a modification of the initial algae concentration (constant D), respectively for each samples was carried out. Algae removal data was then analysed graphically and compared to the actual removal data. Figures 5.3 to 5.5 present a comparison between the predicted and actual algae removal data.

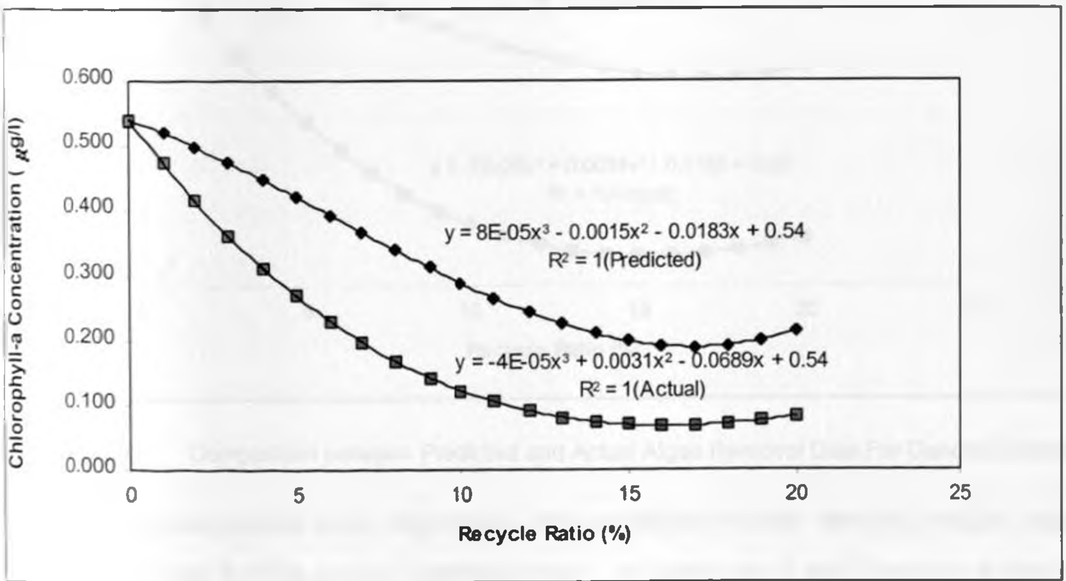


FIGURE 5.3 Comparison between Predicted and Actual Algae Removal Data For Wamunyu I Sample

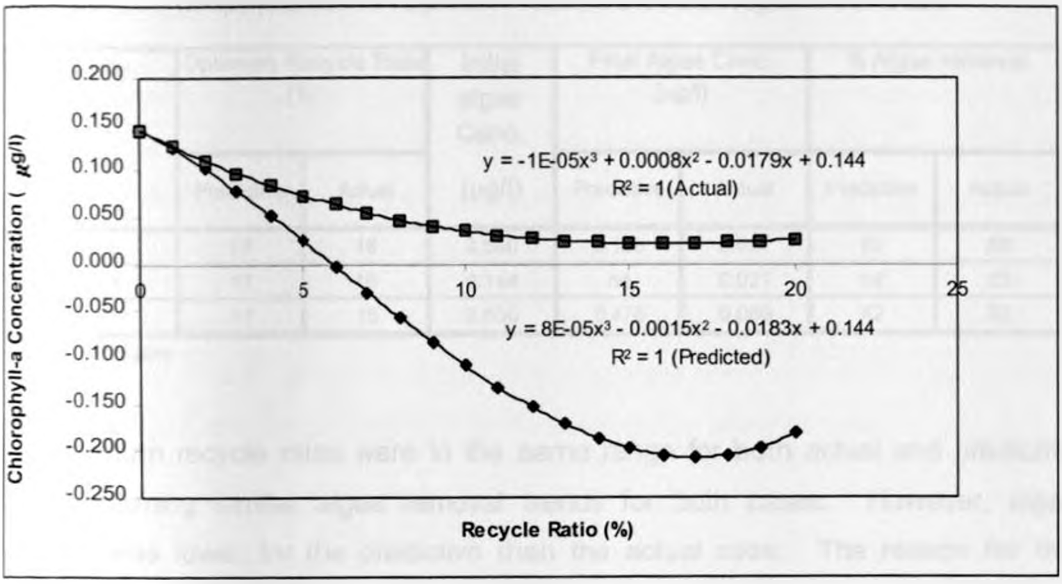


FIGURE 5.4 Comparison between Predicted and Actual Algae Removal Data For Wamunyu II Sample

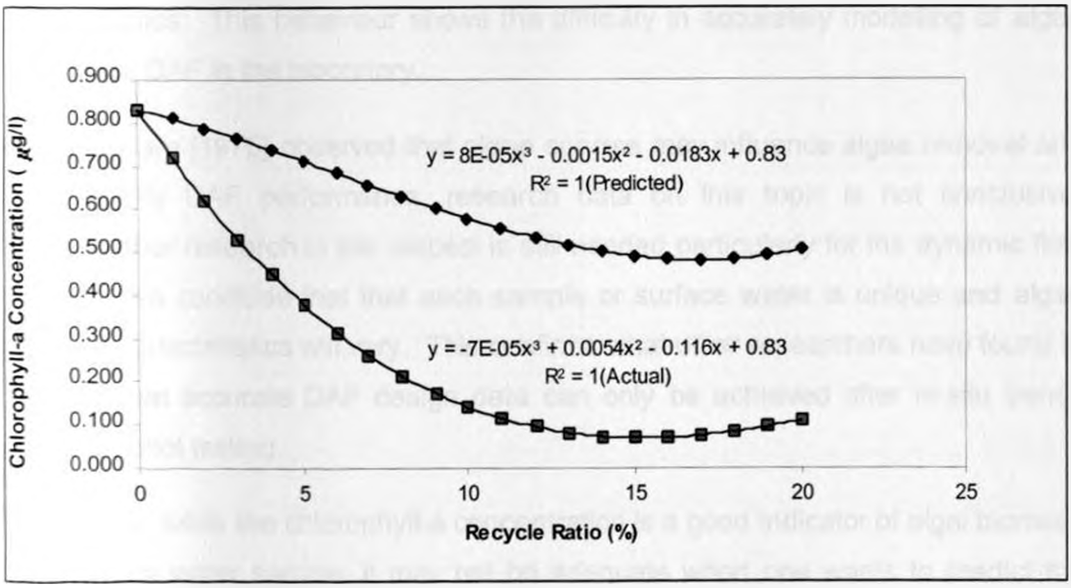


FIGURE 5.5 Comparison between Predicted and Actual Algae Removal Data For Dandora Sample

Although similar trends were registered, the predictive model removal results were much lower than for the actual observed case. In Wamunyu I and Dandora samples the predictive and actual algae removal data were divergent from the start while for the Wamunyu II sample they diverged after about 3 % recycle. Additionally, for Wamunyu II sample where the initial algae concentration was less than that for the laboratory sample, unrealistic predictive algae removal data was obtained. Table 5.6 below gives a summary of the various optimum removal parameters for both actual and predictive algae removal data.

TABLE 5.6 Comparison between Optimum Predictive and Actual Algae Removal data

Sample	Optimum Recycle Rate (%)		Initial algae Conc. (µg/l)	Final Algae Conc. (µg/l)		% Algae removal	
	Predictive	Actual		Predictive	Actual	Predictive	Actual
Wamunyu i	17	16	0.540	0.188	0.067	65	88
Wamunyu ii	17	16	0.144	nd	0.021	nd	85
Dandora	17	15	0.830	0.478	0.069	42	92

nd - not detectable

The optimum recycle rates were in the same range for both actual and predictive data confirming similar algae removal trends for both cases. However, algae removal was lower for the predictive than the actual case. The reason for this behaviour could be as a result of the differing algae species composition in the various samples as seen in the phytoplankton analyses and also surface water characteristics. This behaviour shows the difficulty in accurately modelling of algae removal by DAF in the laboratory.

Although Bare [1975] observed that algae species may influence algae removal and subsequently DAF performance, research data on this topic is not conclusive. Whilst, further research in this respect is still needed particularly for the dynamic flow case we can conclude that that each sample or surface water is unique and algae removal characteristics will vary. This confirms what other researchers have found in the past that accurate DAF design data can only be achieved after in-situ bench scale and pilot testing.

Additionally, while the chlorophyll-a concentration is a good indicator of algal biomass present in a water sample, it may not be adequate when one wants to predict the behaviour of a particular water. Algae species determination should be carried out and DAF design decisions based on the results obtained. Since no attempt was made to culture each algal species separately and therefore monitor its performance, the differences in the results of the water samples tested can be attributed to the individual sample water characteristics and algae species composition.

Nevertheless, it is important to note that DAF is effective in the removal of algae, as demonstrated in the results, so that the water applied to subsequent treatment stages is low in algae counts.

5.3.2 Turbidity removal

Turbidity in water is caused by the presence of suspended matter such as clay, silt, finely divided organic and inorganic matter, plankton and other organisms. Turbidity is an expression of the optical property that causes light to be scattered and absorbed rather than transmitted in straight lines through the sample.

Presence of algae therefore increases the turbidity of water. However, as demonstrated in the various samples analysed raw water turbidity has no direct relationship with the algae content or composition in the water sample.

A summary of the bench scale batch results for turbidity removal after 20 minutes flotation time is presented in Table 5.7, details are presented in Appendix 2 of this study report.

TABLE 5.7 Summary of the Residual Turbidity Results

Water sample	Wamunyu i	Wamunyu ii	JKUAT Reservoir	Ruiru dam	Laboratory Cultured	Dandora Sewerage
Raw water Turbidity (NTU)	20	37	2.5	1.5	25	48
Residual Turbidity after DAF (NTU)						
10% Recycle Ratio	7.5	10.0	1.1	1.0	3.8	10.0
20% Recycle Ratio	3.0	7.0	1.0	0.7	3.0	8.0
50% Recycle Ratio	2.5	5.0	0.6	0.5	3.5	6.0
Average Residual Turbidity (NTU)	4.3	7.3	0.9	0.7	3.4	8.0
Average Turbidity Removal	78%	80%	64%	51%	86%	83%

During the experimentation Dissolved Air Flotation was able to achieve the turbidity removal rates of 78 percent and above in the samples tested with the exception of JKUAT and Ruiru samples which had very low initial turbidities.

The average residual turbidities (Table 5.7) were obtained by getting the mean of the residual turbidities for the different recycle ratios after flotation. All the values were below 10 NTU and thus within acceptable ranges to subsequent treatment by sand filtration [Kawamura, 1991]. The results show excellent DAF performance as they are a clear indication of the significant reduction in the particulate matter in the water samples tested after flotation.

Tropical waters are characterised by having large fluctuations in turbidities dependant on the season. During flood periods, turbidities can go to as high as 1000 NTU. Janssens and Buekens, [1993] recommended a maximum turbidity of 100 NTU in the raw water for optimum DAF unit operation. In areas where turbidities higher than 100 NTU are recorded during flood periods, pre-settlement tanks are recommended to stabilise the turbidities before treatment by DAF.

5.3.3 Colour improvement

The visible colour of water is the result of the different wavelengths not absorbed by the water itself or the result of dissolved and particulate substances present.

Different species of phyto and zooplankton can also give water an apparent colour. [Chapman and Hall, 1992]. A dark or bluegreen colour can be caused by blue-green algae, a green colour by green algae and a yellow–brown colour by diatoms and dinoflagellates.

A summary of the colour changes recorded during experimentation is presented in Table 5.8 below.

TABLE 5.8 Summary of the Colour Improvement Results

Water sample	Wamunyu I	Wamunyu ii	JKUAT Reservoir	Ruiru dam	Laboratory Cultured	Dandora Sewerage
Apparent Raw water Color (°H)	80	80	5	10	70	80
Residual Color after DAF (°H)						
10% Recycle Ratio	30	20	<5	5	30	20
20% Recycle Ratio	15	15	<5	<5	10	15
50% Recycle Ratio	10	10	<5	<5	10	10
Average Residual Color after DAF (°H)	18	15	-	-	17	15
Average color Improvement	77.1%	81.3%	-	-	76.2%	81.3%

There was significant color improvement above 75 percent in all the samples tested. Colour changes from greenish brownish to clear in the visual spectrum particularly in samples with high chlorophyll-a concentrations were recorded signifying removal of algae and other particulate matter.

The colour ranges obtained after flotation are within the acceptable 0 – 30 °H range expected after the clarification stage in water treatment [Kawamura,1991].

5.3.4 Effect of coagulant dose on DAF performance

In the study Analytical Alum, Aluminium Potassium Sulphate $AlK(SO_4)_2 . 12 H_2O$ was used as the coagulant.

Coagulant dose has a significant effect on the flotation performance. This is illustrated from the data in Figures 5.6 to 5.8 in which alum doses were varied at a constant recycle rate of 20 percent . In the figures the particulate removal was examined using the turbidity and chlorophyll - a concentration after flotation.

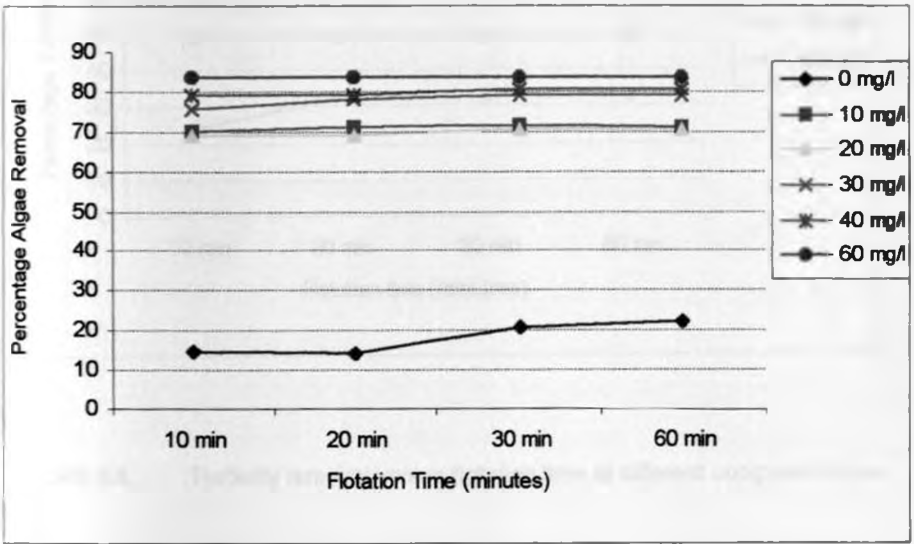


FIGURE 5.6 Algae removal versus flotation time at different coagulant doses

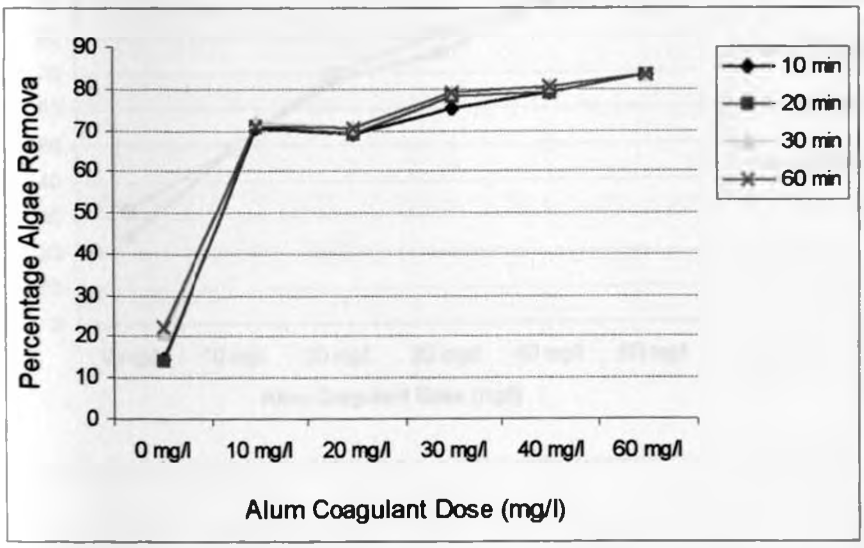


FIGURE 5.7 Coagulant Dose Effect on Algae Removal

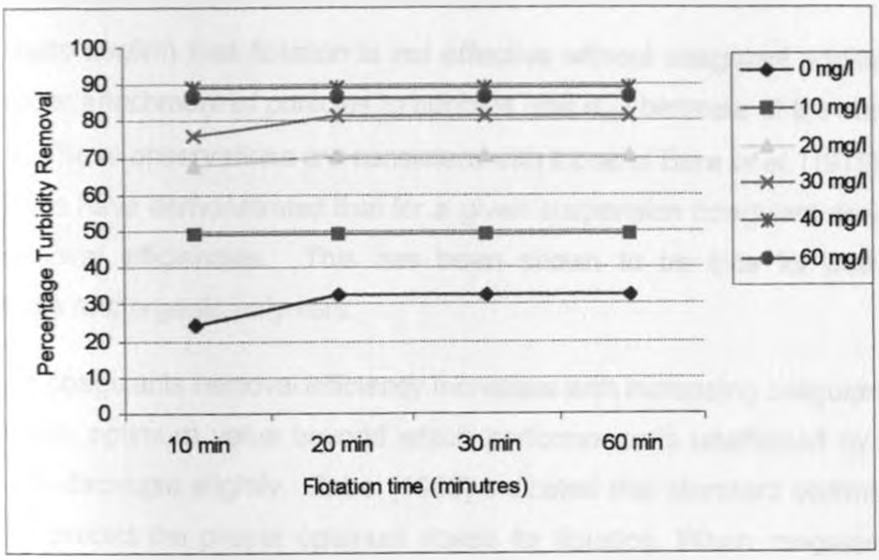


FIGURE 5.8 Turbidity removal versus flotation time at different coagulant doses.

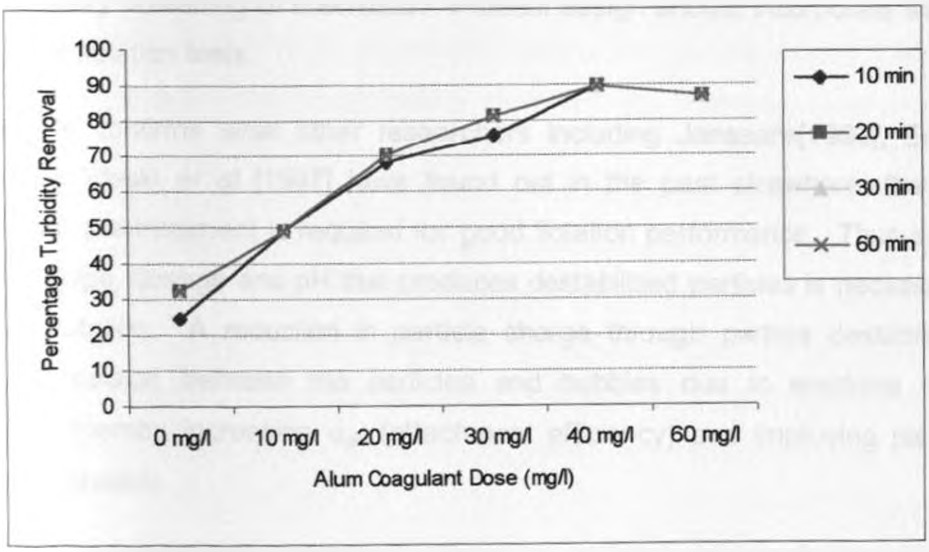


FIGURE 5.9 Coagulant dose effect on turbidity removal

Figures 5.6 and 5.7 show algae removal while figure 5.8 and 5.9 shows turbidity removal. DAF without the use of coagulants resulted in poor algae removal, about 20 percent and poor turbidity removal, about 30 percent emphasizing the need for destabilised floc material, efficient coagulation/flocculation for effective algae and particulate removal. As observed from the results higher removals were recorded with increase in coagulant dose.

The results confirm that flotation is not effective without coagulant addition. This is due to poor attachment of particles to bubbles (low α_{pb}) because of the stable particle system. These observations are consistent with those of Bare *et al.* [1975] and Zabel [1985] who have demonstrated that for a given suspension coagulant dosage affects DAF removal efficiencies. This has been shown to be true for both inorganic coagulants and organic polymers.

For most coagulants removal efficiency increases with increasing coagulant doses up to a certain optimum value beyond which performance is unaffected by dosage or may even decrease slightly. Zabel [1985] indicated that standard sedimentation jar tests will predict the proper optimum doses for flotation. When coagulant doses in excess of the optimum as determined by jar tests are applied to flotation systems, a deterioration in effluent quality was noted. This can be attributed to the production of a weaker floc at higher doses and its breakdown when air and turbulence are introduced to the flotation system. This jar test method should however only be used for preliminary screening of chemicals. Prudent design should incorporate the data from actual flotation tests.

The results confirms what other researchers including Janssens[1992], Edzwald [1993] and Vlaski *et al* [1997] have found out in the past elsewhere, that good coagulation pre-treatment is required for good flotation performance. Thus suitable coagulant type, dosage and pH that produces destabilized particles is necessary for effective flotation. A reduction in particle charge through particle destabilization reduces repulsion between the particles and bubbles due to electrical charge interaction thereby increasing α_{pb} (attachment efficiency) and improving particle - bubble attachment.

The particle destabilization mechanism depends upon the coagulant chemistry and conditions of use. Alum was used at pH 6 - 8 in this research so precipitation of aluminium hydroxide is expected as the alum dose is increased. Particle destabilization occurs by particle enmeshment or by heterocoagulation.

Edzwald [1993] found that when alum was used as the coagulant, it precipitated as $AL(OH)_3$ adding particles and increased the particle concentration (ϕp). Theoretically 1 mg/l of alum can produce 0.26 mg/l of $AL(OH)_3$ so when a moderately high alum dose is used the particles can yield additional particle volume of significant quantity. This may explain increase in turbidity after optimum dose is reached.

Dosages above the optimum cause charge reversal of the floc, high residual dissolved aluminium and consequently a deterioration in performance.

Table 5.9 gives a summary of the algae and optimum alum dose data for the various samples tested.

TABLE 5.9 Algae concentration and optimum alum dose data

Water sample	Wamunyu i	Wamunyu ii	JKUAT Reservoir	Ruiru dam	Laboratory Cultured	Dandora Sewerage
Predominant Algae type						
Blue Green algae						✓
Green Algae	✓	✓				
Diatoms & Dinoflagellates			✓	✓	✓	
Chlorophyll-a Concentration (μg/l)	0.54	0.144	0.038	0.075	0.0342	0.83
Optimum Alum Dose (mg/l)	30	40	10	10	20	120

As demonstrated in the results above, samples with blue green and green algae as the predominant species and therefore higher chlorophyll-a concentrations required higher doses of alum than in those where Diatoms and Dinoflagellates formed the predominant species. This is particularly evident in the Dandora sample in which high concentrations of blue-green algae were recorded. The alum dose required for this sample was exceptionally high. Bare *et al* [1975] observed that some species of algae particularly Scenedesmus species have bristles forming a random field around the main structure. It is thought that the field of bristles acted somewhat like a flocculated particle in that it was capable of entrapping minute bubbles of air. This natural trapping action, therefore decreased the amount of chemical requirement needed to achieve required removal as compared with dosage needed for algae species without bristles. Although he did not carry out further tests in this direction, he postulated that the configuration of the different types of algae particles influenced the coagulant requirement.

From the above results, it is clearly demonstrated that the algae species and by extension the chlorophyll-a concentration affects the coagulation chemistry hence coagulant dosage and flocculation conditions required. More research is required to study the influence of algae species on coagulation/flocculation requirements, since coagulation is a complex process that depends on all surface water characteristics, algae species and composition included.

Surface water characteristics affect DAF indirectly because they influence the treatment conditions prior to DAF. Once successful destabilisation through coagulation/flocculation is achieved, removal of particulates by DAF is effective. This is clearly demonstrated in Figures 5.6, 5.7 and 5.8 above.

5.3.5 Effect of recycle ratio on DAF performance

The effect of varying the recycle ratios on DAF treatment was also studied. Typical results are presented in figures 5.9 to 5.11. Optimum alum dosages were used.

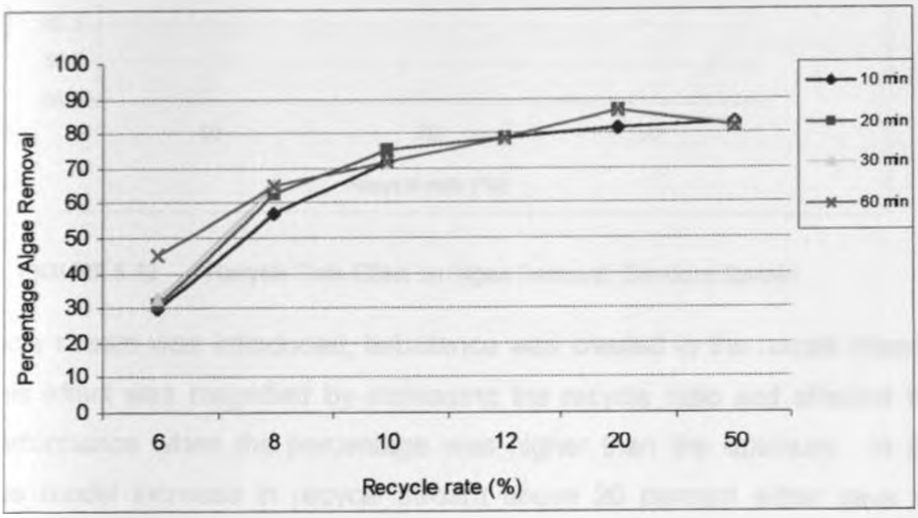


FIGURE 5.10 Recycle Ratio Effect on Algae Removal : laboratory sample

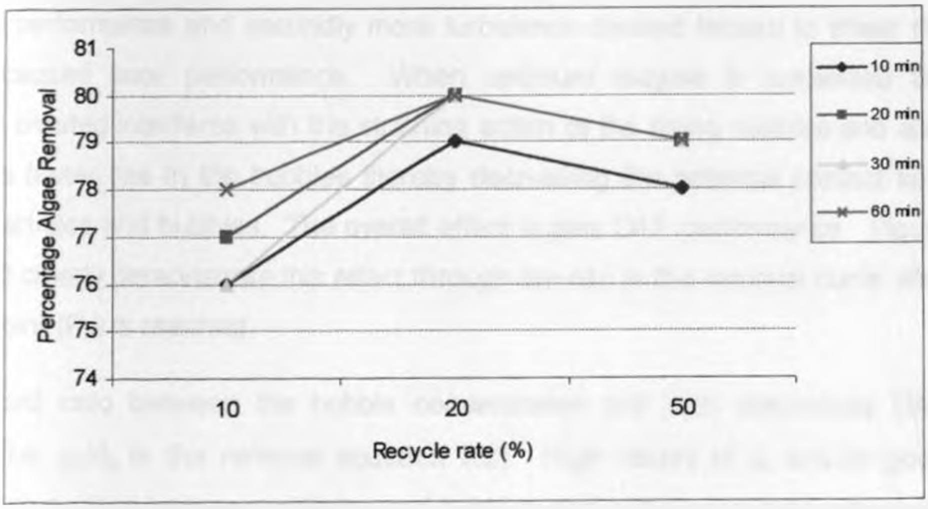


FIGURE 5.11 Recycle Rate Effect on Algae Removal: Wamunyu I Sample

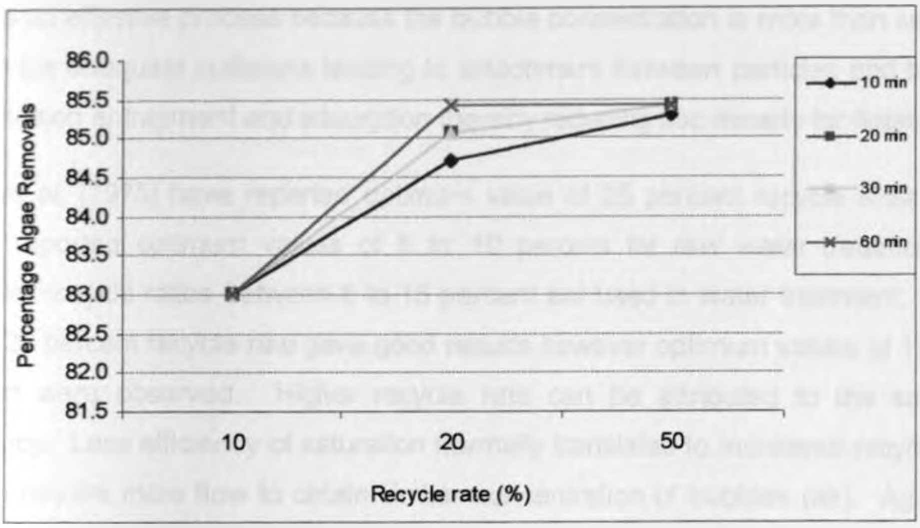


FIGURE 5.12 Recycle Rate Effect on Algae Removal: Dandora Sample

When recycle stream was introduced, turbulence was created in the nozzle (needle valve). This effect was magnified by increasing the recycle ratio and affected the flotation performance when the percentage was higher than the optimum. In the bench scale model increase in recycle stream above 20 percent either gave no significant improvement in performance or led to a decrease in performance. The effect of increased air is twofold. First more bubbles were available thereby enhancing performance and secondly more turbulence created tended to shear the floc and caused poor performance. When optimum recycle is surpassed the turbulence created interferes with the straining action of the rising bubbles and also results in a faster rise in the bubbles thereby decreasing the potential contact time between particles and bubbles. The overall effect is poor DAF performance. Figure 5.1 and 5.2 clearly demonstrate this effect through the rise in the removal curve after optimum point (P_X) is reached.

The resultant ratio between the bubble concentration and size determines DAF efficiency (i.e. ϕ_b/d_b in the removal equation 2.2). High values of ϕ_b ensure good collision opportunities between particles and bubbles and sufficient bubble volume to lower the density of particles. Research has shown that bubble volume concentration can be increased by increasing the recycle ratio upto an optimum. The bubble size however depends mostly on the saturation pressure which in this study is limited to between 483 kPa .

DAF is an effective process because the bubble concentration is more than sufficient to provide adequate collisions leading to attachment between particles and bubbles by adhesion entrapment and adsorption thereby reducing floc density for flotation.

Bare *et al.* [1975] have reported optimum value of 25 percent recycle while Zabel 1985] reported optimum values of 8 to 10 percent for raw water treatment. In practice, recycle ratios between 8 to 15 percent are used in water treatment. In this study 20 percent recycle rate gave good results however optimum values of 15 to 17 percent were observed. Higher recycle rate can be attributed to the saturator efficiency. Less efficiency of saturation normally translates to increased recycle flow as you require more flow to obtain similar concentration of bubbles (air). Again the best recycle ratio for a particular system can only be determined after carrying out flotation tests.

5.3.6 Sludge formation

Due to the size and the configuration of the flotation column used in the batch tests it was difficult to remove the sludge formed after DAF without disrupting or mixing it with the supernatant. And as a result, the solids concentration of the sludge layer formed could not be determined.

Nevertheless, from experimental observations, alum formed a good stable uniform sludge layer after DAF between 2 to 3 mm thick, on top of the supernatant. This layer can easily be scrapped off or removed using flooding in the practical application of the process.

5.4 Comparison of study results with other research findings

While attempting to compare the performance of DAF process through removal of various parameters in this study with those of other researchers it is important to note that the model set-up and raw water sample characteristics must be taken into consideration. Direct comparison of the results from this study with those of earlier researchers is thus difficult since both factors mentioned above do not correspond.

Table 5.10 below shows the comparison between the study results and those of other research carried out elsewhere.

TABLE 5.10 Comparison of study results with other findings

COUNTRY	Algae type and Concentration	Optimum Process Parameters		Algae	Turbidity	Remarks
		Saturation Pressure (kPa)	*Recycle Ratio* (%)	*Removal Efficiencies* (%)	*Removal Efficiencies* (%)	
SOUTH AFRICA (Pilot continous flow plant)	5 - 33 μg/l (Diatoms - *90%*)	550	8 - 13	>80	>96	Based on study carried out by V. Botes and L.R.J. van Vuuren on *Dissolved Air Flotation for the removal of algae and inorganic turbidity on a large scale* [1985].
NETHERLANDS (Pilot continous flow plant)	29.5 μg/l (Blue green - *99%*)	500	5-10	> 92	>86	Based on study carried out by A. Vlaski, A.N. van Breemen and G.J. Alaersts on *Algae laden water Treatment by Dissolved Air Flotation* [1997].
USA (Pilot continous flow plant)	5×10^4 algal cells/ml (Green algae & Diatoms)	483	8	>94	>87	Based on study carried out by J.K. Edzwald and B.J. Wingler on the *Chemical and Physical aspects of Dissolved Air Flotation for the removal of algae* [1990].
This Study (Bench scale batch model)	.03 - .83 μg/l (Green algae, Blue green Dinoflagellates & Diatoms)	483	10 - 20	>78	>78	Based on this study carried out at the University of Nairobi, Kenya, on the *Performance of Dissolved Air Flotation process for algae removal in surface water treatment in Kenya* [2000].

As table 5.10 above shows although on the whole excellent DAF performance was noted both in this study and those carried out elsewhere differences were registered in this study particularly in regards to the optimum recycle ratio and slightly lower percentage removals obtained.

This may be attributed to the following:-

(i) The difference in the characteristics of the water being tested particularly the algal species and the concentrations. This could possibly be the most influencing factor.

(ii) There was no way of verifying the saturator efficiency and this could have a great impact particularly on the recycle ratios applied. The ranges obtained in this study are however within those reported to be in use elsewhere (see Table 2.4 in this report).

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Based on the batch bench-scale laboratory experiment results, the following conclusions were drawn:-

(i) There were different types of algae present in the samples tested. Diatoms and dinoflagellates were the predominant algae types in the laboratory cultured, Ruiru dam and JKUAT samples. In the Wamunyu specimen, green algae was predominant in both the dry and wet season.

(ii) Scenedesmus quadricauda algae species was found common in most of the samples tested.

(iii) The study results show that clarification of surface water laden with blue-green, green, diatoms and dinoflagellate algae types using the DAF model is effective. Algae removal of between 70 and 90 percent, turbidity reduction of over 80 percent and colour improvement of over 75 percent were achieved. This confirms that DAF can be utilised in the treatment of algae laden surface water in Kenya. However, DAF is not included in the Design Manual in Kenya as a water treatment method.

(iv) The algae removal efficiency increased with increasing coagulant dose up to an optimum coagulant dose value, beyond which the removal was insignificant with an increase in coagulant. The effect of algae type and species on coagulant dose was not investigated.

(v) The recycle ratio has an effect on the performance of DAF. Algae removal increased with an increase in recycle ratio up to a point where turbulence effects induced by high recycle ratios resulted to a decrease in removal efficiency.

6.2 Recommendations

The following are recommendations for further research:-

(i) It is necessary to investigate the algae type and species present in the various surface waters in Kenya. This investigation should cover all the seasons of the year.

(ii) Detailed tests on DAF should be carried out for the different surface waters including the study on the effects of seasonal variation in water quality.

(iii) Further research is required on the effect of different algae type and species on the coagulation process.

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Appendix 1

Phytoplankton Analyses

WAMUNYU I WATER SUPPLY RAW WATER PHYTOPLANKTON ANALYSES - MARCH 2000			
e type	Green algae	Blue green	Dinoflagellates
ndance in sample	*95.1%*	*4.9%*	*0.0%*
e Species	Oocystis sp. Cosmarium depressum Scenedesmus quadricauda Scenedesmus arcuatus Pediastrum duplex Westella botryoides Franceia ovalis	Microsystis aeruginosa	
rophyll-a Concentration (ug/l)			*0.54*

s of Department of Botany: University of Nairobi, Chiromo Campus.

Algae type	Species	Total number in 10 drops	Abundance (%)
algae	*Oocystis sp.*	12	5.9
	Cosmarium depressum	4	2.0
	Scenedesmus quadricauda	123	60.6
	Scenedesmus arcuatus	9	4.4
	Pediastrum duplex	21	10.3
	Westella botryoides	17	8.4
	Franceia ovalis	7	3.4
green algae	*Microsystis aeruginosa*	10	4.9
agellates	*not detected*	0	0.0
		203	*100.0*

collected on March15 - Raw water from Athi river next to raw water intake.

WAMUNYU II WATER SUPPLY RAW WATER PHYTOPLANKTON ANALYSES - APRIL 2000			
...ae type	Green algae	Blue green	Dinoflagellates
...ndance in sample	*59.6%*	*0.0%*	*40.4%*
...ae Species	Oocystis solitaria. Scenedesmus quadricauda Staurastrum spp. Dictyosphaerium pulchellum		Ceratium cornutum
...orophyll-a Concentration (ug/l)			***0.144***

...esy of Department of Botany: University of Nairobi, Chiromo Campus.

Algae type	Species	Total number in 10 drops	Abundance (%)
...een algae	*Oocystis solitaria.*	4	7.7
	Scenedesmus quadricauda	5	9.6
	Staurastrum spp.	17	32.7
	Dictyosphaerium pulchellum	5	9.6
...e-green algae	*not detected*	0	0.0
...oflagellates	*Ceratium cornutum*	21	40.4
		52	***100.0***

...le collected on April 18 - Raw water from Athi river next to raw water intake.

JKUAT WATER SUPPLY RAW WATER PHYTOPLANKTON ANALYSES - JUNE 2000			
ae type	Green algae	Diatoms	Dinoflagellates
ındance in sample	*0.0%*	*35.7%*	*64.3%*
ae Species		Fragilaria	Gymnodinium tenuissimum Ceratium cornutum
orophyll-a Concentration (ug/l)			***0.038***

tesy of Department of Botany: University of Nairobi, Chiromo Campus.

Algae type	Species	Total number in 10 drops	Abundance Percentage
en algae	*not detected*	0	0.0
oms	*Fragilaria*	5	35.7
oflagellates	*Gymnodinium tenuissimum*	8	57.1
	Ceratium cornutum	1	7.1
		14	***100.0***

ple collected on June 21 - Raw water from Surface water reservoir 50 m from the T/Works .

JKUAT WATER SUPPLY RAW WATER PHYTOPLANKTON ANALYSES - JUNE 2000			
type	Green algae	Diatoms	Dinoflagellates
dance in sample	*0.0%*	*35.7%*	*64.3%*
Species		Fragilaria	Gymnodinium tenuissimum Ceratium comutum
rophyll-a Concentration (ug/l)			*0.038*

sy of Department of Botany: University of Nairobi, Chiromo Campus.

Algae type	Species	Total number in 10 drops	Abundance (%)
n algae	*not detected*	0	0.0
ms	*Fragilaria*	5	35.7
flagellates	*Gymnodinium tenuissimum*	8	57.1
	Ceratium cornutum	1	7.1
		14	***100.0***

le collected on June 21 - Raw water from Surface water reservoir 50 m from the T/Works .

RUIRU DAM PHYTOPLANKTON ANALYSES - AUGUST 2000			
type	Green algae	Blue green	Diatoms & Dinoflagellates
dance in sample	*12.0%*	*12.0%*	*76.0%*
Species	Closterium spp. Oocystis spp.	Microsystis aeruginosa	Synedra spp. Glenodinium spp.
rophyll-a Concentration (ug/l)			***0.075***

sy of Department of Botany: University of Nairobi, Chiromo Campus.

Algae type	Species	Total number in 10 drops	Abundance (%)
n algae	*Closterium spp.*	2	8.0
	Oocystis spp.	1	4.0
-green algae	*Microsystis aeruginosa*	3	12.0
oms	*Synedra spp.*	4	16.0
flagellates	*Glenodinium spp.*	15	60.0
		25	***100.0***

le obtained from the 16", 12" and 9" ferrous Raw water pipes at Kabete T/works from Ruiru Dam on 1st August.

LABORATORY ALGAE CULTURE PHYTOPLANKTON ANALYSES - JUNE 2000			
ae type	Green algae	Blue green	Dinoflagellates
ndance in sample	*37.6%*	*16.2%*	*46.2%*
ae Species	Oocystis spp. Scenedesmus quadricauda Closterium spp. Westella botryoides	Microsystis aeruginosa	Ceratium cornutum
orophyll-a Concentration (ug/l)			***0.34***

tesy of Department of Botany: University of Nairobi, Chiromo Campus.

Algae type	Species	Total number in 10 drops	Abundance (%)
een algae	*Oocystis spp.*	17	9.8
	Scenedesmus quadricauda	21	12.1
	Closterium spp.	18	10.4
	Westella botryoides	9	5.2
e-green algae	*Microsystis aeruginosa*	28	16.2
noflagellates	*Ceratium comutum*	80	46.2
		173	***100.0***

oratory cultured algae water sample.

DANDORA SEWERAGE PONDS EFFLUENT PHYTOPLANKTON ANALYSES - JULY 2000			
ype	Green algae	Blue green	Dinoflagellates
ance in sample	*8.5%*	*91.3%*	*0.2%*
Species	Oocystis sp. Carteria cordiformis Scenedesmus quadricauda Scenedesmus dimorphus Closterium sp. Elakatotarix gelatinosa Glococystis gigas Westella botryoides Spaerocystis sp.	Spirulina laxima Microsystis aeruginosa	Gymnodinium inversum
phyll-a Concentration (ug/l)			***0.83***

of Department of Botany: University of Nairobi, Chiromo Campus.

Algae type	Species	Total number in 10 drops	Abundance (%)
algae	*Oocystis sp.*	23	5.1
	Carteria cordiformis	1	0.2
	Scenedesmus quadricauda	2	0.4
	Scenedesmus dimorphus	1	0.2
	Closterium sp.	1	0.2
	Elakatotarix gelatinosa	5	1.1
	Glococystis gigas	1	0.2
	Westella botryoides	3	0.7
	Spaerocystis sp.	1	0.2
green algae	*Spirulina laxima*	404	90.0
	Microsystis aeruginosa	6	1.3
flagellates	*Gymnodinium inversum*	1	0.2
		449	***100.0***

le collected on July 18 - effluent at the outlet into Nairobi river.

Appendix 2

DAF EXPERIMENTAL DATA

DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 17/03/2000

Run No.: *WA1*

Sample Temperature (°C) : *22*

Alum Dose (mg/l) : *30*

Rapid mix : Speed : *120 r.p.m* Time : *30 sec.*

Flocculation : Speed : *40 r.p.m* Time : *15 min.*

Saturation Pressure (kPa) : *483*

TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol (ml)	Recycle Vol. (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (ug/l)	Clarified water (ug/l)
4000	400	10	0		20		80		8.01		0.54	
4000	400	10	10	<1	20	8	80	30		7.87	0.54	0.132
4000	400	10	20	<1	20	7.5	80	30		7.88	0.54	0.123
4000	400	10	30	<1	20	7.5	80	30		7.88	0.54	0.128
4000	400	10	60	1	20	7	80	30		7.87	0.54	0.121

Comments & Observations :-

Raw water pH was lowered by use of mineral acid.

Sludge layer not uniformly formed.

DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 17/03/2000

Run No.: *WA2*

Sample Temperature (°C) : *22*

Alum Dose (mg/l) : *30*

Rapid mix : Speed : *120 r.p.m* Time : *30 sec.*

Flocculation : Speed : *40 r.p.m* Time : *15 min.*

Saturation Pressure (kPa) : *483*

TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol. (ml)	Recycle Vol. (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (ug/l)	Clarified water (ug/l)
4000	800	20	0		20		80		8		0.53	
4000	800	20	10	1.5	20	4	80	15		7.87	0.53	0.11
4000	800	20	20	2	20	3	80	15		7.87	0.53	0.108
4000	800	20	30	2	20	2.5	80	15		7.86	0.53	0.108
4000	800	20	60	2	20	2.5	80	15		7.86	0.53	0.106

Comments & Observations :-

Raw water pH was lowered by use of mineral acid.

Sludge layer uniformly formed. over the entire cross-section.

DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 17/03/2000

Run No.: *WA3*

Sample Temperature (°C) : *22*

Alum Dose (mg/l) : *30*

Rapid mix : Speed : *120 r.p.m* Time : *30 sec.*

Flocculation : Speed : *40 r.p.m* Time : *15 min.*

Saturation Pressure (kPa) : *483*

TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol. (ml)	Recycle Vol. (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (ug/l)	Clarified water (ug/l)
4000	2000	50	0		20		80		8		0.5	
4000	2000	50	10	2	20	4	80	10		7.86	0.5	0.108
4000	2000	50	20	2	20	2.5	80	10		7.85	0.5	0.106
4000	2000	50	30	2	20	2	80	10		7.86	0.5	0.106
4000	2000	50	60	2	20	2	80	10		7.88	0.5	0.106

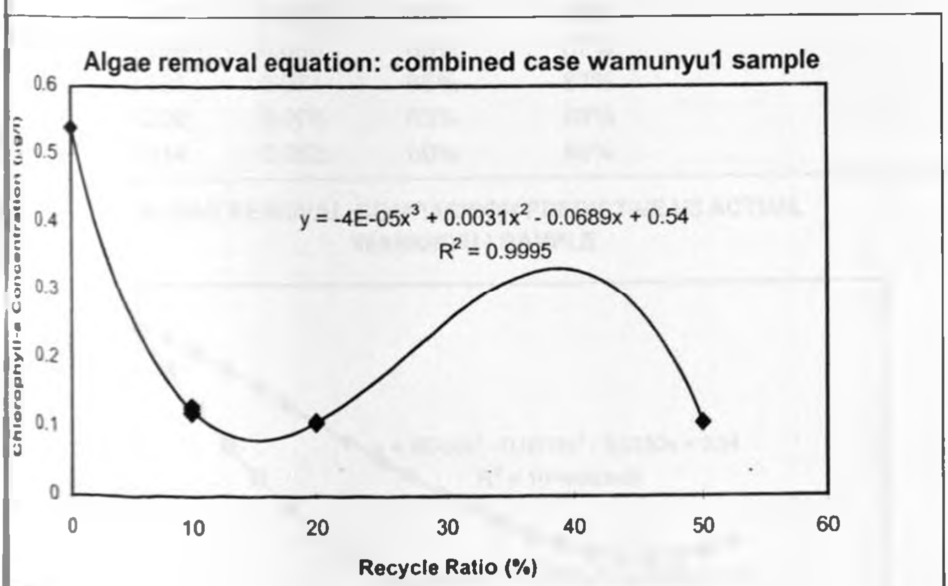
Comments & Observations :-

Raw water pH was lowered by use of mineral acid.

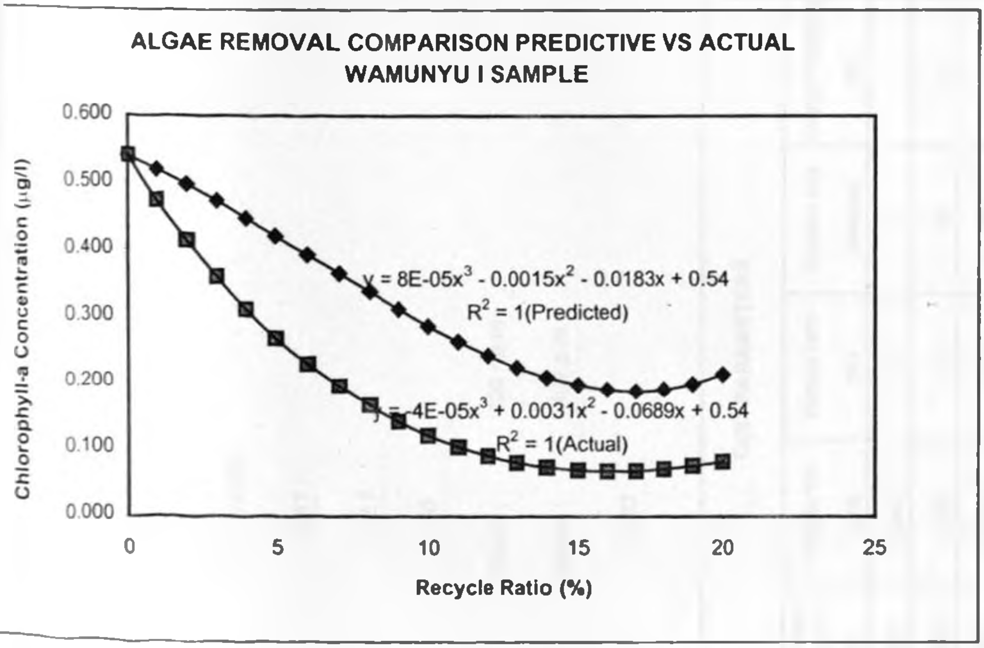
Sludge layer uniformly formed. over the entire cross-section.

Recycle ratio	Flotation	Algae			Turbidity			Color		
% of Influent sample	Time in minutes	initial concentration (ug/l)	final concentration (ug/l)	% removal	initial (NTU)	final (NTU)	% removal	initial (^{O} H)	final (^{O} H)	% improvement
6	10									
	20									
	30									
	60									
8	10									
	20									
	30									
	60									
10	10	0.54	0.132	76	20	8	60	80	30	63
	20	0.54	0.123	77	20	7.5	63	80	30	63
	30	0.54	0.128	76	20	7.5	63	80	30	63
	60	0.54	0.121	78	20	7	65	80	30	63
12	10									
	20									
	30									
	60									
20	10	0.53	0.11	79	20	4	80	80	15	81
	20	0.53	0.108	80	20	3	85	80	15	81
	30	0.53	0.108	80	20	2.5	88	80	15	81
	60	0.53	0.106	80	20	2.5	88	80	15	81
50	10	0.50	0.108	78	20	4	80	80	10	88
	20	0.50	0.106	79	20	2.5	88	80	10	88
	30	0.50	0.106	79	20	2	90	80	10	88
	60	0.50	0.106	79	20	2	90	80	10	88

Recycle Ratio(%)	Algae Conc. (μg/l)
0	0.54
10	0.132
10	0.123
10	0.128
10	0.121
20	0.11
20	0.108
20	0.108
20	0.106
50	0.108
50	0.106
50	0.106
50	0.106



ycle %	Predictive Algae (μg/l)	Actual Algae (μg/l)	Predictive Algae % Removal	Actual Algae % Removal
)	0.540	0.540	0%	0%
I	0.520	0.474	4%	12%
2	0.498	0.414	8%	23%
3	0.474	0.360	12%	33%
4	0.448	0.311	17%	42%
5	0.421	0.268	22%	50%
6	0.393	0.230	27%	57%
7	0.366	0.196	32%	64%
8	0.339	0.167	37%	69%
9	0.312	0.142	42%	74%
10	0.287	0.121	47%	78%
11	0.264	0.104	51%	81%
12	0.243	0.090	55%	83%
13	0.224	0.080	58%	85%
14	0.209	0.073	61%	86%
15	0.198	0.069	63%	87%
16	0.191	0.067	65%	88%
17	0.188	0.068	65%	87%
18	0.191	0.071	65%	87%
19	0.200	0.076	63%	86%
20	0.214	0.082	60%	85%



DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 03/04/2000

Run No.: LA1

Sample Temperature (°C) : 22.1

Alum Dose (mg/l) : 20

Rapid mix : Speed : 120 r.p.m Time : 30 sec.

Flocculation : Speed : 40 r.p.m Time : 15 min.

Saturation Pressure (kPa) : 483

TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol. (ml)	Recycle Vol. (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (ug/l)	Clarified water (ug/l)
4000	240	6	0		25		70		7.14		0.342	
4000	240	6	10	<1	25	4.5	70	50		6.9	0.342	0.241
4000	240	6	20	1	25	4.2	70	50		6.9	0.342	0.238
4000	240	6	30	1	25	4.2	70	50		7	0.342	0.232
4000	240	6	60	1	25	4	70	50		6.9	0.342	0.188

Comments Observations:-

Sludge cake not fully formed only patches floating at the end of ten minutes.

DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 06/04/2000

Run No.: LA3

Sample Temperature (°C) : 22

Alum Dose (mg/l) : 20

Rapid mix : Speed : 120 r.p.m Time : 30 sec.

Flocculation : Speed : 40 r.p.m Time : 15 min.

Saturation Pressure (kPa) : 483

TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol. (ml)	Recycle Vol. (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (ug/l)	Clarified water (ug/l)
4000	400	10	0		25		70		7.14		0.33	
4000	400	10	10	1	25	4	70	40		6.9	0.33	0.093
4000	400	10	20	1.5	25	3.8	70	30		6.9	0.33	0.083
4000	400	10	30	2	25	3.7	70	30		6.9	0.33	0.093
4000	400	10	60	2	25	3.7	70	30		6.9	0.33	0.093

Comments & Observations :-

Uniformly formed sludge layer.

DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 03/04/2000

Run No.: *LA2*

Sample Temperature (°C) : *22*

Alum Dose (mg/l) : *20*

Rapid mix : Speed : *120 r.p.m* Time : *30 sec.*

Flocculation : Speed : *40 r.p.m* Time : *15 min.*

Saturation Pressure (kPa) : *483*

TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol (ml)	Recycle Vol (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (ug/l)	Clarified water (ug/l)
4000	320	8	0		25		70		7.1		0.341	
4000	320	8	10	1	25	3.9	70	30		6.87	0.341	0.147
4000	320	8	20	1.5	25	3.8	70	30		6.89	0.341	0.127
4000	320	8	30	1.5	25	3.8	70	30		6.86	0.341	0.121
4000	320	8	60	1.5	25	3.6	70	30		6.9	0.341	0.121

Comments & Observations:-
Sludge layer fully formed and uniform throughout the cross-section of the flotation unit.

Laboratory Sample

DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 06/04/2000

Run No.: *LA4*

Sample Temperature (°C) : 22

Alum Dose (mg/l) : 20

Rapid mix : Speed : *120 r.p.m* Time : *30 sec.*

Flocculation : Speed : *40 r.p.m* Time : *15 min.*

Saturation Pressure (kPa) : 483

TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol. (ml)	Recycle Vol (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (ug/l)	Clarified water (ug/l)
4000	480	12	0		23		70		7.1		0.34	
4000	480	12	10	1.5	23	3.5	70	15		6.87	0.34	0.073
4000	480	12	20	1.5	23	3.4	70	15		6.74	0.34	0.073
4000	480	12	30	1.5	23	3.4	70	15		6.8	0.34	0.073
4000	480	12	60	1.5	23	3.4	70	15		6.83	0.34	0.073

Comments & Observations :-

Uniformly formed sludge layer.

DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 06/04/2000

Run No.: LA5

Sample Temperature (°C) : 22

Alum Dose (mg/l) : 20

Rapid mix : Speed : 120 r.p.m Time : 30 sec.

Flocculation : Speed : 40 r.p.m Time : 15 min.

Saturation Pressure (kPa) : 483

TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol. (ml)	Recycle Vol. (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (ug/l)	Clarified water (ug/l)
4000	800	20	0		24		70		7.14		0.34	
4000	800	20	10	2	24	3.3	70	10		6.8.	0.34	0.047
4000	800	20	20	2	24	3	70	10		6.79	0.34	0.047
4000	800	20	30	2	24	3	70	10		6.92	0.34	0.047
4000	800	20	60	2	24	3	70	10		6.9	0.34	0.047

Comments:-
Uniformly formed sludge layer.

DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 07/04/2000

Run No.: *LA6*

Sample Temperature (°C) : *22*

Alum Dose (mg/l) : *20*

Rapid mix : Speed : *120 r.p.m* Time : *30 sec.*

Flocculation : Speed : *40 r.p.m* Time : *15 min.*

Saturation Pressure (kPa) : *483*

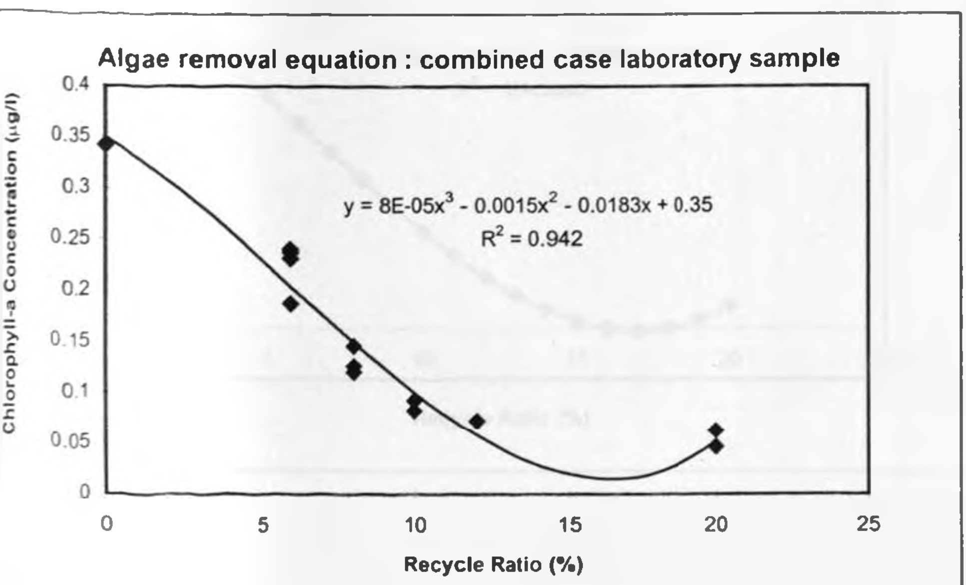
TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol (ml)	Recycle Vol (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (ug/l)	Clarified water (ug/l)
4000	2000	50	0		25		70		7.14		0.34	
4000	2000	50	10	2	25	3.5	70	10		6.87	0.34	0.058
4000	2000	50	20	2	25	3.5	70	10		6.9	0.34	0.061
4000	2000	50	30	2	25	3.3	70	10		6.93	0.34	0.06
4000	2000	50	60	2	25	3.2	70	10		6.9	0.34	0.061

Comments & Observations :-

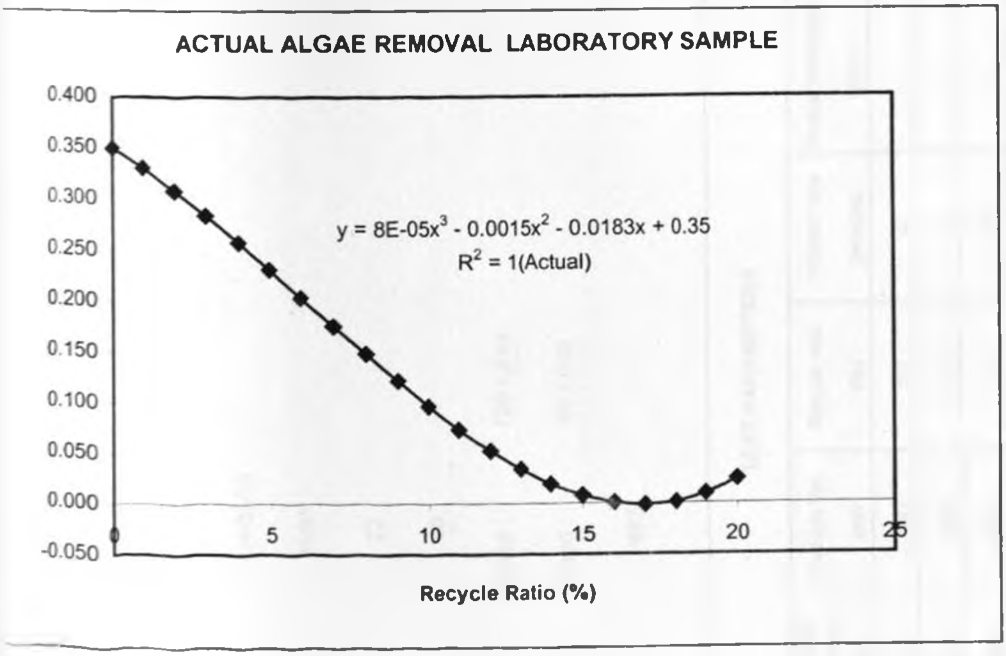
Uniformly formed sludge layer.

Recycle ratio	Flotation	Algae			Turbidity			Color		
% of Influent sample	Time in minutes	initial concentration (ug/l)	final concentration (ug/l)	% removal	initial (NTU)	final (NTU)	% removal	initial (^{O} H)	final (^{O} H)	% improvement
6	10	0.342	0.241	30	25	4.5	82	70	50	29
	20	0.342	0.238	30	25	4.2	83	70	50	29
	30	0.342	0.232	32	25	4.2	83	70	50	29
	60	0.342	0.188	45	25	4	84	70	50	29
8	10	0.341	0.147	57	25	3.9	84	70	30	57
	20	0.341	0.127	63	25	3.8	85	70	30	57
	30	0.341	0.121	65	25	3.8	85	70	30	57
	60	0.341	0.121	65	25	3.6	86	70	30	57
10	10	0.33	0.093	72	25	4	84	70	40	43
	20	0.33	0.083	75	25	3.8	85	70	30	57
	30	0.33	0.093	72	25	3.7	85	70	30	57
	60	0.33	0.093	72	25	3.7	85	70	30	57
12	10	0.34	0.073	79	23	3.5	85	70	15	79
	20	0.34	0.073	79	23	3.4	85	70	15	79
	30	0.34	0.073	79	23	3.4	85	70	15	79
	60	0.34	0.073	79	23	3.4	85	70	15	79
20	10	0.34	0.063	81	24	3.3	86	70	15	79
	20	0.34	0.047	86	24	3	88	70	10	86
	30	0.34	0.047	86	24	3	88	70	10	86
	60	0.34	0.047	86	24	3	88	70	10	86
50	10	0.34	0.058	83	25	3.5	86	70	10	86
	20	0.34	0.061	82	25	3.5	86	70	10	86
	30	0.34	0.06	82	25	3.3	87	70	10	86
	60	0.34	0.061	82	25	3.2	87	70	10	86

Recycle Ratio(%)	Algae Conc. (μg/l)
0	0.342
6	0.241
6	0.238
6	0.232
6	0.188
8	0.147
8	0.127
8	0.121
8	0.121
10	0.093
10	0.083
10	0.093
10	0.093
12	0.073
12	0.073
12	0.073
12	0.073
20	0.063
20	0.047
20	0.047
20	0.047



Recycle %	Actual Algae (μg/l)	Actual Algae % Removal
0	0.350	0%
1	0.330	6%
2	0.308	12%
3	0.284	19%
4	0.258	26%
5	0.231	34%
6	0.203	42%
7	0.176	50%
8	0.149	58%
9	0.122	65%
10	0.097	72%
11	0.074	79%
12	0.053	85%
13	0.034	90%
14	0.019	94%
15	0.008	98%
16	0.001	100%
17	-0.002	100%
18	0.001	100%
19	0.010	97%
20	0.024	93%



DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 19/04/2000

Run No.: *WB1*

Sample Temperature (°C) : *22*

Alum Dose (mg/l) : *40*

Rapid mix : Speed : *120 r.p.m* Time : *30 sec.*

Flocculation : Speed : *40 r.p.m* Time : *15 min.*

Saturation Pressure (kPa) : *483*

TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol (ml)	Recycle Vol. (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (ug/l)	Clarified water (ug/l)
4000	*400*	*10*	*0*		*37*		*80*		*7.6*		*0.144*	
4000	*400*	*10*	*10*	*1*	*37*	*11*	*80*	*20*		*7.5*	*0.144*	*0.04*
4000	*400*	*10*	*20*	*1*	*37*	*10*	*80*	*20*		*7.5*	*0.144*	*0.035*
4000	*400*	*10*	*30*	*1*	*37*	*10*	*80*	*20*		*7.47*	*0.144*	*0.035*
4000	*400*	*10*	*60*	*1*	*37*	*10*	*80*	*20*		*7.48*	*0.144*	*0.035*

Comments & Observations :-

Thinly formed sludge layer.

DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 19/04/2000

Run No.: WB2

Sample Temperature (°C) : 22

Alum Dose (mg/l) : 40

Rapid mix : Speed : 120 r.p.m Time : 30 sec.

Flocculation : Speed : 40 r.p.m Time : 15 min.

Saturation Pressure (kPa) : 483

TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol. (ml)	Recycle Vol. (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (ug/l)	Clarified water (ug/l)
4000	800	20	0		37		80		7.66		0.144	
4000	800	20	10	3	37	7	80	15		7.48	0.144	0.031
4000	800	20	20	3	37	7	80	15		7.42	0.144	0.03
4000	800	20	30	3	37	7	80	15		7.42	0.144	0.03
4000	800	20	60	3	37	5	80	15		7.41	0.144	0.03

Comments & Observations :-

Thick well formed sludge layer.

DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 19/04/2000

Run No.: *WB3*

Sample Temperature (°C) : *22*

Alum Dose (mg/l) : *40*

Rapid mix : Speed : *120 r.p.m* Time : *30 sec.*

Flocculation : Speed : *40 r.p.m* Time : *15 min.*

Saturation Pressure (kPa) : *483*

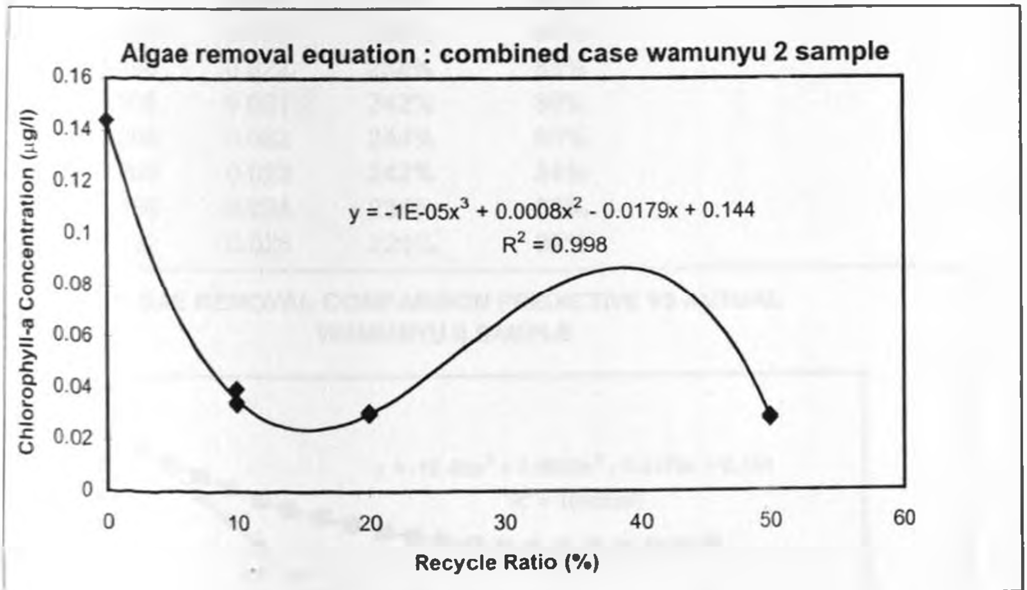
TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol. (ml)	Recycle Vol (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (ug/l)	Clarified water (ug/l)
4000	2000	50	0		37		80		7.67		0.144	
4000	2000	50	10	3	37	5	80	10		7.49	0.144	0.029
4000	2000	50	20	3	37	5	80	10		7.46	0.144	0.029
4000	2000	50	30	3	37	5	80	10		7.48	0.144	0.028
4000	2000	50	60	3	37	5	80	10		7.48	0.144	0.028

Comments and Observations :-

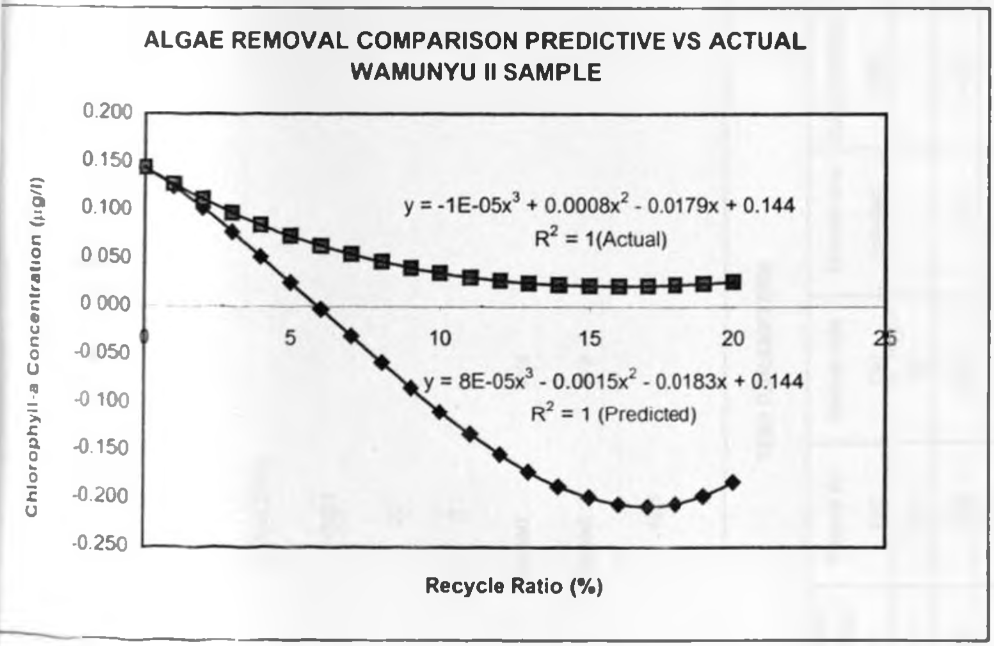
Thick well formed sludge layer.

Recycle ratio % of Influent sample	Flotation Time in minutes	Algae initial concentration (ug/l)	Algae final concentration (ug/l)	Algae % removal	Turbidity initial (NTU)	Turbidity final (NTU)	Turbidity % removal	Color initial (°H)	Color final (°H)	Color % improvement
6	10									
	20									
	30									
	60									
8	10									
	20									
	30									
	60									
10	10	0.144	0.04	72	37	11	70	80	20	75
	20	0.144	0.035	76	37	10	73	80	20	75
	30	0.144	0.035	76	37	10	73	80	20	75
	60	0.144	0.034	76	37	10	73	80	20	75
12	10									
	20									
	30									
	60									
20	10	0.144	0.031	78	37	7	81	80	15	81
	20	0.144	0.03	79	37	7	81	80	15	81
	30	0.144	0.03	79	37	7	81	80	15	81
	60	0.144	0.03	79	37	7	81	80	15	81
50	10	0.144	0.029	80	37	5	86	80	10	88
	20	0.144	0.029	80	37	5	86	80	10	88
	30	0.144	0.028	81	37	5	86	80	10	88
	60	0.144	0.028	81	37	5	86	80	10	88

Recycle Ratio(%)	Algae Conc. (µg/l)
0	0.144
10	0.04
10	0.035
10	0.035
10	0.034
20	0.031
20	0.03
20	0.03
20	0.03
50	0.029
50	0.029
50	0.028
50	0.028



Recycle %	Predictive Algae (μg/l)	Actual Algae (μg/l)	Predictive Algae % Removal	Actual Algae % Removal
0	0.144	0.144	0%	0%
1	0.124	0.127	14%	12%
2	0.102	0.111	29%	23%
3	0.078	0.097	46%	32%
4	0.052	0.085	64%	41%
5	0.025	0.073	83%	49%
6	-0.003	0.063	102%	56%
7	-0.030	0.054	121%	62%
8	-0.057	0.047	140%	67%
9	-0.084	0.040	158%	72%
10	-0.109	0.035	176%	76%
11	-0.132	0.031	192%	79%
12	-0.153	0.027	207%	81%
13	-0.172	0.025	219%	83%
14	-0.187	0.023	230%	84%
15	-0.198	0.022	238%	85%
16	-0.205	0.021	242%	85%
17	-0.208	0.022	244%	85%
18	-0.205	0.023	242%	84%
19	-0.196	0.024	236%	83%
20	-0.182	0.026	226%	82%



DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 20/04/2000

Run No.: CG1

Sample Temperature (°C) : 22

Alum Dose (mg/l) : 0

Rapid mix : Speed : n/a Time : n/a

Flocculation : Speed : n/a Time : n/a

Saturation Pressure (kPa) : 483

TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol (ml)	Recycle Vol. (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (µg/l)	Clarified water (µg/l)
4000	800	20	0		37		80		7.6		0.144	
4000	800	20	10	<1	37	28	80	60		7.6	0.144	0.123
4000	800	20	20	<1	37	25	80	60		7.6	0.144	0.124
4000	800	20	30	<1	37	25	80	60		7.6	0.144	0.114
4000	800	20	60	<1	37	25	80	60		7.6	0.144	0.112

Comments & Observations :-

No unifrom sludge formed, only thin patches formed.

Laboratory Sample

DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 20/04/2000

Run No.: CG2

Sample Temperature (°C) : 22

Alum Dose (mg/l) : 10

Rapid mix : Speed : 120 r.p.m Time : 30 sec.

Flocculation : Speed : 40 r.p.m Time : 15 min.

Saturation Pressure (kPa) : 483

TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol (ml)	Recycle Vol. (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (µg/l)	Clarified water (µg/l)
4000	800	20	0		37		80		7.65		0.144	
4000	800	20	10	<1	37	19	80	35		7.4	0.144	0.043
4000	800	20	20	<1	37	19	80	35		7.38	0.144	0.042
4000	800	20	30	<1	37	19	80	30		7.4	0.144	0.041
4000	800	20	60	<1	37	19	80	30		7.41	0.144	0.042

Comments & Observations :-

Sludge layer not uniformly formed in the entire cross setion.

DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 20/04/2000

Run No.: *CG3*

Sample Temperature (°C) : *22*

Alum Dose (mg/l) : *20*

Rapid mix : Speed : *120 r.p.m* Time : *30 sec.*

Flocculation : Speed : *40 r.p.m* Time : *15 min.*

Saturation Pressure (kPa) : *483*

TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol (ml)	Recycle Vol. (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (μg/l)	Clarified water (μg/l)
4000	800	20	0		37		80		7.65		0.144	
4000	800	20	10	1.5	37	12	80	30		7.22	0.144	0.044
4000	800	20	20	2	37	11	80	20		7.21	0.144	0.044
4000	800	20	30	2	37	11	80	20		7.18	0.144	0.042
4000	800	20	60	2	37	11	80	20		7.18	0.144	0.042

Comments & Observations :-

Stable sludge layer formed.

DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 20/04/2000

Run No.: CG4

Sample Temperature (°C) : 22

Alum Dose (mg/l) : 30

Rapid mix : Speed : 120 r.p.m Time : 30 sec.

Flocculation : Speed : 40 r.p.m Time : 15 min.

Saturation Pressure (kPa) : 483

TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol (ml)	Recycle Vol (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (µg/l)	Clarified water (µg/l)
4000	800	20	0		37		80		7.65		0.144	
4000	800	20	10	2	37	9	80	20		7.12	0.144	0.035
4000	800	20	20	2	37	7	80	15		7.11	0.144	0.031
4000	800	20	30	2	37	7	80	15		7.11	0.144	0.03
4000	800	20	60	2	37	7	80	15		7.11	0.144	0.03

Comments & Observations :-

Stable uniform sludge layer formed.

DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 21/04/2000

Run No.: CG5

Sample Temperature (°C) : *22*

Alum Dose (mg/l) : *40*

Rapid mix : Speed : *120 r.p.m* Time : *30 sec.*

Flocculation : Speed : *40 r.p.m* Time : *15 min.*

Saturation Pressure (kPa) : *483*

TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol. (ml)	Recycle Vol (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (µg/l)	Clarified water (µg/l)
4000	800	20	0		37		80		7.66		0.144	
4000	800	20	10	3	37	4	80	15		7.08	0.144	0.03
4000	800	20	20	3	37	4	80	10		7.02	0.144	0.03
4000	800	20	30	3	37	4	80	10		7.02	0.144	0.028
4000	800	20	60	3	37	4	80	10		7.02	0.144	0.028

Comments & Observations :-

Thick well formed sludge layer formed.

Laboratory Sample

DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 21/04/2000

Run No.: CG6

Sample Temperature (°C) : 22

Alum Dose (mg/l) : 30

Rapid mix : Speed : 120 r.p.m Time : 30 sec.

Flocculation : Speed : 40 r.p.m Time : 15 min.

Saturation Pressure (kPa) : 483

TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol (ml)	Recycle Vol. (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (µg/l)	Clarified water (µg/l)
4000	800	20	0		37		80		7.65		0.144	
4000	800	20	10	4	37	5	80	5		7.02	0.144	0.024
4000	800	20	20	4	37	5	80	5		7.01	0.144	0.024
4000	800	20	30	4	37	5	80	5		7.01	0.144	0.024
4000	800	20	60	4	37	5	80	5		7.01	0.144	0.024

Comments & Observations :-

Thick well formed sludge layer formed.

Alum dose	Time	Algae			Turbidity			Color		
(mg/l)	minutes	initial concentration (µg/l)	final concentration (µg/l)	% removal	initial (NTU)	final (NTU)	% removal	initial (° H)	final (° H)	% improvement
0	10	0.144	0.123	15%	37	28	24%	80	60	25%
	20	0.144	0.124	14%	37	25	32%	80	60	25%
	30	0.144	0.114	21%	37	25	32%	80	60	25%
	60	0.144	0.112	22%	37	25	32%	80	60	25%
10	10	0.144	0.043	70%	37	19	49%	80	35	56%
	20	0.144	0.042	71%	37	19	49%	80	35	56%
	30	0.144	0.041	72%	37	19	49%	80	30	63%
	60	0.144	0.042	71%	37	19	49%	80	30	63%
20	10	0.141	0.044	69%	37	12	68%	80	30	63%
	20	0.141	0.044	69%	37	11	70%	80	20	75%
	30	0.141	0.042	70%	37	11	70%	80	20	75%
	60	0.141	0.042	70%	37	11	70%	80	20	75%
30	10	0.141	0.035	75%	37	9	76%	80	20	75%
	20	0.141	0.031	78%	37	7	81%	80	15	81%
	30	0.141	0.03	79%	37	7	81%	80	15	81%
	60	0.141	0.03	79%	37	7	81%	80	15	81%
40	10	0.144	0.03	79%	37	4	89%	80	15	81%
	20	0.144	0.03	79%	37	4	89%	80	10	88%
	30	0.144	0.028	81%	37	4	89%	80	10	88%
	60	0.144	0.028	81%	37	4	89%	80	10	88%
60	10	0.144	0.024	83%	37	5	86%	80	5	94%
	20	0.144	0.024	83%	37	5	86%	80	5	94%
	30	0.144	0.024	83%	37	5	86%	80	5	94%
	60	0.144	0.024	83%	37	5	86%	80	5	94%

JKUAT Sample

DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 22/06/2000

Run No.: *JK1*

Sample Temperature (°C) : *22*

Alum Dose (mg/l) : *10*

Rapid mix : Speed : *120 r.p.m* Time : *30 sec.*

Flocculation : Speed : *40 r.p.m* Time : *15 min.*

Saturation Pressure (kPa) : *483*

TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol. (ml)	Recycle Vol. (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (ug/l)	Clarified water (ug/l)
4000	400	10	0		2.5		5		7.57		0.038	
4000	400	10	10	1	2.5	1.2	5	<5		7.2	0.038	ND
4000	400	10	20	1	2.5	1.1	5	<5		7.22	0.038	ND
4000	400	10	30	1	2.5	1.2	5	<5		7.32	0.038	ND
4000	400	10	60	1	2.5	1.2	5	<5		7.24	0.038	ND

Comments & Observations:-

JKUAT Sample

DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 22/06/2000

Run No.: JK2

Sample Temperature (°C) : 22

Alum Dose (mg/l) : 10

Rapid mix : Speed : 120 r.p.m Time : 30 sec.

Flocculation : Speed : 40 r.p.m Time : 15 min.

Saturation Pressure (kPa) : 483

TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol (ml)	Recycle Vol. (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (ug/l)	Clarified water (ug/l)
4000	800	20	0		2.5		5		7.57		0.038	
4000	800	20	10	2	2.5	1	5	<5		7.46	0.038	ND
4000	800	20	20	2	2.5	1	5	<5		7.48	0.038	ND
4000	800	20	30	2	2.5	1	5	<5		7.45	0.038	ND
4000	800	20	60	2	2.5	1	5	<5		7.48	0.038	ND

Comments & Observations:-

Uniformly formed sludge layer.

JKUAT Sample

DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 22/06/2000

Run No.: JK3

Sample Temperature (°C) : 22

Alum Dose (mg/l) : 10

Rapid mix : Speed : 120 r.p.m Time : 30 sec.

Flocculation : Speed : 40 r.p.m Time : 15 min.

Saturation Pressure (kPa) : 483

TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol. (ml)	Recycle Vol. (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (ug/l)	Clarified water (ug/l)
4000	2000	50	0		2.5		5		7.57		0.038	
4000	2000	50	10	2	2.5	0.6	5	<5		7.47	0.038	ND
4000	2000	50	20	2	2.5	0.6	5	<5		7.48	0.038	ND
4000	2000	50	30	2	2.5	0.6	5	<5		7.48	0.038	ND
4000	2000	50	60	2	2.5	0.6	5	<5		7.48	0.038	ND

Comments & Observations :-

Uniformly formed sludge layer.

Recycle ratio	Flotation	Algae			Turbidity			Color		
% of Influent sample	Time in minutes	initial concentration (ug/l)	final concentration (ug/l)	% removal	initial (NTU)	final (NTU)	% removal	initial (° H)	final (° H)	% improvement
6	10									
	20									
	30									
	60									
8	10									
	20									
	30									
	60									
10	10	0.038	nd		2.5	1.2	52	5	<5	
	20	0.038	nd		2.5	1.1	56	5	<5	
	30	0.038	nd		2.5	1.2	52	5	<5	
	60	0.038	nd		2.5	1.2	52	5	<5	
12	10									
	20									
	30									
	60									
20	10	0.038	nd		2.5	1	60	5	<5	
	20	0.038	nd		2.5	1	60	5	<5	
	30	0.038	nd		2.5	1	60	5	<5	
	60	0.038	nd		2.5	1	60	5	<5	
50	10	0.038	nd		2.5	0.6	76	5	<5	
	20	0.038	nd		2.5	0.6	76	5	<5	
	30	0.038	nd		2.5	0.6	76	5	<5	
	60	0.038	nd		2.5	0.6	76	5	<5	
100	10									
	20									
	30									
	60									

Dandora Ponds Sample

DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 19/07/2000

Run No.: *DA1*

Sample Temperature (°C) : *22*

Alum Dose (mg/l) : *120*

Rapid mix : Speed : *120 r.p.m* Time : *30 sec.*

Flocculation : Speed : *40 r.p.m* Time : *15 min.*

Saturation Pressure (kPa) : *483*

TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol. (ml)	Recycle Vol (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (ug/l)	Clarified water (ug/l)
4000	400	10	0		48		80		7.02		0.83	
4000	400	10	10	2	48	11	80	20		6.54	0.83	0.14
4000	400	10	20	2	48	10	80	20		6.48	0.83	0.14
4000	400	10	30	2	48	10	80	20		6.53	0.83	0.14
4000	400	10	60	2	48	10	80	20		6.48	0.83	0.14

Comments & Observations :-
Uniformly formed sludge layer.

Dandora Ponds Sample

DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 19/07/2000

Run No.: *DA2*

Sample Temperature (°C) : *22*

Alum Dose (mg/l) : *120*

Rapid mix : Speed : *120 r.p.m* Time : *30 sec.*

Flocculation : Speed : *40 r.p.m* Time : *15 min.*

Saturation Pressure (kPa) : *483*

TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol (ml)	Recycle Vol (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (ug/l)	Clarified water (ug/l)
4000	800	20	0		48		80		7.05		0.83	
4000	800	20	10	3	48	8	80	15		6.56	0.83	0.127
4000	800	20	20	3	48	8	80	15		6.57	0.83	0.124
4000	800	20	30	3	48	8	80	15		6.54	0.83	0.124
4000	800	20	60	3	48	8	80	15		6.57	0.83	0.121

Comments & Observations :-

Thick well formed sludge layer.

Dandora Ponds Sample

DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 19/07/2000

Run No.: *DA3*

Sample Temperature (°C) : *22*

Alum Dose (mg/l) : *120*

Rapid mix : Speed : *120 r.p.m* Time : *30 sec.*

Flocculation : Speed : *40 r.p.m* Time : *15 min.*

Saturation Pressure (kPa) : *483*

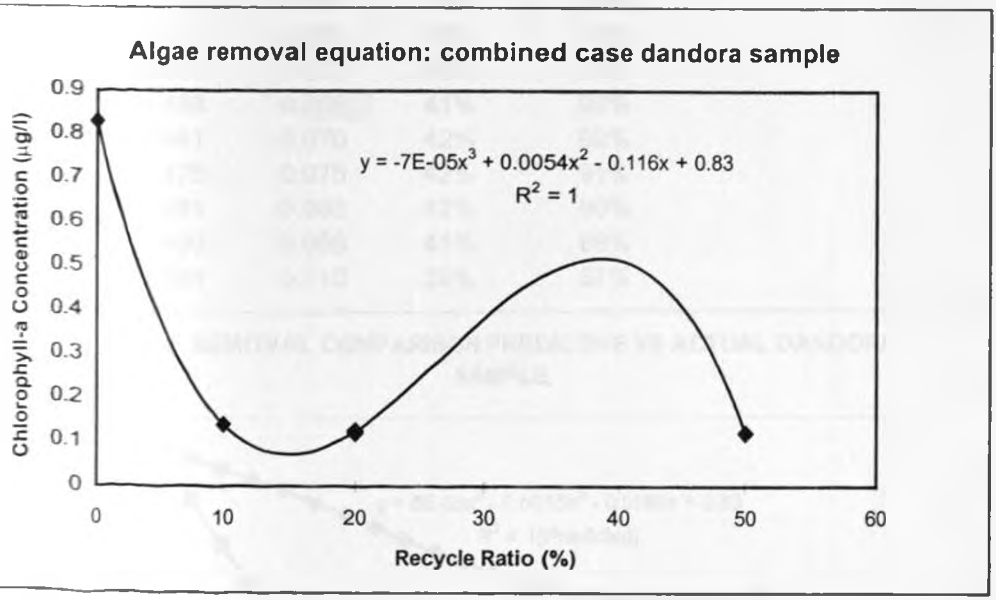
TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol. (ml)	Recycle Vol. (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (ug/l)	Clarified water (ug/l)
4000	2000	50	0		48		80		7.02		0.83	
4000	2000	50	10	3	48	6	80	10		6.58	0.83	0.122
4000	2000	50	20	3	48	6	80	10		6.5	0.83	0.121
4000	2000	50	30	3	48	6	80	10		6.56	0.83	0.121
4000	2000	50	60	3	48	6	80	10		6.59	0.83	0.121

Comments & Observations :-

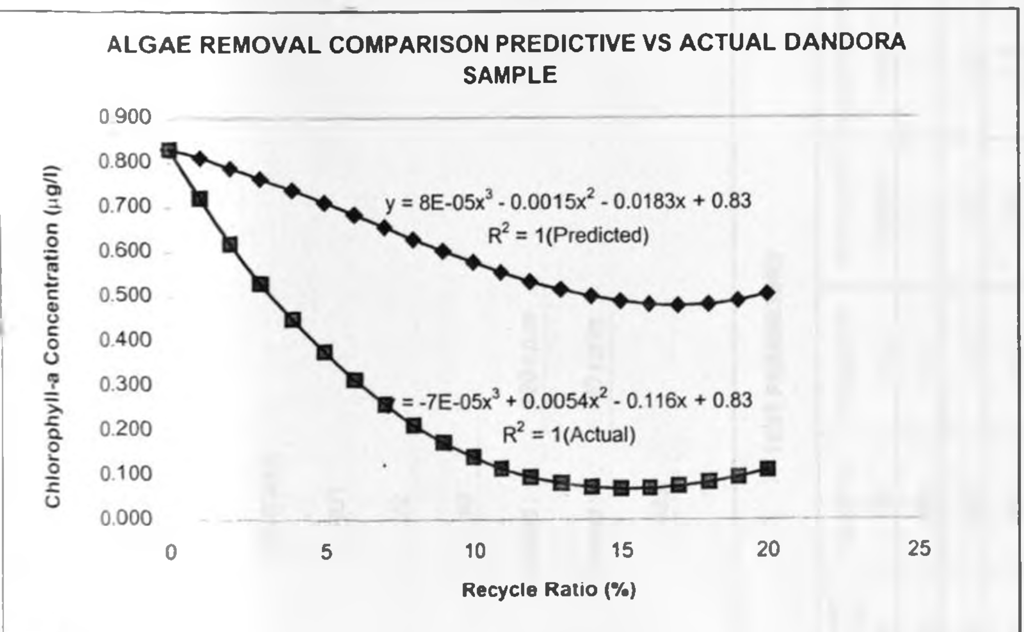
Thick well formed sludge layer.

Recycle ratio	Flotation	Algae			Turbidity			Color		
% of Influent sample	Time in minutes	initial concentration (ug/l)	final concentration (ug/l)	% removal	initial (NTU)	final (NTU)	% removal	initial (° H)	final (° H)	% improvement
6	10									
	20									
	30									
	60									
8	10									
	20									
	30									
	60									
10	10	0.83	0.14	83	48	11	77	80	20	75
	20	0.83	0.14	83	48	10	79	80	20	75
	30	0.83	0.14	83	48	10	79	80	20	75
	60	0.83	0.14	83	48	10	79	80	20	75
12	10									
	20									
	30									
	60									
20	10	0.83	0.127	85	48	8	83	80	15	81
	20	0.83	0.124	85	48	8	83	80	15	81
	30	0.83	0.124	85	48	8	83	80	15	81
	60	0.83	0.121	85	48	8	83	80	15	81
50	10	0.83	0.122	85	48	6	88	80	10	88
	20	0.83	0.121	85	48	6	88	80	10	88
	30	0.83	0.121	85	48	6	88	80	10	88
	60	0.83	0.121	85	48	6	88	80	10	88

Recycle Ratio(%)	Algae Conc. (μg/l)
0	0.83
10	0.14
10	0.14
10	0.14
10	0.14
20	0.127
20	0.124
20	0.124
20	0.121
50	0.122
50	0.121
50	0.121
50	0.121



Recycle %	Predictive Algae (μg/l)	Actual Algae (μg/l)	Predictive Algae % Removal	Actual Algae % Removal
0	0.830	0.830	0%	0%
1	0.810	0.719	2%	13%
2	0.788	0.619	5%	25%
3	0.764	0.529	8%	36%
4	0.738	0.448	11%	46%
5	0.711	0.376	14%	55%
6	0.683	0.313	18%	62%
7	0.656	0.259	21%	69%
8	0.629	0.212	24%	74%
9	0.602	0.172	27%	79%
10	0.577	0.140	30%	83%
11	0.554	0.114	33%	86%
12	0.533	0.095	36%	89%
13	0.514	0.081	38%	90%
14	0.499	0.072	40%	91%
15	0.488	0.069	41%	92%
16	0.481	0.070	42%	92%
17	0.478	0.075	42%	91%
18	0.481	0.083	42%	90%
19	0.490	0.095	41%	89%
20	0.504	0.110	39%	87%



DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 02/08/2000

Run No.: *RU1*

Sample Temperature (°C) : 22

Alum Dose (mg/l) : *10*

Rapid mix : Speed : *120 r.p.m* Time : *30 sec.*

Flocculation : Speed : *40 r.p.m* Time : *15 min.*

Saturation Pressure (kPa) : *483*

TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol. (ml)	Recycle Vol. (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (ug/l)	Clarified water (ug/l)
4000	400	10	0		1.5		10		7.16		0.075	
4000	400	10	10	1.5	1.5	1	10	5		7	0.075	ND
4000	400	10	20	1.5	1.5	1	10	5		6.92	0.075	ND
4000	400	10	30	1.5	1.5	1	10	5		6.97	0.075	ND
4000	400	10	60	1.5	1.5	1	10	5		6.98	0.075	ND

Comments & Observations :-

Uniformly formed sludge layer.

DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 02/08/2000

Run No.: *RU2*

Sample Temperature (°C) : *22*

Alum Dose (mg/l) : *10*

Rapid mix : Speed : *120 r.p.m* Time : *30 sec.*

Flocculation : Speed : *40 r.p.m* Time : *15 min.*

Saturation Pressure (kPa) : *483*

TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol (ml)	Recycle Vol (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (ug/l)	Clarified water (ug/l)
4000	800	20	0		1.5		10		7.14		0.075	
4000	800	20	10	2	1.5	0.8	10	<5		6.94	0.075	ND
4000	800	20	20	2	1.5	0.7	10	<5		6.97	0.075	ND
4000	800	20	30	2	1.5	0.7	10	<5		6.98	0.075	ND
4000	800	20	60	2	1.5	0.7	10	<5		6.97	0.075	ND

Comments & Observations :-

Well formed sludge layer.

Ruiru Dam Sample

DISSOLVED AIR FLOTATION DATA COLLECTION SHEET

Date : 02/08/2000

Run No.: RU3

Sample Temperature (°C) : 22

Alum Dose (mg/l) : 10

Rapid mix : Speed : 120 r.p.m Time : 30 sec.

Flocculation : Speed : 40 r.p.m Time : 15 min.

Saturation Pressure (kPa) : 483

TEST PARAMETERS					TURBIDITY		COLOR		pH		CHLOROPHYLL - A	
Raw Water Sample Vol (ml)	Recycle Vol (ml)	Recycle ratio (%)	Flotation time (minutes)	Sludge Thickness (mm)	Raw water (NTU)	Clarified water (NTU)	Raw water (°H)	Clarified water (°H)	Raw water	Clarified water	Raw water (ug/l)	Clarified water (ug/l)
4000	2000	50	0		1.5		10		7.14		0.075	
4000	2000	50	10	2	1.5	0.5	10	<5		6.97	0.075	ND
4000	2000	50	20	2	1.5	0.5	10	<5		6.95	0.075	ND
4000	2000	50	30	2	1.5	0.5	10	<5		6.96	0.075	ND
4000	2000	50	60	2	1.5	0.5	10	<5		6.97	0.075	ND

Comments & Observations :-

Well formed sludge layer.

Recycle ratio	Flotation	Algae			Turbidity			Color		
% of Influent sample	Time in minutes	initial concentration (ug/l)	final concentration (ug/l)	% removal	initial (NTU)	final (NTU)	% removal	initial (^{O} H)	final (^{O} H)	% improvement
6	10									
	20									
	30									
	60									
8	10									
	20									
	30									
	60									
10	10	0.075	nd		1.5	1	33	10	5	50
	20	0.075	nd		1.5	1	33	10	5	50
	30	0.075	nd		1.5	1	33	10	5	50
	60	0.075	nd		1.5	1	33	10	5	50
12	10									
	20									
	30									
	60									
20	10	0.075	nd		1.5	0.8	47	10	<5	
	20	0.075	nd		1.5	0.7	53	10	<5	
	30	0.075	nd		1.5	0.7	53	10	<5	
	60	0.075	nd		1.5	0.7	53	10	<5	
50	10	0.075	nd		1.5	0.5	67	10	<5	
	20	0.075	nd		1.5	0.5	67	10	<5	
	30	0.075	nd		1.5	0.5	67	10	<5	
	60	0.075	nd		1.5	0.5	67	10	<5	
100	10									
	20									
	30									
	60									

Appendix 3
DETAILED WATER ANALYSES

UNIVERSITY OF NAIROBI

DEPARTMENT OF CIVIL ENGINEERING

File:
Telegrams: "Varsity" Nairobi
Telephone: Nairobi 334244

PUBLIC HEALTH ENGINEERING LABORATORIES

P.O. Box 30197
NAIROBI.
KENYA.

CHEMICAL ANALYSIS FOR WATER SAMPLES

SAMPLE DESCRIPTION WAMUNYU WATER SUPPLY

RAW WATER SAMPLE I

PARAMETER	RESULT	REMARKS
p^H	9.97	
APPARENT COLOUR, °H	80	
TRUE COLOUR, °H	50	
CONDUCTIVITY, µS/cm	319	
TURBIDITY, F.T.U.	20	
CALCIUM HARDNESS as $CaCo_3$, mg/l	18	
TOTAL HARDNESS as $CaCo_3$, mg/l	50	
TOTAL ALKALINITY as $CaCo_3$, mg/l	74	
CARBONATE ALKALINITY, mg/l	15	
IRON, mg/l	0.02	
FLUORIDES, mg/l	0.99	
SULPHATES, mg/l	80	
PHOSPHATES, mg/l	0.04	
SILICA, mg/l	70	
DISSOLVED OXYGEN, p.p.m.	5.0	
NITRATES, mg/l	0.56	
MANGANESE, mg/l	0	
CHLORIDES, mg/l	80	
CHROMIUM, mg/l	0.03	
COPPER, mg/l	0.02	
TOTAL COLIFORM/100ml	-	
TOTAL FAECAL COLIFORM/100ml	-	
DISSOLVED SOLIDS, mg/l	270	
SUSPENDED SOLIDS, mg/l	30	
TOTAL SOLIDS, mg/l	300	
BIOCHEMICAL OXYGEN DEMAND, mg/l	40	
CHEMICAL OXYGEN DEMAND, mg/l	52	

GENERAL REMARKS The water sample is green in colour and very turbid. There appears to be a lot of algal growth.

SIGNED: W. Mulaku. DATE: March 2000.

UNIVERSITY OF NAIROBI

DEPARTMENT OF CIVIL ENGINEERING

File:
Telegrams: "Varsity" Nairobi
Telephone: Nairobi 334244

PUBLIC HEALTH ENGINEERING LABORATORIES

P.O. Box 30197
NAIROBI.
KENYA

CHEMICAL ANALYSIS FOR WATER SAMPLES

SAMPLE DESCRIPTION WAMUNYU WATER SUPPLY

RAW WATER SAMPLE II

PARAMETER	RESULT	REMARKS
p^H	7.66	
APPARENT COLOUR, °H	80	
TRUE COLOUR, °H	70	
CONDUCTIVITY, µS/cm	1650	
TURBIDITY, F.T.U.	37	
CALCIUM HARDNESS as $CaCo_3$, mg/l	10	
TOTAL HARDNESS as $CaCo_3$, mg/l	32	
TOTAL ALKALINITY as $CaCo_3$ mg/l	80	
CARBONATE ALKALINITY, mg/l	0	
IRON, mg/l	0.04	
FLUORIDES, mg/l	0.74	
SULPHATES, mg/l	100	
PHOSPHATES, mg/l	0.04	
SILICA, mg/l	100	
DISSOLVED OXYGEN, p.p.m.	5.2	
NITRATES, mg/l	0.48	
MANGANESE, mg/l	0	
CHLORIDES, mg/l	80	
CHROMIUM, mg/l	0.02	
COPPER, mg/l	0.03	
TOTAL COLIFORM/100ml	-	
TOTAL FAECAL COLIFORM/100ml	-	
DISSOLVED SOLIDS, mg/l	380	
SUSPENDED SOLIDS, mg/l	40	
TOTAL SOLIDS, mg/l	420	
BIOCHEMICAL OXYGEN DEMAND, mg/l	40	
CHEMICAL OXYGEN DEMAND, mg/l	52	

GENERAL REMARKS The water sample is brown in colour and very turbid. It appears to be carrying a heavy silt load.

SIGNED: W. Mulaku. DATE: April 2000

UNIVERSITY OF NAIROBI

DEPARTMENT OF CIVIL ENGINEERING

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PUBLIC HEALTH ENGINEERING LABORATORIES

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NAIROBI.
KENYA

CHEMICAL ANALYSIS FOR WATER SAMPLES

SAMPLE DESCRIPTION JKUAT SURFACE WATER RESERVOIR

RAW WATER SAMPLE

PARAMETER	RESULT	REMARKS
pH	7.57	
APPARENT COLOUR, °H	5	
TRUE COLOUR, °H	5	
CONDUCTIVITY, µS/cm	78	
TURBIDITY, F.T.U.	2.5	
CALCIUM HARDNESS as $CaCo_3$, mg/l	8	
TOTAL HARDNESS as $CaCo_3$, mg/l	28	
TOTAL ALKALINITY as $CaCo_3$ mg/l	41	
CARBONATE ALKALINITY, mg/l	0	
IRON, mg/l	0.02	
FLUORIDES, mg/l	0.97	
SULPHATES, mg/l	86	
PHOSPHATES, mg/l	0.03	
SILICA, mg/l	55	
DISSOLVED OXYGEN, p.p.m.	5.1	
NITRATES, mg/l	0.03	
MANGANESE, mg/l	0	
CHLORIDES, mg/l	18	
CHROMIUM, mg/l	0.01	
COPPER, mg/l	0.02	
TOTAL COLIFORM/100ml	-	
TOTAL FAECAL COLIFORM/100ml	-	
DISSOLVED SOLIDS, mg/l	196	
SUSPENDED SOLIDS, mg/l	0	
TOTAL SOLIDS, mg/l	196	
BIOCHEMICAL OXYGEN DEMAND, mg/l	0	
CHEMICAL OXYGEN DEMAND, mg/l	0	

GENERAL REMARKS This is a clear water sample.

SIGNED: W. Mulaku DATE: June 2000

UNIVERSITY OF NAIROBI
DEPARTMENT OF CIVIL ENGINEERING

File:
Telegrams: "Varsity" Nairobi
Telephone: Nairobi 334244

PUBLIC HEALTH ENGINEERING
LABORATORIES

P.O. Box 30197
NAIROBI.
KENYA.

CHEMICAL ANALYSIS FOR WATER SAMPLES

SAMPLE DESCRIPTION RUIRU DAM

RAW WATER SAMPLE

PARAMETER	RESULT	REMARKS
p^H	7.16	
APPARENT COLOUR, °H	10	
TRUE COLOUR, °H	<5	
CONDUCTIVITY, µS/cm	52	
TURBIDITY, F.T.U.	1.5	
CALCIUM HARDNESS as $CaCo_3$, mg/l	10	
TOTAL HARDNESS as $CaCo_3$, mg/l	36	
TOTAL ALKALINITY as $CaCo_3$ mg/l	40	
CARBONATE ALKALINITY, mg/l	0	
IRON, mg/l	0.02	
FLUORIDES, mg/l	0.92	
SULPHATES, mg/l	56	
PHOSPHATES, mg/l	0.02	
SILICA, mg/l	100	
DISSOLVED OXYGEN, p.p.m.	5.0	
NITRATES, mg/l	0.01	
MANGANESE, mg/l	0	
CHLORIDES, mg/l	12	
CHROMIUM, mg/l	0	
COPPER, mg/l	0.03	
TOTAL COLIFORM/100ml	-	
TOTAL FAECAL COLIFORM/100ml	-	
DISSOLVED SOLIDS, mg/l	270	
SUSPENDED SOLIDS, mg/l	10	
TOTAL SOLIDS, mg/l	280	
BIOCHEMICAL OXYGEN DEMAND, mg/l	0	
CHEMICAL OXYGEN DEMAND, mg/l	0	

GENERAL REMARKS The water sample is clear with some floating debris.

SIGNED: W. Mulaku. DATE: August 2000

UNIVERSITY OF NAIROBI

DEPARTMENT OF CIVIL ENGINEERING

File:
Telegrams: "Varsity" Nairobi
Telephone: Nairobi 334244

PUBLIC HEALTH ENGINEERING LABORATORIES

P.O. Box 30197
NAIROBI.
KENYA.

CHEMICAL ANALYSIS FOR WATER SAMPLES

SAMPLE DESCRIPTION DANDORA SEWERAGE PONDS EFFLUENT SAMPLE

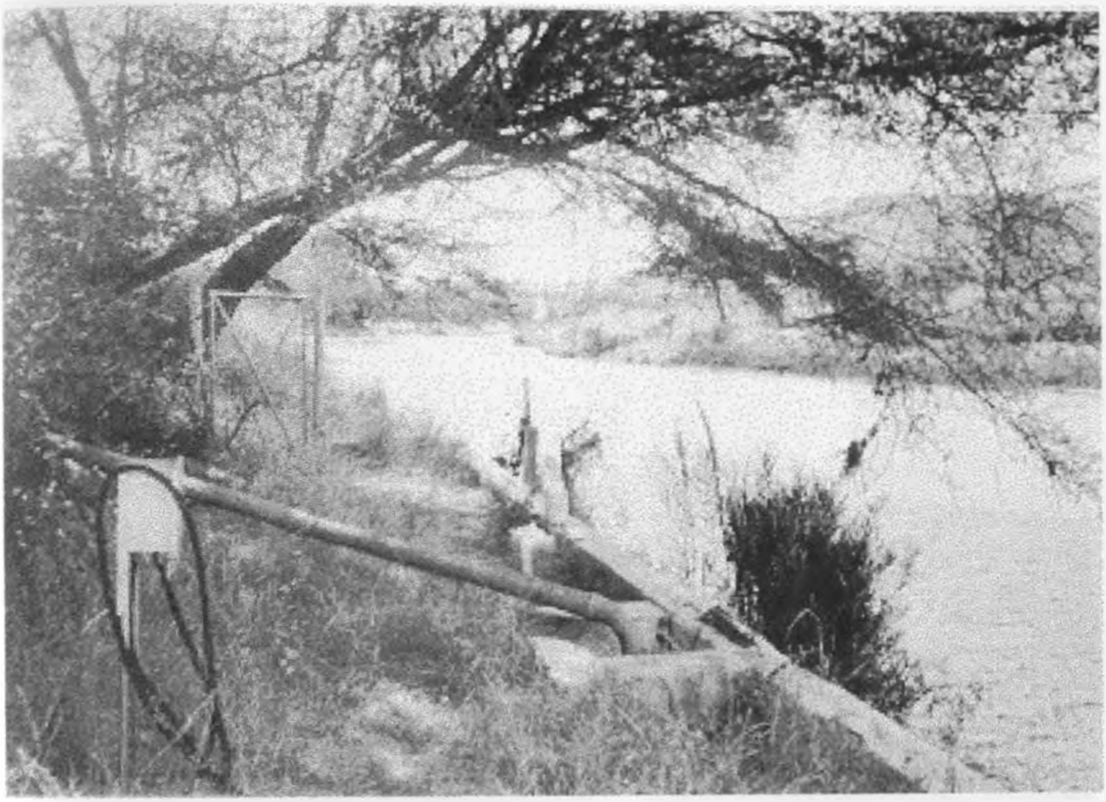
PARAMETER	RESULT	REMARKS
p^H	7.02	
APPARENT COLOUR, °H	80	
TRUE COLOUR, °H	60	
CONDUCTIVITY, µS/cm	835	
TURBIDITY, F.T.U.	48	
CALCIUM HARDNESS as CaCo₃, mg/l	42	
TOTAL HARDNESS as CaCo₃, mg/l	130	
TOTAL ALKALINITY as CaCo₃ mg/l	160	
CARBONATE ALKALINITY, mg/l	0	
IRON, mg/l	0.4	
FLUORIDES, mg/l	1.2	
SULPHATES, mg/l	110	
PHOSPHATES, mg/l	0.04	
SILICA, mg/l	80	
DISSOLVED OXYGEN, p.p.m.	4.9	
NITRATES, mg/l	0.04	
MANGANESE, mg/l	0	
CHLORIDES, mg/l	60	
CHROMIUM, mg/l	0.02	
COPPER, mg/l	0.01	
TOTAL COLIFORM/100ml	-	
TOTAL FAECAL COLIFORM/100ml	-	
DISSOLVED SOLIDS, mg/l	280	
SUSPENDED SOLIDS, mg/l	40	
TOTAL SOLIDS, mg/l	320	
BIOCHEMICAL OXYGEN DEMAND, mg/l	120	
CHEMICAL OXYGEN DEMAND, mg/l	156	

GENERAL REMARKS The water sample is green with blue-black floating particles. It is also very turbid. There appears to be alot of algae growth.

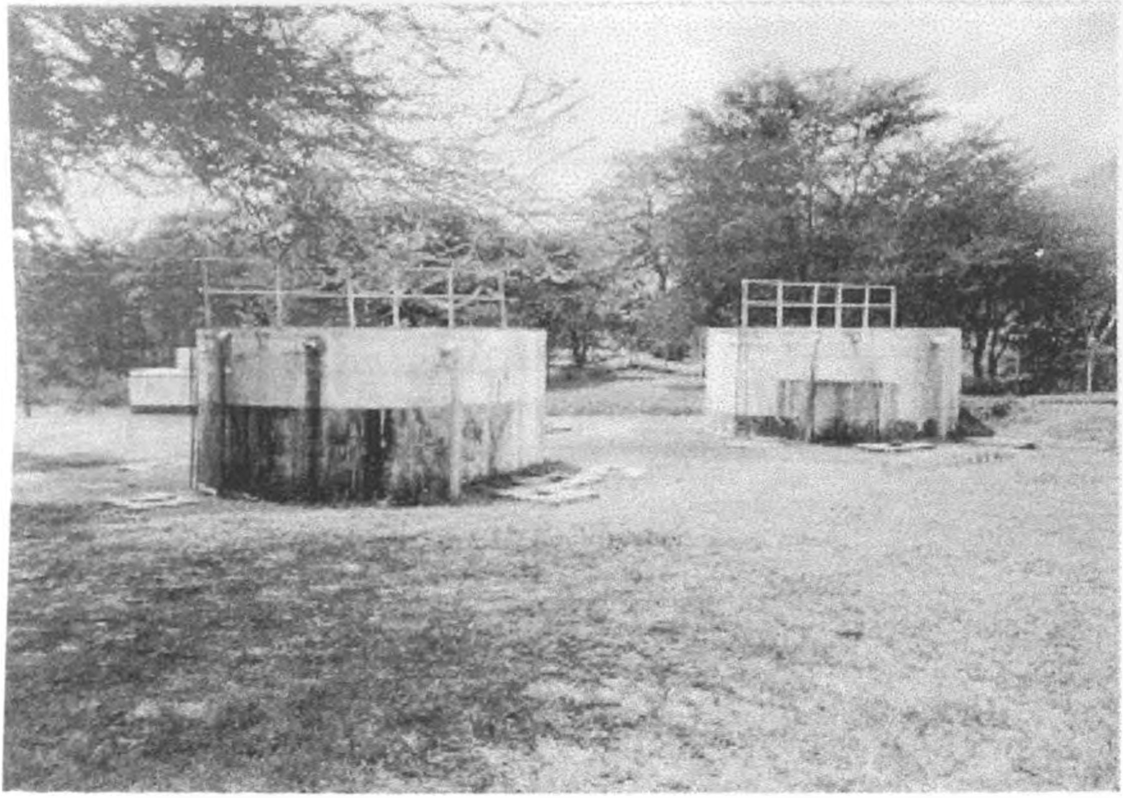
SIGNED: W. Mulaku DATE: July 2000

Appendix 4

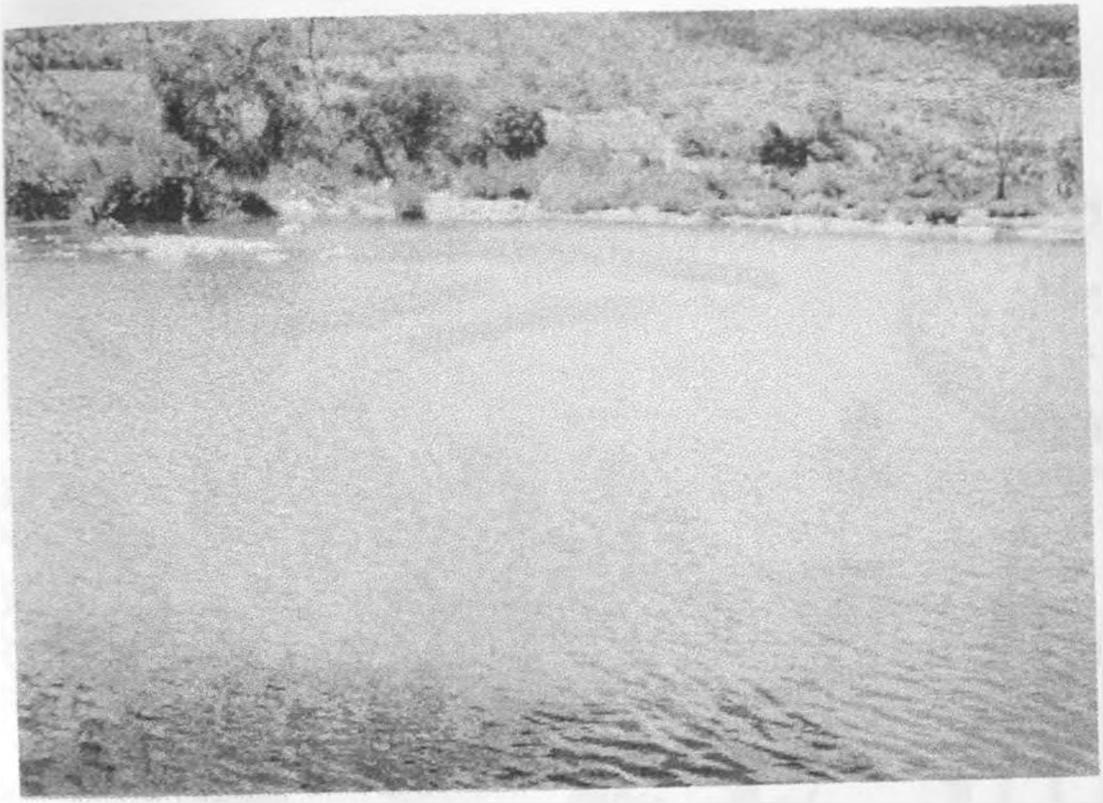
PLATES



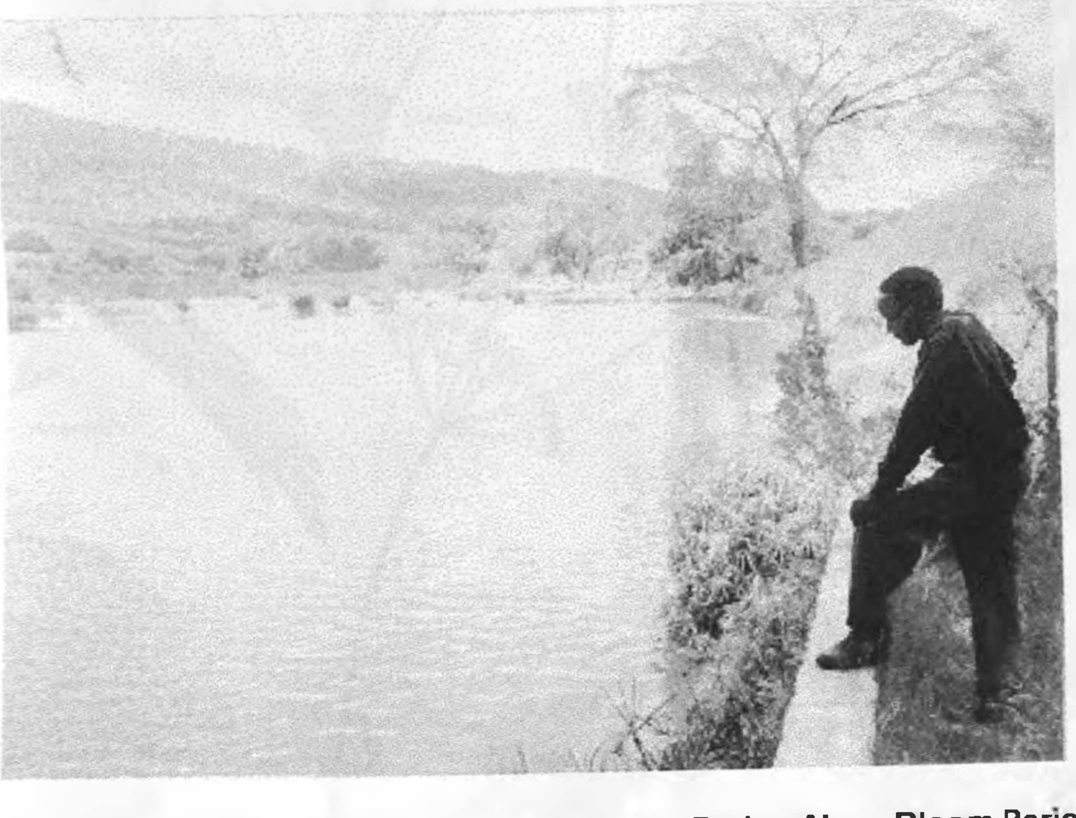
Wamunyu Waterworks Intake Structure



Wamunyu Waterworks Treatment Units



Athi River upstream of Wamunyu Intake Works During Algae Bloom Period



Athi River downstream of Wamunyu Intake Works During Algae Bloom Period

ALGAE IMPORTANT IN WATER SUPPLIES

(Extract from THE BIOLOGY SERIES: MONERA AND PROTISTA; 1970 by Robert Leftwich MILLIKEN PUBLISHING COMPANY, MISSOURI)

TASTE AND ODOR ALGAE

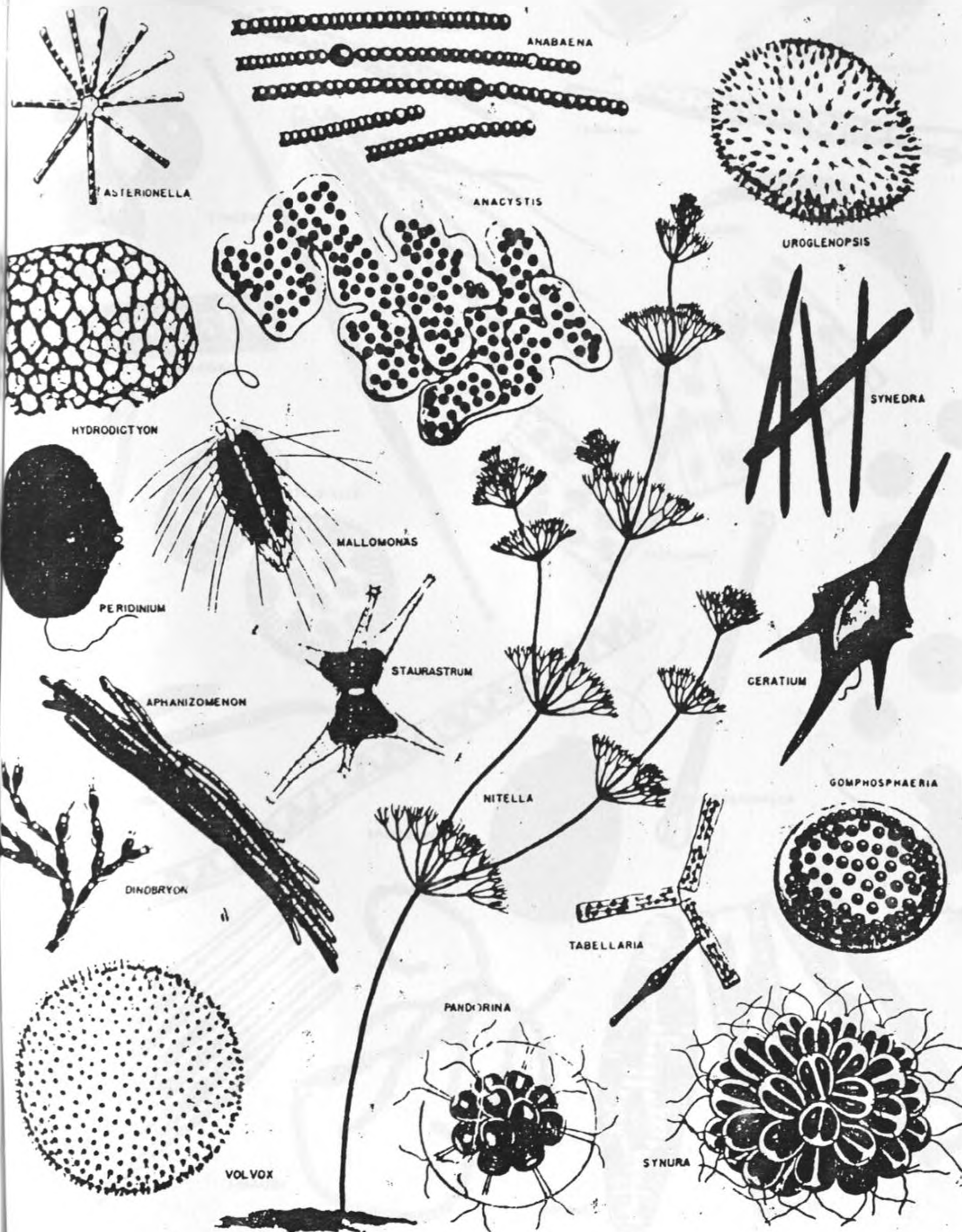


PLATE I

FILTER CLOGGING ALGAE

(Extract from: THE BIOLOGY SERIES: MONERA AND PROTISTA: 1970, by Robert Leftwich MILIKEN PUBLISHING COMPANY MISSOURI)

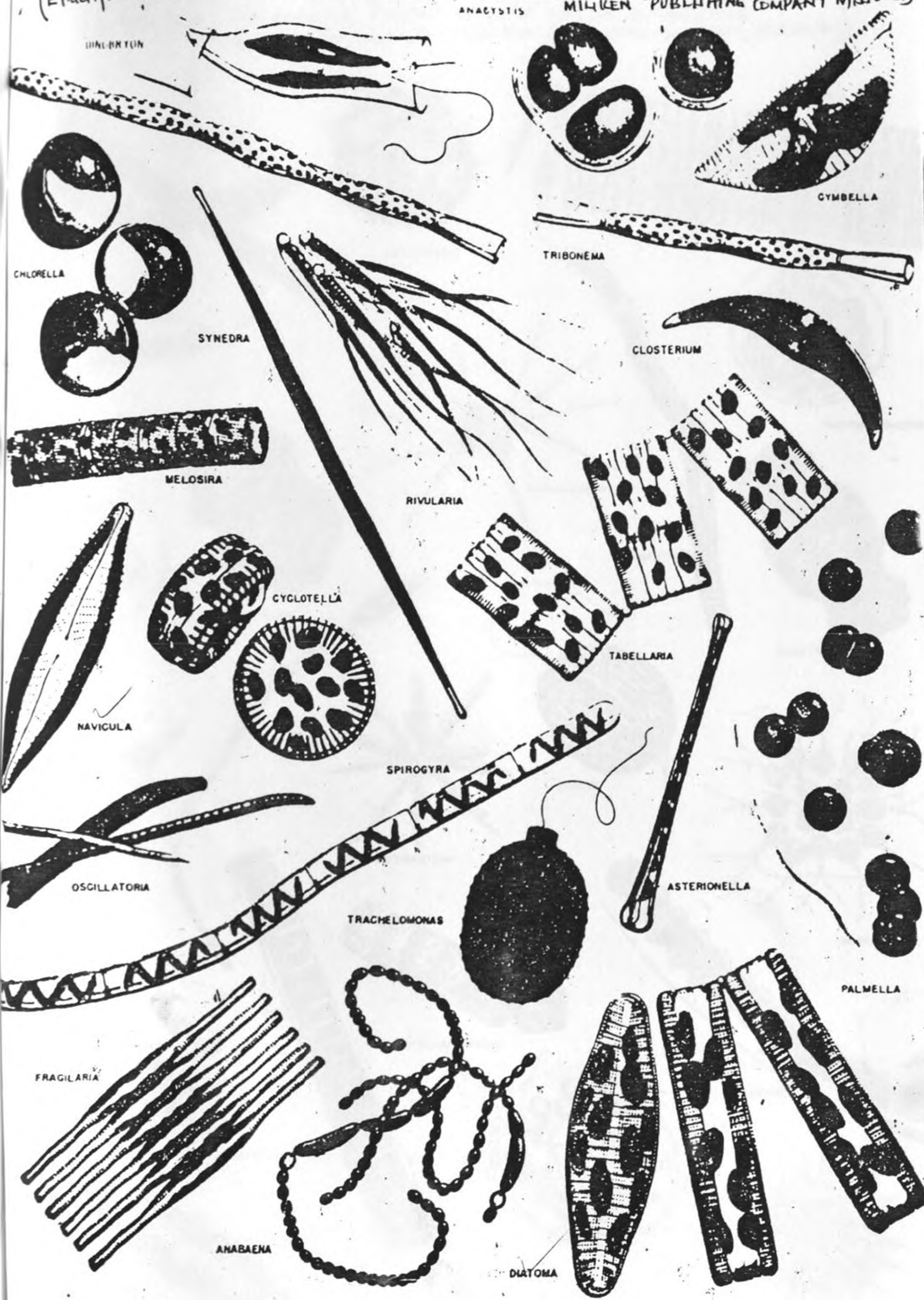


PLATE 2

PLANKTON AND OTHER SURFACE WATER ALGAE

(Extract from: THE BIOLOGY SERIES: MONERA AND PROTISTANS 1970
by Robert Leftwich: MILLIKEN PUBLISHING COMPANY, MISSOURI)

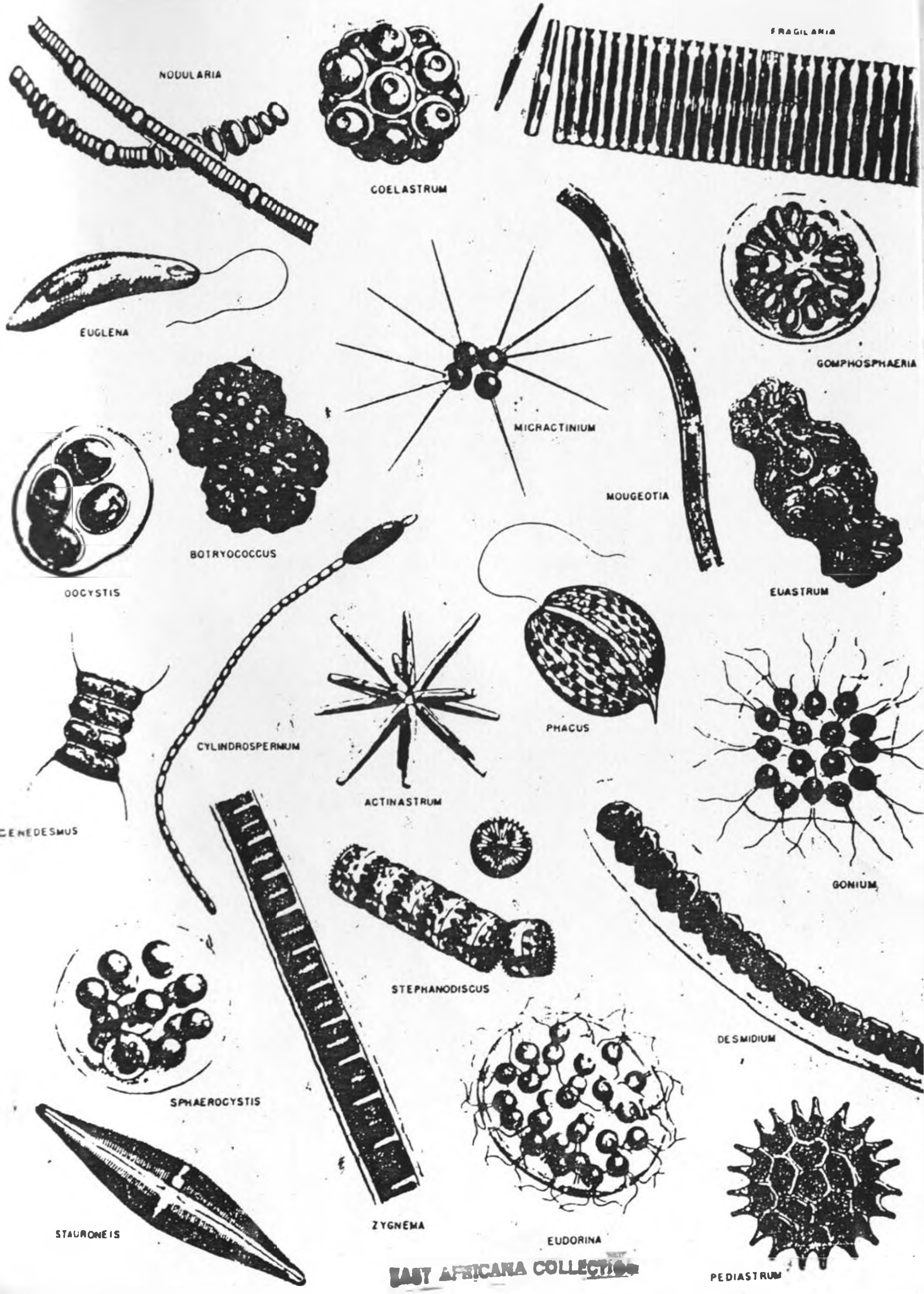


PLATE 5