# DECLARATION OF CANDIDATE

I, Harold Arthur Nicholls, hereby declare that this thesis is my own work and that it has not been submitted for a degree at another University.

Signed by candidate

January 1983

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# BIOLOGICAL NITROGEN AND PHOSPHORUS REMOVAL ON LARGE PLANTS

BY

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# SYNOPSIS

Full scale implementation of biological excess phosphorus removal by means of the activated sludge process commenced in South Africa at the Johannesburg Alexandra Plant in 1974 . Originally the plant was designed to operate in the nitrifying extended aeration mode ; but by switching off some surface aerators around the common inlet point for the influent and underflow recycle, an anoxic zone was created to induce denitrification. This operational modification worked very successfully. Later additional aerators were switched off to create an anaerobic - anoxic zone at the head of the aeration basin, in this manner attempting to induce the prerequisite conditions for excess biological uptake of phosphorus as put forward by Barnard (i.e. by stimulating P release under anaerobic conditions) . This revised operational procedure was not successful due to difficulties experienced in controlling mixing in the anaerobic - anoxic zone. However the experience gained from this investigation together with research findings at laboratory and pilot scale level at the National Institute for Water Research, the University of Cape Town, and Johannesburg instilled sufficient confidence into City Council staff to proceed with the design of the 150 Ml/d Goudkoppie Plant, initially for nitrogen removal and to subsequently modify it to a 5 stage Phoredox process for both nitrogen and phosphorus removal. Before the plant was commissioned (1976) it was necessary to proceed with extensions to the Northern Works and these were also based on the 5 stage Phoredox process.

All the Johannesburg activated sludge plants were comprehensively monitored to determine their performance under cyclic flow and load conditions. The data collected from the Goudkoppie plant were particularly comprehensive and exhaustive.

Concomitant with the monitoring program extensive research into the single stage nitrification/denitrification/excess phosphorus removal process was being undertaken by the three agencies mentioned earlier. Of particular interest was the development by the University of Cape Town of a general kinetic model of the single sludge activated sludge process that described carbonaceous degradation, nitrification and denitrification behaviour under cyclic flow and load conditions. This dissertation critically evaluates the predictions of this model against the observed responses on the Goudkoppie and Northern Works.

As new information and hypotheses on the mechanism of excess biological removal became known from the three agencies checks were made on the above works to test compliance against observed performance. Particular attention was given to the University of Cape Town's hypothesis that a certain minimum concentration of readily biodegradable COD in the anaerobic zone was necessary to stimulate excess phosphorus uptake. Consideration was also given to the Johannesburg group's belief that any deficiency in the readily biodegradable COD in the influent sewage could be supplemented by permitting thickened raw sludge to ferment under acid conditions and returning the liquid phase directly to the anaerobic zone.

The principle findings from these investigations are briefly as follows:

1. The general model predicted the observed response of the large scale plants with remarkable accuracy. It can also be used for predicting the behaviour of a proposed plant under a range of assumed influent flow and load conditions and for the optimisation of existing works performance.

2. The readily biodegradable COD hypothesis for excess phosphorus removal appears to be supported by the observed phosphorus removal response of the Goudkoppie and Northern Works.

Important corollaries to this conclusion are :

(a) Any action that increases this COD fraction in the influent improves excess phosphorus removal. In this regard industries discharging readily biodegradable COD in their effluents should not be encouraged to carry out pretreatment.

(b) Any action that decreases this fraction in the influent should be avoided. At the Goudkoppie Works it was found that deposition and fermentation of solids took place in a flow balancing tank, which was situated upstream of the biological reactors and readily biodegradable COD was lost from the system as methane gas. Daily flushing of accumulated sludge virtually completely eliminated this effect.

3. Oxygen and nitrate entering the anaerobic reactor via the influent or the recycle from the final clarifiers enable facultative anaerobic bacteria or denitrifiers to metabolise some or all of the readily biodegradable COD available. This situation does not permit an adequate release of phosphorus and uptake in the subsequent aerobic process is detrimentally affected.

This problem was present at both the Goudkoppie and Northern Works and different procedures were adopted for its solution. At the Goudkoppie Works nitrates in the clarifier underflow recycle were reduced by limiting the oxygen input to the aerobic reactor, thus limiting the nitrification capability of the plant. This method of control however appeared to be a contributory factor to the development of very poor settling sludges. At the Northern Works the readily biodegradable component of the influent COD was supplemented by adding settled liquors from a digester operated under acid fermentation conditions.

4. From (3) above evidently the nitrification - denitrification behaviour of a plant can have a crucial effect on its propensity for excess phosphorus removal. In terms of the kinetics of denitrification as developed by the University of Cape Town, the denitrification contribution per unit volume of the secondary anoxic reactor is very minor compared to that of the primary anoxic reactor. This was verified on both the Goudkoppie and Northern Works. It was so apparent that the secondary anoxic zone has been omitted from the new Works at Bushkoppies. The volume previously allocated to the secondary anoxic zone should preferably be allocated additionally to the primary anoxic reactor. However this reactor also has a denitrification capacity determined principally by its volume, the mass fraction of sludge it contains, and the magnitude and nature of the influent COD. The nitrification capacity of the process again is fixed largely by the TKN content of the influent. A qualitative measure for judging the nitrification - denitrification behaviour of a process is the TKN/COD ratio of the influent. Where this ratio is above a certain value it may be impossible to attain adequate denitrification - a situation that is present at the Northern Works. The phosphorus removal propensity is therefore dependent not only on the presence of an adequate level of readily biodegradable COD in the influent but also on the TKN/COD ratio which determines the denitrification capability of the plant.

5. The difficulties experienced in obtaining adequate denitrification at the Goudkoppie and Northern Works suggest that the Phoredox process, in which the nitrate concentration in the underflow recycle is the same as in the effluent, limits this process to TKN/COD ratios less than some upper limiting value. It also suggests that alternative process configurations, such as the UCT process, in which the nitrate discharge to the anaerobic reactor can be controlled independently of the concentration in the effluent, have advantages over the Phoredox system when the limiting TKN/COD ratio is exceeded.

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# LIST OF SYMBOLS

| Symbol | Description | Units |
|---|---|---|
| ADP | Adenosine diphosphate | |
| ATP | Adenosine triphosphate | |
| b | Specific endogenous repiration rate<br>Subscripts h or n refer to heterotrophic or nitrifiers respectively | |
| COD | Chemical oxygen demand | mg/l |
| f | Unbiodegradable fraction of the active organisms | mg VSS/mg VSS |
| $f_{bs}$ | Rapidly biodegradable fraction of the influent COD | mg COD/mg COD |
| $f_{ca}$ | Ratio easily : total biodegradable COD in the influent | mg COD/mg COD |
| $f_{n}$ | Fraction of total nitrogen in the VSS | mg N/mg VSS |
| $f_{na}$ | Fraction of influent TKN in the free and saline ammonia form | mg N/mg N |
| $f_{nu}$ | Soluble unbiodegradable organic nitrogen fraction | mg N/mg N |
| $f_{oe}$ | Fraction of nitrogen released through endogenous respiration in the organic nitrogen form | mg N/mg N |
| $f_{os}$ | Fraction of nitrogen required for cell synthesis in the organic nitrogen form | mg N/mg N |
| $f_{pe}$ | fraction of phosphorus as P in the endogenous residue | mg P/mg VSS |
| $f_{pi}$ | fraction of phosphorus as P in the inert volatile solids | mg P/mg VSS |

| Symbol | Description | Units |
|---|---|---|
| $f_{us}$ | Unbiodegradable soluble fraction of the influent COD | mg COD/mg COD |
| $f_{up}$ | Unbiodegradable particulate fraction of the influent COD | mg VSS/mg COD |
| $f_{xm}$ | Maximum allowable unaerated mass fraction to ensure nitrification | $m^3/m^3$ |
| $f_{xp}$ | Primary anoxic mass fraction | $m^3/m^3$ |
| $f_{xs}$ | Secondary anoxic mass fraction | $m^3/m^3$ |
| $k_a$ | Maximum specific nitrification rate constant | mg N/mg VASS/h |
| $K_a$ | Substrate adsorption rate coefficient | 1/mg VSS/d |
| $K_{mp}$ | Maximum specific growth rate coefficient for heterotrophic organisms utilising stored particulate substrate | mg COD/mg VSS/d |
| $K_n$ | half saturation value for nitrification | mg N/l |
| $K_{sp}$ | Saturation coefficient for heterotrophic cells synthesised from particulate substrate | mg COD/l |
| $K_{ss}$ | Saturation coefficient for heterotrophic cells synthesised from soluble substrate | mg COD/l |
| $K_r$ | Conversion rate constant for organic nitrogen | 1/mg VSS/d |
| $K_{120}$ | First denitrification rate constant at 20°C | mg N/mg VASS/h |
| $K_{220}$ | Second denitrification rate constant at 20°C | mg N/mg vass/h |
| $K_{320}$ | Third denitrification rate constant at 20°C | mg N/mg VASS/h |

| Symbol | Description | Units |
|---|---|---|
| MLSS | Mixed Liquor Suspended Solids | mg/l |
| $N_e$ | TKN concentration in the effluent | mg N/l |
| $N_{ii}$ | TKN concentration in the influent | mg N/l |
| $N_{nr}$ | Nitrate concentration in underflow | mg N/l influent |
| $N_s$ | Nitrogen concentration required for sludge production | mg N/l |
| P | COD equivalent of volatile solids | mg COD/mg VSS |
| $P_f$ | Phosphorus propensity factor | |
| Q | Feed flow rate | l/d |
| $Q_r$ | Returned sludge flow rate | l/d |
| $R_s$ | Sludge age | d |
| s | Recycle ratio | |
| S | Unmetabolised biodegradable COD in the effluent | mg COD/l |
| SF | Safety factor | |
| $S_{bi}$ | Biodegradable COD in the influent | mg COD/l |
| $S_{bsi}$ | Readily biodegradable COD in the influent | mg COD/l |
| $S_{bsa}$ | Readily biodegradable COD in the anaerobic reactor | mg COD/l |
| $S_{pi}$ | Particulate unbiodegradable COD in the influent | mg COD/l |
| $S_{ti}$ | Total COD in the influent | mg COD/l |
| $S_{ui}$ | Soluble unbiodegradable COD in the influent | mg COD/l |
| $S_{xii}$ | Unbiodegradable particulate COD in the influent | mg COD/l |
| T | Temperature | °C |
| TKN | Total Kjeldahl nitrogen concentration | mg N/l |

| Symbol | Description | Units |
|---|---|---|
| V | Volume of reactor | l |
| VASS | Volatile active solids concentration | mg/l |
| VSS | Volatile settlable solids | mg/l |
| $X_a$ | Active volatile solids concentration in mixed liquor | mg VSS/l |
| $X_e$ | Endogenous volatile solids concentration in mixed liquor | mg VSS/l |
| $X_i$ | Inert volatile solids concentration in mixed liquor | mg VSS/l |
| $X_{ii}$ | Unbiodegradable influent volatile solids concentration | mg/l |
| $X_T$ | Total solids concentration in mixed liquor | mg/l |
| $Y_h$ | Yield coefficient for heterotrophic organisms utilising stored COD | mg VSS/mg COD |
| $Y_n$ | Yield coefficient for *Nitrosomonas* | mg VSS/mg N |
| $\theta$ | General parameter for pH dependency coefficients. Subscript h or n refers to heterotrophic organism or *Nitrosomonas* respectively | |
| $\mu_h$ | Specific growth rate of heterotrophic organisms. Subscript m refers to maximum value | /d |
| $\mu_n$ | Specific growth rate of *Nitrosomonas* | /d |
| $\Delta$ P | Phosphorus as P removed from the influent influent and incorporated into the waste sludge per day | mg/l/d |
| $\alpha$ | Fraction of phosphorus present in the activated sludge | mg P/mg VSS |

# CHAPTER ONE

## INTRODUCTION

## 1. HISTORICAL BACKGROUND

Johannesburg was founded in 1866 when gold was discovered on the farm Langlaagte, and soon became a thriving mining camp. Today it is not only the largest city in South Africa but also the financial hub of the country. It is surrounded by satellite towns which form the Witwatersrand complex covering 17 000 square kilometres and accomodating a population of approximately 5 million people.

The Witwatersrand at an altitude of approximately 1 800 m above sea level runs in an east - west direction and forms a natural watershed, with drainage to the north to the Indian Ocean and to the south, the Atlantic Ocean. Before discharging to the oceans the rivers draining the Witwatersrand are impounded in a number of dams, two of which are in close proximity to Johannesburg, viz., the Vaal Dam in the southern and the Hartebeespoort Dam in the northern drainage basins respectively. In order to make use of gravity sewerage, advantage has been taken of the natural drainage by the siting of wastewater treatment plants near the banks of rivers feeding these dams, so that the treated effluents inevitably find their way to the storage dams.

### 1.1. Johannesburg sewerage systems

From the turn of the century until the early 1930's the only form of wastewater purification was land irrigation. From 1930 until the late

1960's most of the plants built in Johannesburg employed the biological filtration process with an anaerobic digestion of the solids.

In 1960 the financial climate resulted in a shortage of capital which led to a change in the type of treatment process : activated sludge plants were predicted to be lower in overall costs than biological filter plants, and were adopted as the basis for future designs.

The first activated sludge plant constructed was a temporary works situated at Palmietfontein on the southeastern outfall sewer to the Olifantsvlei Works, designed as a modified Orbal extended aeration plant. (1971) . This plant produced a well nitrified effluent which discharged via maturation ponds into the Klip River, and hence to the Vaal Barrage. Although the effluent was of a high quality in terms of BOD and ammonia removal, it soon became evident that the presence of nitrates and phosphorus in the effluent caused eutrophication in the Barrage.

A second installation (1974), also temporary, was the Alexandra plant constructed to relieve the overloaded Bruma sewer flowing to the Northern Works. The plant was sited on a small tract of land between the existing sewer and the Jukskei River. It was of the extended aeration type but due to space limitations on the site, the waste sludge from the plant was returned to the sewer for final treatment in the digesters at the Northern Works, thus eliminating the need for sludge treatment facilities. The plant produced a well nitrified effluent which discharged into the Jukskei River and hence the Hartebeespoort Dam.

The first major permanent activated sludge installation, a nitrifying extended aeration activated sludge plant, was the Olifantsvlei Works (1974) . Its design was very similar in principle to the Orbal process except that the four orbal rings were converted into four rectangular tanks in series. At the time, as far as is known, this was the largest plant of its kind in operation. The effluent discharged into the Klip River, flowing into the Vaal Barrage.

All the effluents from the plants described above found their way to the two storage dams, the Vaal Barrage and Hartebeespoort Dam. From a study of the historical development of eutrophication problems in these dams it became apparent that these effluents were the major cause, in particular in the Hartebeespoort Dam, of eutrophication. Eutrophication in this dam caused, at various times, prolific growth of algae and, at a later stage, an explosive growth of waterhyacinth (E. CRASSIPES) , Scott and Steyn (1979) .

Waterhyacinth was first noted in the tributaries of the Hartebeespoort Dam in 1959 and from then on was controlled by mechanical means (Anon. 1971) . However, in 1971, when the level of the dam was increased the inundation of partially vegetated areas provided a favourable environment for rapid proliferation. By 1976, weed coverage was so large (± 70 percent of the surface area) that the recreational use of the dam was severely restricted. Chemical methods of control had to be resorted to (Scott and Steyn, 1979), but it was evident that the problem would be alleviated only be reducing the inflow of nitrates and phosphorus to the dam.

## 1.2. Nutrient removal from Johannesburg effluents

Johannesburg, being the main contributor of treated effluents to the two basins draining the Witwatersrand, quite early on (1973) recognised the importance of nutrient limitation in their discharges. Earlier attempts included the construction of large scale maturation ponds, still existant. Although these ponds induced a considerable improvement in some pollution parameters, particularly the bacteriological and volatile solid parameters, they contributed little removal of phosphorus and nitrogen.

In 1974, Barnard reported that nitrate nitrogen could be removed in the activated sludge process by creating zones in the process where no oxygen is supplied (anoxic zones) , the nitrate replacing the oxygen as the hydrogen ion (or electron) acceptor - the Bardenpho process. To Johannesburg this work presented the possibility of reducing the nitrogen content in some of the existing activated sludge plants, if these could be suitably modified. Modifications were made to the Alexandra and Olifantsvlei plants in 1974 and by trial and error operational procedures developed to optimise the nitrogen removal. The success attained in this endeavour verified the soundness of Barnard's proposals and the Johannesburg City Council decided as a policy that all future works should include nitrogen removal. Based on experience gained on the Alexandra and Olifantsvlei plants, and taking due account of theoretical developments on biological nitrogen removal elsewhere, the first plant designed specifically to incorporate nitrogen removal was the one to be located at Goudkoppie (1976)

While the Goudkoppie plant was under construction, Barnard announced further developments in nutrient removal. From research reported in the literature and experience on a pilot plant he hypothesised that if the organism mass in the activated sludge process is stressed under conditions of no oxygen and no nitrate (anaerobic condition) such that the release of phosphorus from the organism mass to the bulk liquid takes place, then, if the mass is subsequently aerated, the mass will take up the released phosphorus and some additional phosphorus from the bulk liquid, and thereby reduce the phosphorus content in the effluent. To achieve this he proposed a modification to the Bardenpho process called the Phoredox process (Fig. 2.8.)

Barnard's proposal again was of great interest to the Johannesburg City Council, but, before embarking on a policy of implementation in future designs, in the absence of full scale experience and adequate evaluation of the hypothesis it was considered essential to test Barnard's hypothesis at full scale.

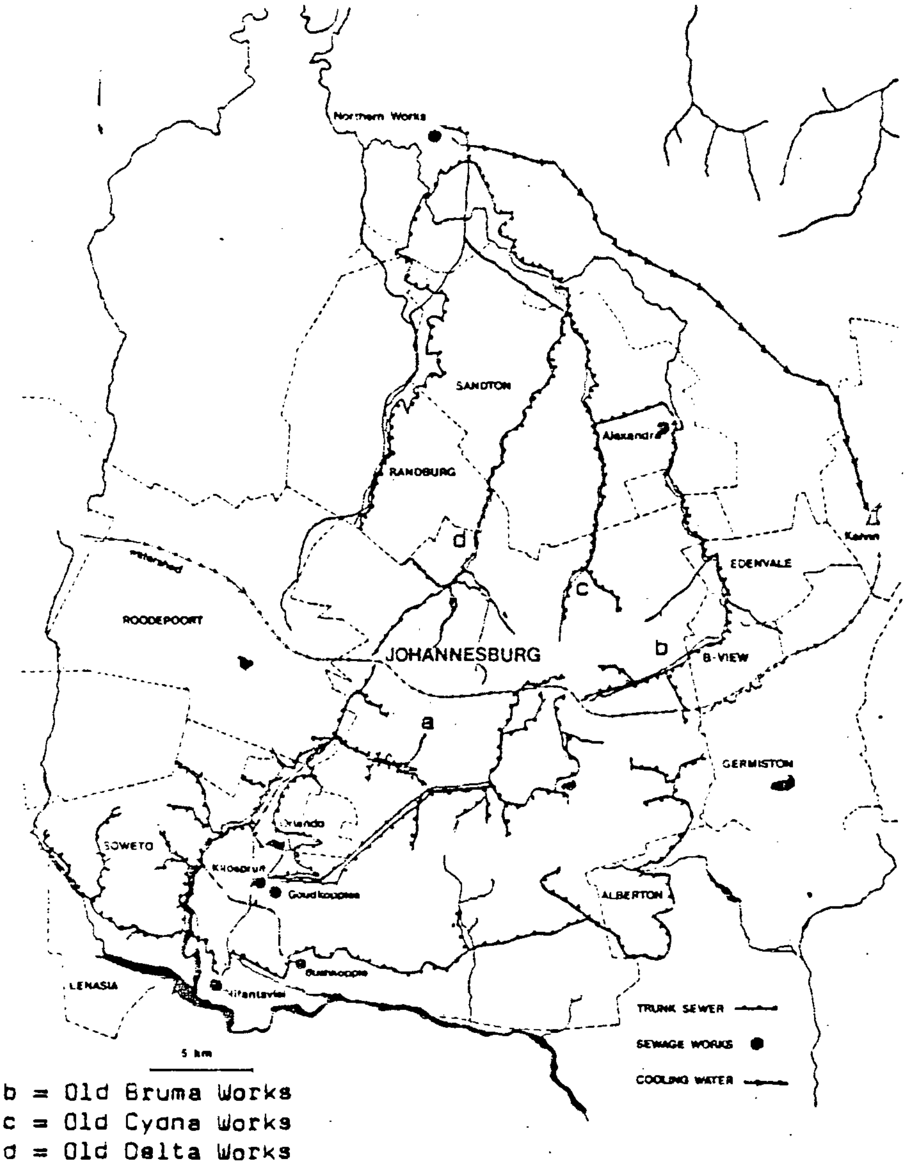
A study of the Alexandra plant design indicated that by suitable modifications and appropriate changes in operation, it should be possible to evaluate the hypothesis. It was recognised that the modifications necessary to the Alexandra plant for both nitrogen and phosphorus removal were unlikely to induce optimal removals, because it was not possible to implement the modifications strictly as required by hypothesis. Furthermore, monitoring of the plant was expected to present some severe difficulties because the plant was not designed with these objectives in mind. For example it was not possible to measure readily, or to control, key process parameters governing nutrient removal such as sludge age, recycle ratio, oxygenation rate control, and others. Consequently it was expected that the results would be more of a qualitative nature lacking completeness and precision.

Despite the problems mentioned above evaluation of the process capability was crucial to Johannesburg for two reasons, it would ; (1) Establish whether nutrient removal on a large plant is possible by appropriate modification of the process or process operation, particularly the latter, thereby to set an example of successful application for other works (2) Identify features in design and operation that require the attention of designers of future installations to operate plants optimally.

With objectives above in mind, and cognizant of the restrictions inherent in the existing plant, the Alexandra plant was modified and evaluated. The success achieved was considered by the City Council to be sufficient to decide on a policy of implementation on all future works. This policy was put into effect immediately. At that time Goudkoppie Works was already under construction ; however, it was possible to make ad hoc changes to the design to incorporate the Phoredox proposals in so far as the physical limitations imposed by construction already completed did allow. At that time also the design of the Northern Works was in its initial stages ; it was possible therefore to incorporate the Phoredox proposals more completely, and this was accordingly done.

The plants above have been in operation now for a number of years and reflect the evolution of the biological nutrient removal concept, starting with modifications of existing plants to induce nutrient removal and culminating in the design of the plants at Goudkoppie and Northern Works.

Over this period research greatly increased understanding of the basic mechanisms of, and the factors controlling biological nitrogen and phosphorus removal. As the information became available so it was implemented by appropriate modifications to existing design (where this was possible) and/or modifications of the operating procedures. The experience thus gained, the problems encountered and procedures to resolve these all should be of interest to both designers and operators of such plants. These considerations formed the main incentive for this enquiry.



b = Old Bruma Works
c = Old Cydna Works
d = Old Delta Works

Fig. 1.1. Johannesburg Metropolitan Drainage Area

# CHAPTER TWO

# REVIEW OF NUTRIENT REMOVAL

## 1. INTRODUCTION

The primary objective of this investigation was to enquire into the behaviour of large scale plants that either have been modified to induce nutrient removal (i.e. removal of nitrogen and phosphorus) or have been designed specifically towards this end. It is not possible to describe the work done in this regard if there is no understanding of the basic principle on which these processes are presumed to operate. Accordingly a review of these principles is essential. It is not the intention here to survey, in depth, the literature on nutrient removal associated with the activated sludge process; this has been done quite competently by a number of authors, Christensen and Harremoës (1972, 1974), Stern and Marais (1974), Menar and Jenkins (1970), Harold (1966), Dawes and Senior (1973), Kulaev (1975) and van Haandel, Ekama and Marais (1981). Rather the intention is to provide only such background as is necessary to appreciate the basis for the modification in the design and operation of existing plants to induce nutrient removal, and for the design of new plants with nutrient removal as an integral part.

The relevant literature review on nutrient removal is best set out by subdividing the discussion into three parts:

(i) Nitrogen removal
(ii) Phosphorus removal
(iii) Modelling of the activated sludge process including the removal of nutrients

## 2. NITROGEN REMOVAL

Nitrogen removal by biological denitrification in the single sludge activated sludge process will be considered as this is the method by which nitrogen is removed in the activated sludge plants under investigation.

In the single stage activated sludge process, to remove nitrogen and the free and saline ammonia in the raw wastewater, ammonia first must be oxidised to nitrate. This is accomplished under aerobic conditions by the Nitrosomonas sp , which oxidise the ammonia to nitrite, and by the Nitrobacter sp , which oxidise the nitrite to nitrate.

Considering the kinetics of nitrification in the activated process, Downing, Painter and Knowles (1964) showed that the conversion of ammonia to nitrite is the rate limiting step because of the slow rate of reproduction of Nitrosomonas . In order that this species be retained in the process, the sludge age must exceed the replication time of this organism. From a mass balance of the nitrifiers over a completely aerobic process the minimum sludge age necessary to just maintain this organism in the system is given by :

$$R_m = \frac{1}{(\mu_{nmT} - b_n)} \qquad (1)$$

where $R_m$ = minimum sludge age in days

$\mu_{nmT}$ = maximum specific growth rate of Nitrosomonas at T C $(d^{-1})$

$b_n$ = specific endogenous respiration of Nitrosomonas $(d^{-1})$

The magnitude of $b_n$ is small relative to $\mu_{nmT}$ at temperatures greater than 12°C and consequently can be neglected for all practical purposes, in which event, $R_m = 1 / \mu_{nmT}$ (2)

The specific growth rate $\mu_{nmT}$ is temperature dependent and can be expressed in terms of the simplified Arrhenius equation

$$\mu_{nmT} = \mu_{nm20} (1{,}123)^{T - 20} \qquad (3)$$

where $\mu_{nm20}$ can have values ranging from 0,2 to 0,7 depending on the source of waste water.

Once nitrification has occurred it becomes possible to remove nitrogen via denitrification.

## 2.1. Denitrification

Denitrification consists of a series of energy yielding biochemical reactions in which the organic material serves as the electron donor, and nitrate serves as the final electron acceptor. The pathways involved in this reaction series have been reported extensively in the literature and are summarised by Christensen and Harremoës (1972, 1974) .

If free oxygen is present, the enzymatic system for the utilisation of nitrate or nitrite as an electron acceptor is inhibited; consequently, in the activated sludge process, if denitrification is to be successful, it is essential that oxygen free zones are created. This may be achieved in a number of ways:

(i) Inclusion in the process configuration of a reactor that is stirred but not aerated whereby the dissolved oxygen concentration is maintained at zero.

(ii) Aeration at a number of points in the reactor chosen such that the dissolved oxygen concentration falls to zero between any two.

(iii) Maintenance of the oxygen concentration at approximately 0,5 mg/l at the surface of the reactor causing regions of even lower dissolved oxygen concentration towards the bottom of the aeration basin. At these low oxygen tensions it is possible that the activated sludge floc can not maintain an aerobic condition throughout and an oxygen free zone is created within the floc.

Quantitative expression of denitrification in (ii) and (iii) above is very difficult because the magnitude of the unaerated zones or the anoxic state in the particles is difficult to express in a reliable manner, and hence, consistent results can not be guaranteed.

## 2.2. Denitrification processes configurations

The potential of biological denitrification using endogenous respiration as the source of electron donors was first recognised by Wuhrmann (1957) when he incorporated a stirred reactor following the aeration basin (see Fig. 2.1.)

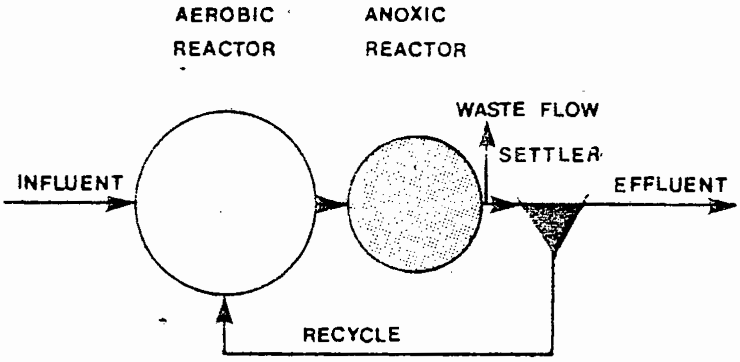


Fig. 2.1. The Wuhrmann configuration for biological nitrogen removal

Wuhrmann (1957) initially claimed that the denitrification rate in the stirred reactor was 0,0017 mg N/mg MLVSS/h , however Christensen, Härremoes and Roed-Jensen (1975), on repeating Wuhrmann's experiments, found that the rate of nitrate utilisation was dependent on the COD adsorbed onto the floc, and obtained rates ranging from 0,0001 - 0,0002 mg N/mg MLVSS/h .

Ludzack and Ettinger (1962) proposed an alternative method in which raw sewage is utilised as the electron source in the denitrification reaction. A stirred unaerated reactor is placed ahead of the main aeration basin, the two reactors being in partial communication, the nitrified sludge from the main aeration basin circulating through this denitrification zone by the stirring action of the mixers and aerators (see Fig. 2.2.) Because of the ready availability of both electron donors and electron acceptors enhanced denitrification was achieved; Ludzack and Ettinger reported a denitrification rate of 0,0053 mg N/mg VSS/h .

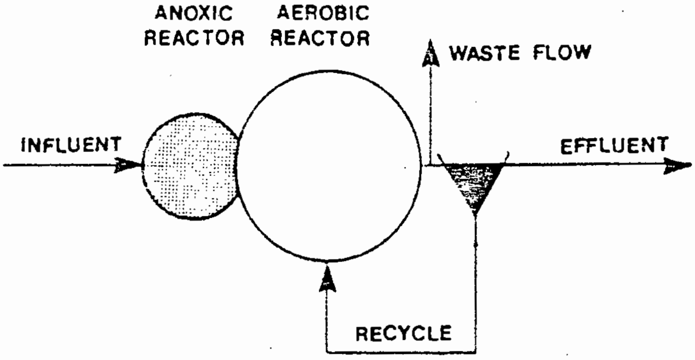


Fig. 2.2. The Ludzack Ettinger denitrification system

Based on the ideas of Ludzack and Ettinger and Wuhrmann, Barnard (1973) designed a process which included a primary denitrification reactor before - and a secondary denitrification reactor after the main basin plus a further reaeration basin in series (Fig. 2.3.) The primary denitrification reactor was separated completely from the aeration basin and a positive recycle ("a" recycle) instituted from the aerobic reactor to the predenitrification reactor; the underflow recycle discharged to the predenitrification reactor; the underflow recycle discharged to the predenitrification reactor ("s" recycle). This process was patented and became known as the Bardenpho process (Fig. 2.3.)

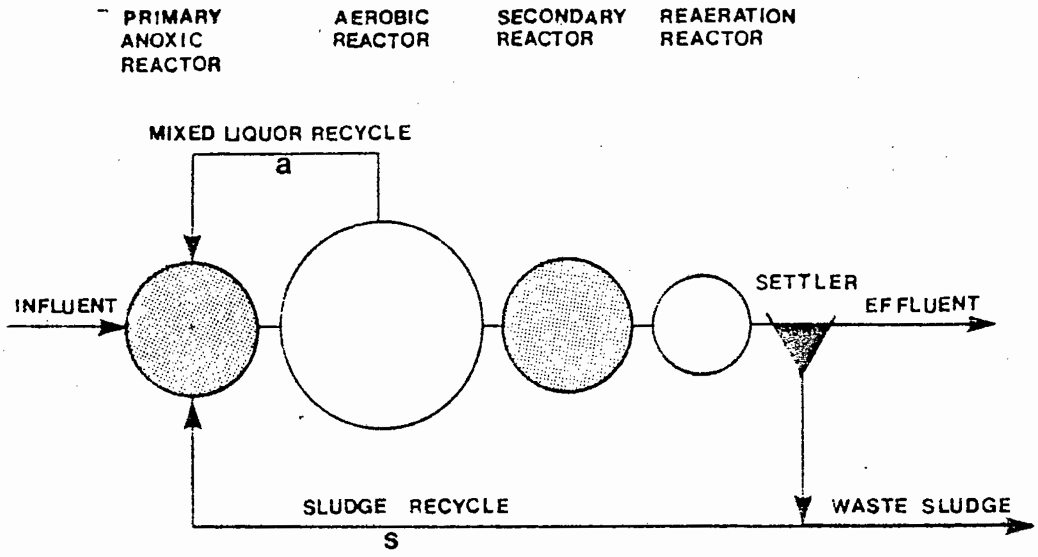


Fig. 2.3. Layout of the Bardenpho process

Barnard reported denitrification rates in the primary and secondary reactors of approximately 0,0036 and 0,0013 mg N/mg MLVSS/h respectively.

Investigations into the Bardenpho process at laboratory scale by Stern and Marais (1974) indicated two denitrification rates in the primary reactor: a rapid rate and a slower rate, both zero order reactions with respect to nitrate and proportional to the active mass $X_a$. The removal rates can be expressed as follows:

$$dN_n/dt = K_a X_a \tag{4}$$

$K_a$ = denitrification rate constant (mg N/mg VASS/h)

$N_n$ = nitrate concentration (mg N/l)

$X_a$ = active mass concentration (mg/l)

Investigating the temperature dependency of equation (4) Marsden and Marais (1977) included a temperature correction factor into the rate equation expressed in the primary reactor:

* First phase

$$K_{1T} = K_{120} (1,2)^{T - 20} \qquad (5)$$

where

$K_{120}$ = 0,030 (mg N/mg VASS/h)

= first rate constant $K_1$ at 20 °C

* Second phase

$$K_{2T} = K_{220} (1,1)^{T - 20} \qquad (6)$$

where

$K_{220}$ = 0,0042 (mg N/mg VASS/h)

= second rate constant $K_2$ at 20 °C

Considering the second anoxic reactor in the Bardenpho process, Stern and Marais (1974) showed that there was only one denitrification rate which also could be expressed by equation (6) with K having the following temperature dependence:

$$K_{3T} = K_{320} (1,03)^{T - 20} \qquad (7)$$

where

$K_{320}$ = 0,003 (mg N/mg VASS/h)

= third rate constant $K_3$ at 20 C

Two theories have been proposed to explain the different rates observed:

(i) Barnard (1975) suggested that the redox potential of the activated sludge in the immediate vicinity of the added raw sewage was lower than that in the remainder of the denitrification reactor. This lower potential resulted in rapid denitrification which continued until the raw sewage feed and the activated sludge were evenly dispersed, at which stage the second denitrification stage became operative.

(ii) Dold, Ekama and Marais (1980) proposed a bi-substrate theory in which it was postulated that raw sewage contained two fractions of different biodegradability:

- a readily biodegradable soluble fraction which is absorbed and metabolised at a very high rate resulting in a rapid utilisation of electron acceptors, in this case nitrate.
- a particulate fraction which must first be adsorbed onto the organism and solubilised by extracellular enzymes prior to metabolism by the organism. The solubilization stage is slow and consequently the rate of nitrate metabolism is slow.

Depending on the mass of slowly biodegradable fraction available in the pre and post denitrification reactors, the rates $K_2$ and $K_3$ differ correspondingly. Integrating equation (4),

$$N_n = KX_aR \quad (8)$$

where R is the nominal retention time over which the reaction takes place. Van Haandel, Dold and Marais (1982) showed that the easily biodegradable material is rapidly utilised, in a matter of minutes i.e. R is very small; furthermore the mass concentration of nitrate removed in this reaction is proportional to the mass concentration of easily biodegradable material. Consequently provided the retention time in the reactor is longer than a few minutes the removal of nitrate due to easily biodegradable material is constant for a particular waste water. The removal rate of nitrate due to the $K_2$ and $K_3$ reactions remains constant per unit of retention time so that the mass concentration removed increases as the retention time increases.

As a consequence of this behavioural pattern, the equation for nitrate removal by the plant can be written:

$$Ns' = \gamma S_{bi} + K_2 X_a R_1 + K_3 X_a R_3 \qquad (9)$$

where

$Ns'$ = mass of nitrate removed (mg N/l)

$\gamma$ = constant depending on the fraction of readily biodegradable COD available in the incoming COD

$S_{bi}$ = biodegradable COD concentration (mg/l)

$K_2$ = second denitrification rate constant in the primary anoxic reactor (mg N/mg $X_a$/h)

$K_3$ = denitrification rate constant in the secondary anoxic reactor (mg N/mg $X_a$/h)

$X_a$ = active mass concentration (mg/l)

$R_1$ = nominal retention time in the primary anoxic reactor (h)

$R_3$ = nominal retention time in the secondary anoxic reactor (h)

Research by Stern and Marais (1974) and van Haandel *et al* (1982) showed:

(i) Equation (9) applies only if nitrate is still present in the effluent from the reactor.

(ii) Over a day the mean concentration of nitrate removed is approximately the same irrespective of whether the flow and load is cyclic or constant.

## 2.3. Nitrification in anoxic/aerobic systems

Denitrification can not occur if nitrification does not take place. Van Haandel, Dold and Marais (1982) analysed the conditions which must be satisfied to ensure a high efficiency of nitrification in an anoxic - aerobic system. They found that when an anoxic zone is present the minimum sludge age for nitrification is given by:

$$R'_{sm} = 1 / \left[ (1 - f_x) \mu_{nmT} - b_{nT} \right] \tag{10}$$

where $f_x$ is the fraction of the mass of sludge in an anoxic state. To ensure high efficiency of nitrification the sludge age $R_s$ must be greater then $R'_{sm}$ and they found that provided $R_s > 1{,}25\ R'_{sm}$ nitrification efficiency will always be high, greater than 95 per cent, and stable under both cyclic and steady flow conditions. As $R'_{sm}$ is affected by the value of $\mu_{nmT}$, for design the lowest $\mu_{nmT}$, at the lowest temperature must be inserted.

## 2.4. Optimization of anoxic - aerobic plants

In design, if the sludge age $R_s$ and the specific growth rate of the nitrifiers $\mu_{nm}$ are specified, then the maximum anoxic mass fraction allowable can be calculated from equation (10). The critical anoxic mass fraction is given by the smallest value of $\mu_{nm}$, hence the calculation must be done at the lowest temperature expected. By choosing a number of sludge ages it is possible to develope a curve relating the anoxic mass fraction $f_x$ to the sludge age $R_s$. At about 30 days sludge age the anoxic mass fraction is about 0,5 if $\mu_{nm20} = 0{,}35$, and Siebritz, Ekama and Marais (1980) found that there is a limit to the magnitude of $f_x$; for a $f_x$ greater than 0,5 poor settling sludges were observed. The empirical rule therefore, is that under no condition should $f_x$ exceed 0,5 - see Fig. 2.4.

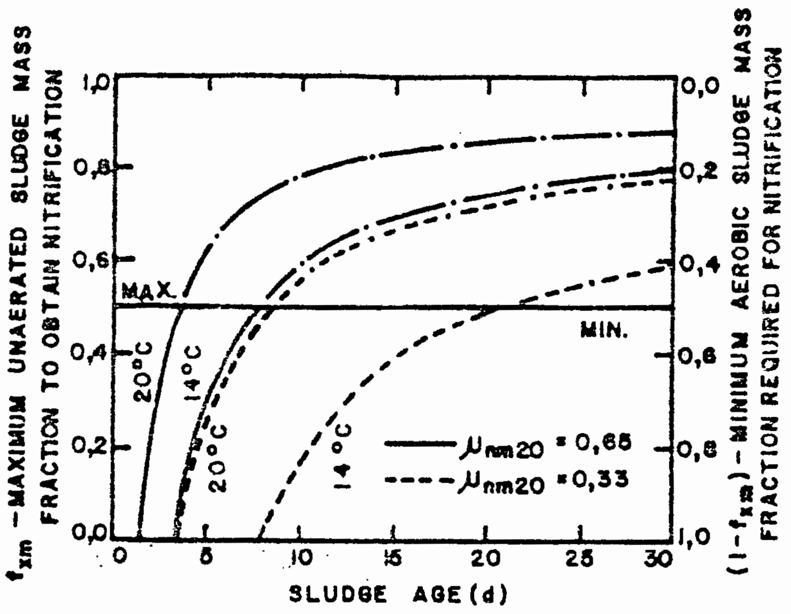


Fig. 2.4. Maximum permissible anoxic volume fraction or minimum aerobic volume fraction required to sustain nitrification versus sludge age for different maximum specific growth rate constants of the nitrifiers at 20 C and 14 C

Having obtained the relationship between $f_x$ and $R_s$, van Haandel, Dold and Marais (1982) then derived an equation whereby, specifying the "a" and "s" recycles (Fig. 2.3.) the anoxic mass fraction can be subdivided into pre- and post- denitrification sub-fractions. This needs to be done at the maximum expected temperatures. The reason for this is that at low temperatures below 14 C $K_2$ and $K_3$ become identical. At this lower temperature because $K_2 = K_3$ the division of $f_x$ into $f_{x1}$ and $f_{x2}$ can be as one pleases, but at the higher temperatures $K_2 > K_3$, and removals greater than at lower temperatures are achieved if $f_{x1}$ and $f_{x2}$ are appropriately selected. Having divided $f_x$ into $f_{x1}$ and $f_{x2}$, then by equating the denitrification potential (van Haandel, Ekama and Marais , 1981) plus the nitrogen required for synthesis to the influent TKN, the TKN/COD ratio the plant can handle for complete denitrification can be determined.

In this manner a maximum TKN/COD ratio versus sludge age can be plotted - see Fig. 2.5.

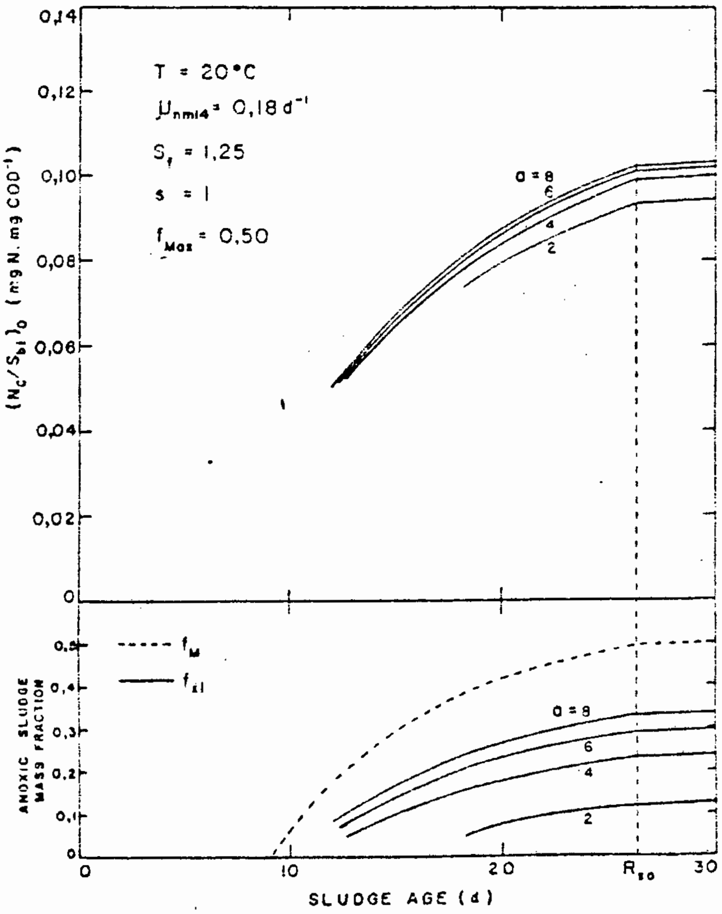


Fig. 2.5. Design chart for selection of optimal nitrogen removal configuration

$N_c$ = Nitrification capacity (mg N/l influent)

$S_{bi}$ = Biodegradable COD concentration of the influent (mg/l)

$N_{ti}$ = Total nitrogen concentration of the influent (mg N/l)

$S_{ti}$ = Total COD concentration of the influent (mg/l)

$\mu_{nm}$ = Specific growth rate for Nitrosomonas ($d^{-1}$)

$S_f$ = Safety factor

a = MLSS recycle ratio

s = Sludge return ratio

$(N_c/S_{bi})_o$ = Maximum ratio for which complete nitrification is possible

$(N_c/S_{bi})_i$ = Maximum ratio for Ludzack Ettinger type process

It is now a simple matter, knowing the TKN/COD ratio and the minimum temperatures, to select the appropriate sludge age and the anoxic mass fraction $f_x$. Knowing the maximum temperatures and recycle ratios, $f_x$ is subdivided into $f_{x1}$ and $f_{x2}$.

If the TKN/COD ratio to be treated is so high that it does not intercept the TKN/COD vs $R_s$ curve (Fig. 2.5.), one would select the maximum allowable $f_x = 0{,}50$, subdivide it into $f_{x1} = 0{,}5$, $f_{x2} = 0$ i.e. a Ludzack - Ettinger process. The plant now no longer can remove all the nitrate generated but it will remove the maximum possible.

The description above essentially contains the basic ideas for optimising nitrate removal from a single sludge nitrification - denitrification system; it allows a rapid assessment of an existing plant as to whether the plant is optimally designed.

## 3. BIOLOGICAL PHOSPHORUS REMOVAL

### 3.1. Introduction

Significant but unexplained removals of phosphorus in the activated sludge process were first noted at the Rilling Road plant at San Antonio Texas by Vacker, Connell and Wells (1967). This appeared to be contrary to the findings of earlier workers such as Sawyer (1944), Wuhrmann (1957), Levin and Shapiro (1965) who, investigating the removal of phosphorus from wastewater by biological means, concluded that normal bacterial metabolism could not bring about substantial phosphorus removal.

The phosphorus content of the activated sludge at the Rilling Road plant, which operated at a sludge age of 3,2 days, was found to be 5 - 7 mg P/mg of dry sludge, which is 2 - 3 times that normally found in similar plants. Endeavouring to explain this high phosphorus content, operational parameters at Rilling Road were compared with other activated sludge plants and one major difference was noted: at the Rilling Road plant oxygen concentration at the head of the plant was zero. Similar observations on high phosphorus removal were made on the Baltimore plant in Maryland USA by Scalf, Pfeffer, Lively and Witherow (1969), where again the dissolved oxygen concentration was virtually zero at the head of the aeration basin. Milbury, McCauley and Hawthorne (1971) in a detailed study of the phosphorus removal behaviour in a conventional (i.e. semi plug flow) activated sludge plant showing excess phosphorus removal, found that the phosphorus profile across the length of the aeration basin showed a high concentration at the influent end tailing off to very low concentrations at the effluent point.

In order to explain excess phosphorus removal two main theories have been developed, both of which are still being debated by many research investigators today.

## 3.2. Chemical precipitation theories

Menar and Jenkins (1970) and Ferguson, Jenkins and Eastman (1973), from an examination of solubility characteristics of various phosphate compounds, postulated that phosphorus could be precipitated at pH values of 7,5 - 8,5 as calcium hydroxy apatite $Ca_5(OH)(PO_4)_3$. They further suggested that where the aeration intensity was low, large quantities of carbon dioxide were produced which remained in solution, resulting in a depression of pH and resolution of precipitated calcium hydroxy apatite. Considering the precipitation of phosphorus further, De Boice and Thomas (1975) developed a steady state computer model to predict the conditions required for precipitation of a number of calcium and phosphorus containing salts. Applying this data to the Baltimore plant they showed that removal of phosphorus as an insoluble calcium salt was theoretically feasible.

Working along somewhat different lines Arvin and Christensen (1979) showed experimentally that denitrification could initiate the precipitation of calcium phosphate inside biofilms. This was said to be a consequence of high pH values which can be created by a combination of the production of alkalinity and the diffusional resistance to its export from the bacterial cell.

### 3.3. Biological removal theories

Biological removal of phosphorus in the activated sludge process implies the incorporation of phosphorus into microorganisms, and its subsequent removal from the process with the waste sludge.
In general terms this may be achieved in two ways:

- phosphorus may be taken into the cell to meet normal metabolic requirements
- phosphorus in excess of that required for immediate metabolism could accumulate within specific areas usually as an osmotically inert polyphosphate

#### 3.3.1. Biological excess accumulation of phosphorus in microorganisms

Phosphorus, an essential element in the life cycle of all living organisms, can enter or leave bacteria in only one form: ortho-phosphate. Entry into the cell is generally by one or other of the following: (Potgieter, 1980)

(i) Diffusion which requires that a concentration gradient of phosphorus exists across the cell membrane; high on the outside, low on the inside of the cell;

phosphorus will transfer from the higher to the lower concentration across the cell wall.

(ii) Active transport in which phosphorus is forced into the cell against a concentration gradient using adenozine triphosphate (ATP) as an energy source.

Normal domestic sewage contains organic phosphate, polyphosphate and orthophosphate. The first two must be converted into the ortho form by extracellular enzymes e g alkaline phosphatase before they can be utilised by the cell. Having entered the cell orthophosphate is involved in a large number of biochemical reactions, one of the most important being the formation of adenosine triphosphate (ATP) which serves as a source of highly utilisable energy to the organisms. When ATP is converted in the metabolic process to adenosine diphosphate (ADP) a large amount of energy, 16Kcal/mole is liberated.

In order to estimate this mass of phosphorus which has entered the cell to satisfy metabolic requirements Marais and Ekama (1976) derived the following equation:

$$\Delta P = \frac{YS_{bi}}{(1 + bR_s)} (\alpha + f_{pe} f \, b \, R_s) + f_{pi} X_{ii} \qquad (11)$$

$\Delta P$ = concentration of phosphorus removed from the influent and incorporated into the sludge wasted / day
$P = (P_{inf} - P_{eff})$ (mg/l)

$\alpha$ = fraction of phosphorus as P in the active sludge mass, normally about 0,03 but much higher if excess removal takes place (mg P/mg VASS)

$f_{pe}$ = fraction of phosphorus as P in the endogenous residue
= 0,015 (mg P/mg VSS)

$f_{pi}$ = fraction of phosphorus as P in the volatile inert fraction in the influent
= 0,015 (mg P/mg VSS)

$Y$ = growth yield coefficient

= 0,45 (mg VASS/mg COD)

$S_{bi}$ = biodegradable influent COD

= $S_{ti}\ (1 - f_{us} - 1{,}48\ f_{up})$ (mg/l)

where

$f_{us}$ = fraction of soluble unbiodegradable COD in influent (mg COD/mg COD)

$f_{up}$ = fraction of particulate unbiodegradable volatile solids in influent (mg VSS/mg COD)

$S_{ti}$ = total influent COD concentration (mg/l)

$b$ = specific endogenous respiration rate

= 0,24 (mg VASS/mg VASS/d)

$R_s$ = sludge age (d)

$X_{ii}$ = unbiodegradable influent volatile solids

= $f_{up} S_{ti} / 1{,}46$ (mg/l)

From equation (11) the concentration of phosphorus removed is a function of influent COD concentration and sludge age. In the case of normal domestic sewage, the $\Delta P$/ COD ratio can range from 0,01 to 0,03, the higher value being where excess phosphorus removal takes place.

### 3.3.2. Non - metabolic accumulation of excess phosphorus in bacteria

The most likely form in which phosphorus may accumulate within the bacterial cell is as high energy, osmotically inert polyphosphate (Dawes and Senior, 1973). This combines with ribonucleic acid, protein lipids and $Mg^{2+}$ to form volutin granules. (A list of some of the organisms known to accumulate polyphosphates is given in Appendix A1). These volutins are spherical in shape and vary in size from 40 to 110 nm in diameter, the larger particles possibly being aggregates of the smaller. (Goodman, Sauer, Sauer and Rush, 1969; as quoted by Dawes and Senior, 1973 , Buchan, 1981)

From the literature (Harold, 1966; Dawes and Senior, 1973) it appears that the main function of polyphosphate in volutin granules is twofold:

(i) To act as a reserve "phosphate pool". Under conditions where the phosphorus requirements of the cell cannot be satisfied by the exogenous supply, the polyphosphates in the "phosphate pool" hydrolyse, releasing orthophosphate for use by the cell.

(ii) To serve as a reserve "energy pool". This can be used to supply the cell with additional energy if required; Dawes and Senior (1973) have shown that the energy associated with the reaction given below releases approximately 9 Kcal/mole which is slightly lower than the energy associated with ATP.

$$(P_i)_n \longrightarrow (P_i)_{n-1} + P_i \qquad (12)$$

$P_i$ = orthophosphate concentration (mole/l)

$n$ = number of orthophosphate molecules in the polymer

In order to form these pools phosphorus must enter the cell and be synthesized into polyphosphate.

Harold (1966) and Dawes and Senior (1973) reporting on transportation of phosphorus within a bacterial cell suggest two principles by which polyphosphate may accumulate in volutin granules:

(i) In growing cells, incoming phosphorus is used in the synthesis of new cells which requires the formation and utilisation of ATP. If growth is stopped because of exhaustion of a nutrient other than phosphorus, competition for ATP is relieved, and polyphosphate accumulates via a reaction catalysed by the enzyme polyphosphate kinase, indicated in Fig. 2.6. by route 2. This phenomenon is generally referred to as <u>luxury uptake</u>.

(ii) In cells that have been subjected to prior phosphorus starvation, very rapid synthesis of polyphosphate results when phosphorus is added, again using polyphosphate kinase and route 2 in Fig. 2.6. This is sometimes referred to as the <u>overplus mechanism</u> .

The polyphosphates, having accumulated within the volutins, may degrade via two routes:

- using polyphosphate kinase (route 3 in Fig. 2.6.)
- using polyphosphatase (route 1 in Fig. 2.6.)

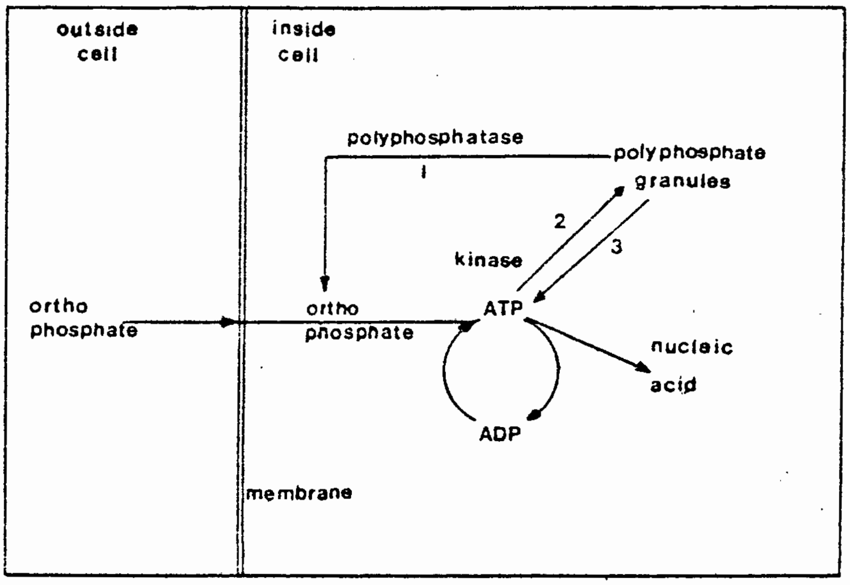


Fig. 2.6. Simplified biochemical pathways depicting phosphorus accumulation

### 3.3.3. Excess phosphorus removal as applied to the activated sludge process

The theories offered above are not easily applied to the activated sludge process because of the complex nature of sewage and the wide variety of living organisms generated by the process. Yall, Boughton, Knudsen and Sinclair (1970) and Garber (1972) have applied theories to the activated sludge process but to date the precise mechanism of phosphorus accumulation has not been fully elucidated. Nevertheless research and development in this field is continuing and highlights from this work are presented.

#### 3.3.3.1. Acinetobacter

Fuhs and Chen (1975) suggested that the bacterium Acinetobacter , a strict aerobe, and one of the most abundant organisms in sewage (Water Pollution Research, 1968), is the main micro-organism responsible for biological phosphorus removal. Using activated sludge taken from a pilot plant removing phosphorus, Lawson (1980) was able to identify 20 different strains of Acinetobacter , some of which exhibited a marked increase in size and change in shape (pleomorphism) concomitant with phosphorus removal. Using electron microscopy to examine the sludge from a number of activated sludge plants which were removing phosphorus Buchan (1981) also noted pleomorphism in an organism strongly resembling Acinetobacter which accumulated significant quantities of phosphorus in volutin granules.

#### 3.3.3.2. The anaerobic zone

A critical evaluation of the above data suggests that a necessary prerequisite for phosphorus removal in the activated sludge process is the presence of a non-aerated, well mixed zone which should desirably be free of nitrates. Davelaar, Davies and Wiechers (1978) indicated in pilot plant experiments that the organisms responsible for phosphorus removal are always present in activated sludge and only need some form of activation to enhance excess phosphorus accumulation. Fuhs and Chen (1975) suggest that the function of this zone is to ferment substrate into a form which can be readily assimilated by Acinetobacter. Furthermore Siebritz, Ekama and Marais (1980) are of the opinion that 25 mg/l of readily biodegradable COD must be present in the anaerobic zone in order to trigger the phosphorus removal mechanism. This COD could well be in the form of volatile acids which are the end product of fermentation.

The degree of anaerobiosis required to achieve fermentation or to trigger the mechanism to accumulate phosphorus was considered by van Haandel et al (1979) who expressed it in terms of an anaerobic potential which is an alternate method for expressing redox potentials.

### 3.3.3.3. Release of phosphorus in the anaerobic zone

Good phosphorus uptake in the aerobic zone has been found to be associated with an adequate release in the anaerobic zone. This release was always associated with uptake of phosphorus in the aerobic zone (Barnard (1974, 1976); McClaren and Wood (1976); Simkins and McClaren (1978). The last named suggested that the release by itself might not be involved directly in the phosphorus removal mechanism, but indicated rather that appropriate conditions have been created in the anaerobic zone which promoted phosphorus uptake in the aerobic zone.

Van Haandel, Ekama and Marais (1979) and Siebritz, Ekama and Marais (1980) endeavoured to define the anaerobic state that resulted in release. They accepted that release is associated with uptake but attempted to establish in terms of measurable parameters when release would occur.

Siebritz, Ekama and Marais (1980) examining the hypothesis that the anaerobic capacity is the critical parameter, observed that phosphorus release could occur in the presence of nitrate if a sufficiently large mass concentration of COD is added to the mixed liquor; this tended to negate the hypothesis that a redox effect was responsible for phosphorus release. From further investigations they concluded that the conditions for phosphorus release are:

(i) Nitrate must be absent

(ii) The concentration of easily biodegradable COD, $S_{bsa}$ in the anaerobic reactor must be greater than 25 mg/l. The $S_{bsa}$ concentration in the anaerobic reactor may be estimated using the following equation (Siebritz et al, 1980)

$$S_{bsa} = \frac{S_{bsi}\,Q - 8{,}6\,N_{nr}\,Q_r}{(Q + Q_r)} \qquad (13)$$

where

$S_{bsa}$ = readily biodegradable COD remaining in the anaerobic reactor (mg COD/l)

$S_{bsi}$ = readily biodegradable COD in the feed (mg COD/l)

$N_{nr}$ = nitrate concentration in the recycle (mg N/l)

$Q$ = feed flow rate (l/d)

$Q_r$ = returned sludge flow rate (l/d)

The mass concentration of phosphorus released will depend on $(S_{bsa} - 25)$ and the actual time of residence in the anaerobic reactor. Apparently the higher the release the greater the uptake that occurs. This led to the establishment of a phosphorus release factor $P_f$ defined as

$$P_f = (S_{bsa} - 20)\, f_{xa} \qquad (14)$$

where $f_{xa}$ is the fraction of sludge in the anaerobic reactor. Siebritz et al (1980) found that a relationship existed between $P_f$ and the percentage concentration of phosphorus with respect to the VASS, and plotted observed against $P_f$ as shown in Fig. 2.7.

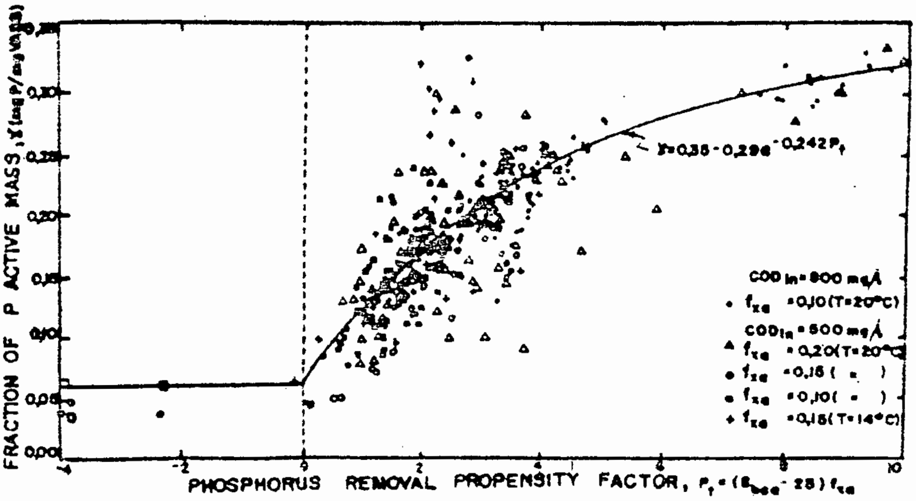


Fig. 2.7. Coefficient of excess phosphorus removal versus phosphorus removal propensity factor observed in the UCT (University of Cape Town) Process

### 3.3.4. Phosphorus removal in single sludge systems

A number of laboratory and pilot plant investigations have been conducted by various workers to develope a single sludge process to remove phosphorus. Barnard (1974) (Fig. 2.3.) in pilot plant studies using the Bardenpho process, noted excess phosphorus removal when the nitrate concentration in the second anoxic zone fell to zero. A release of phosphorus in this zone was observed with subsequent uptake in the reaeration zone. To obtain release in a most expeditious manner he modified the Bardenpho process by the incorporation of a nitrogen- and oxygen- free anaerobic zone at the head of the primary anoxic zone as shown in Fig. 2.8. and called the system the Phoredox process. He assumed that nitrates returned to this zone in the underflow from the final clarifiers would be negligible.

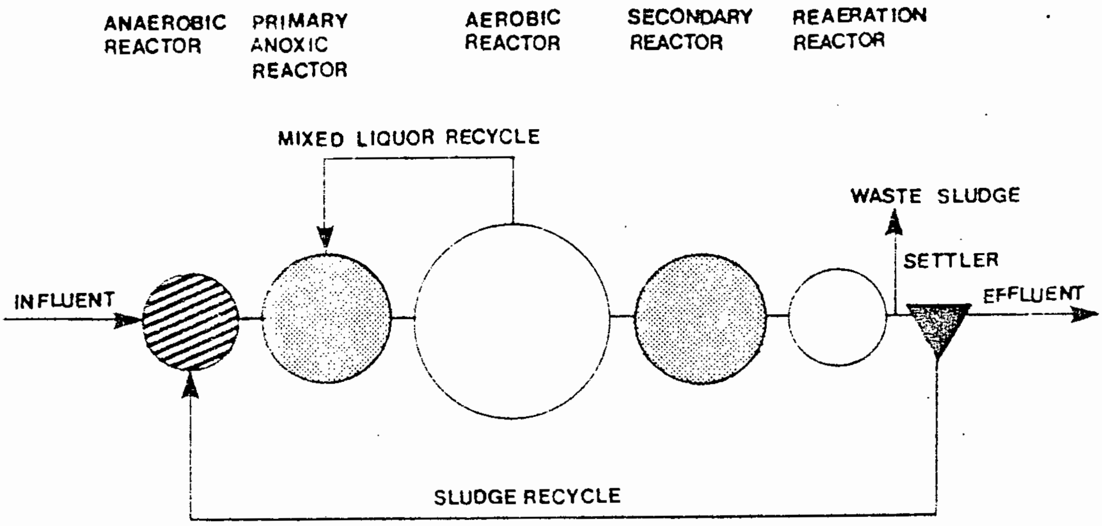


Fig. 2.8. The Phoredox activated sludge process configuration

Investigations into the behaviour of the Phoredox process have indicated that : (Simkins and McClaren, 1978; Marsden and Marais, 1977)

(i) when nitrate was not zero in the effluent excess removal of phosphorus declined sharply

(ii) the second anoxic zone removed virtually no phosphorus

In attempting to quantify this removal with the Phoredox process, Marsden and Marais (1977) and Hoffman and Marais (1977) found that the combined effect of metabolic uptake and luxury uptake is limited and related to the influent COD concentrations and the sludge age.

$$P = S_{ti} \frac{(1 - f_{us} - f_{up})\, Y_h\, (\alpha + f_p\, f\, b_{hT}\, R_s)}{(1 + b_{hT}\, R_s)} + \frac{f_p\, f_{up}}{P} \qquad (15)$$

where

$S_{bi}$ = biodegradable COD (mg/l)

= fraction of phosphorus present in the active mass (mg P/mg VASS)

VASS = volatile active suspended solids (mg/l)

$f_p$ = fraction of phosphorus present in the inert and endogenous mass (mg P/mg VSS)

$P$ = phosphorus concentration per unit influent flow discharged with the waste sludge (mg P/l)

Siebritz, Ekama and Marais (1980) using the Modified Phoredox i.e. a Phoredox system without a secondary anoxic zone, found that as the TKN/COD ratio of the plant increased above about 0,07 the nitrate in the effluent increased proportionally with the increase. As the effluent nitrate concentration is also the concentration recycled to the anaerobic reactor, if equation (13) is applied to determine $S_{bsa}$ in the anaerobic reactor, the $S_{bsa}$ concentration in the anaerobic reactor will be reduced to less than 25 mg/l if the nitrate concentration in the recycle attains a few mg/l in value, phosphorus release will cease and excess uptake will terminate.

In order to overcome the situation where TKN/COD ratio is so high that the Modified Phoredox process can not establish the minimum $S_{bsa}$ for phosphorus removal, Siebritz, Ekama and Marais (1980) developed a further modification of the Phoredox process (Fig. 2.9.) called the UCT process.

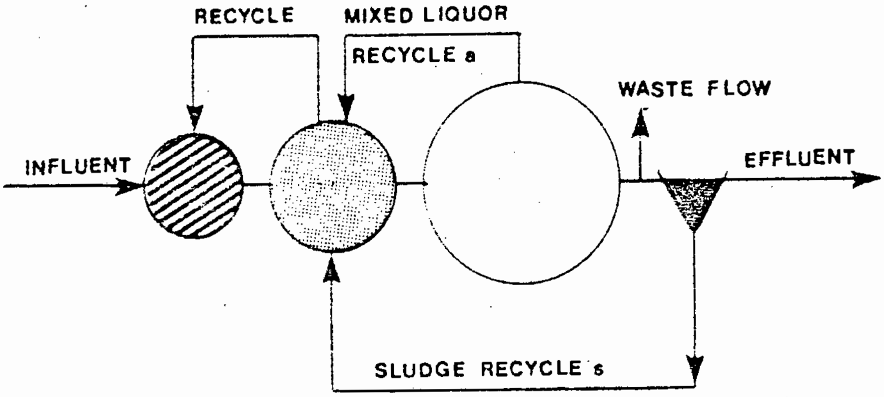


Fig. 2.9. The process configuration of the University of Cape Town Modification of the activated sludge process

By returning the underflow from the final clarifiers to the primary anoxic zone the nitrate can be reduced to zero by controlling the "a" recycle. An additional recycle is introduced from the anoxic zone to the anaerobic zone and, because no nitrate is present in the recycle, the $S_{bsa}$ is not depleted, and conditions favourable for phosphorus release are established (see Fig. 2.9.) i.e. in terms of Siebritz's hypothesis the highest value of $S_{bsa}$ will be maintained in the anaerobic reactor. This modification lends itself to a situation where the feed wastewater has a TKN/COD ratio higher than 0,07 to 0,08.

From the discussion above it would appear that in terms of the findings of the Cape Town group, the Phoredox five stage process is appropriate only if the TKN/COD ratio is less than about 0,07. At higher TKN/COD ratios the appropriate system would appear to be the UCT process.

The prerequisite conditions for phosphorus release and uptake that have emerged are of great utility both for design of new works, and assessment of the phosphorus removal property in existing works and the effect of modification of such works.

## 4. ACTIVATED SLUDGE MODELS

The models described in the previous section for nitrification and denitrification, are derived from a general model, and, are strictly valid only for the constrained conditions of constant flow and load. The nitrification and denitrification behaviour can be analysed also by means of the general model under constant flow and load conditions. The response, however, of the general model is so similar to that using the approximate model that there is little point in using the general model when analysing constant flow and load conditions, particularly when the general model requires the use of a large computer.

When cyclic load and flow conditions are imposed on the plant then the theoretical response can be obtained only by the use of the general activated sludge model. A general model, which will be used in analysis of the response of large scale plants is that developed by Dold, Ekama and Marais (1980) for aerobic processes, and extended to incorporate denitrification by van Haandel, Ekama and Marais (1981). It is not the intention here to go into a detailed description of the model. This is extensively discussed in two papers of Dold <u>et al</u> (1980)

and van Haandel et al (1981) and in a report by van Haandel and Marais (1981) . Use will be made of the model to simulate two large scale plants, that of Goudkoppies and the Northern Works respectively, these being the only plants where it was possible to monitor all the important variables such as COD, flow, TKN, recycles (a and s recycles), and process variables (MLVSS, oxygen utilisation rate, nitrate, ammonia, temperature, etc.). If the predicted reponses correspond closely with the observed, not only will it contribute to the reliability of the model but will allow both assessment of the phosphorus removal property and the modifications that would promote optimal removal of nitrate and phosphorus.

# CHAPTER THREE

## NUTRIENT REMOVAL AT THE JOHANNESBURG ALEXANDRA PLANT

### 1. INTRODUCTION

The main outfall sewers to the Northern Works generally follow the river valleys as can be seen in Fig. 1.1. By 1970 it was evident that the outfall connecting the now defunct Bruma Works to the Northern Works was rapidly becoming overloaded and that urgent remedial measures would have to be instituted. Relief was provided by the construction of a temporary 27 Ml/d facility at Alexandra Township, after which the Works was named. The only available site was a very narrow strip of land sandwiched between the outfall sewer and the Jukskei River, necessitating special design features:

* a small head loss through the plant
* compact design
* low capital cost as the plant was expected to operate for only six years
* limitation of area and close proximity to a residential area precluded the establishment of sludge handling facilities. Sludge could however be returned to the sewer for digestion at the Northern Works.

When all these points were considered there was no economic alternative to the extended aeration activated sludge process.

## 2. DESIGN OF THE PLANT

The feed to the plant, which included nightsoil from the Alexandra Township, was drawn directly from the Bruma sewer, rough control being exercised by hand operation of a penstock valve, and the rate of flow being monitored by a flume type flow meter. Typical hourly flow and daily flow characteristics are presented in Figs. 3.1. and 3.1. respectively.

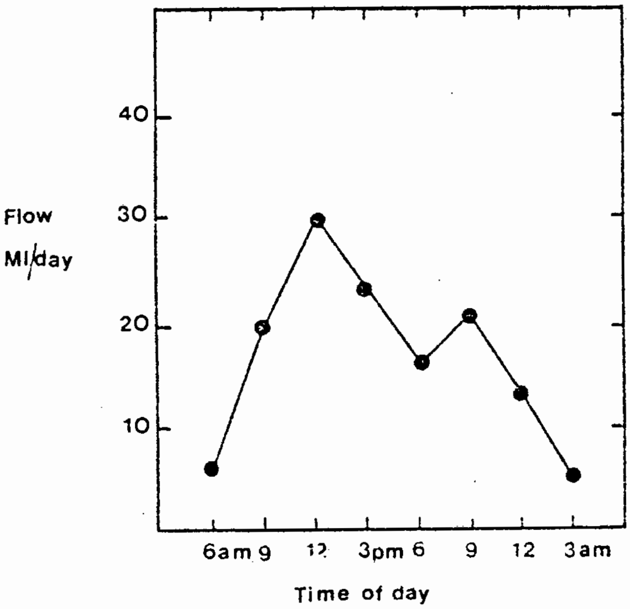


Fig. 3.1.

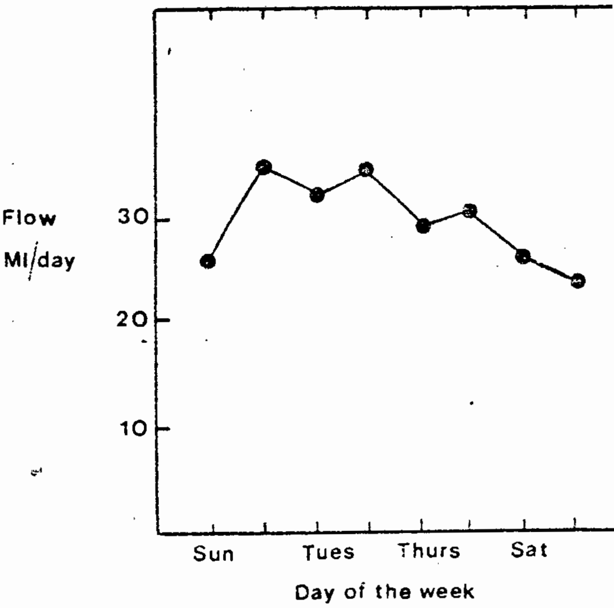


Fig. 3.2.

Johannesburg Alexandra Plant

Hourly feed flow variation to plant over a day

Daily feed flow variation to plant over a week

COD and TKN concentrations were monitored at 8 day intervals by taking 0,5 l grab samples every hour and compounding these over 24 hours. The plant, designed to nitrify completely, consisted of two mechanically aerated basins in series, the first comprising 60% of the total volume. Plant layout is shown in Fig. 3.3., design data in Table 3.1.

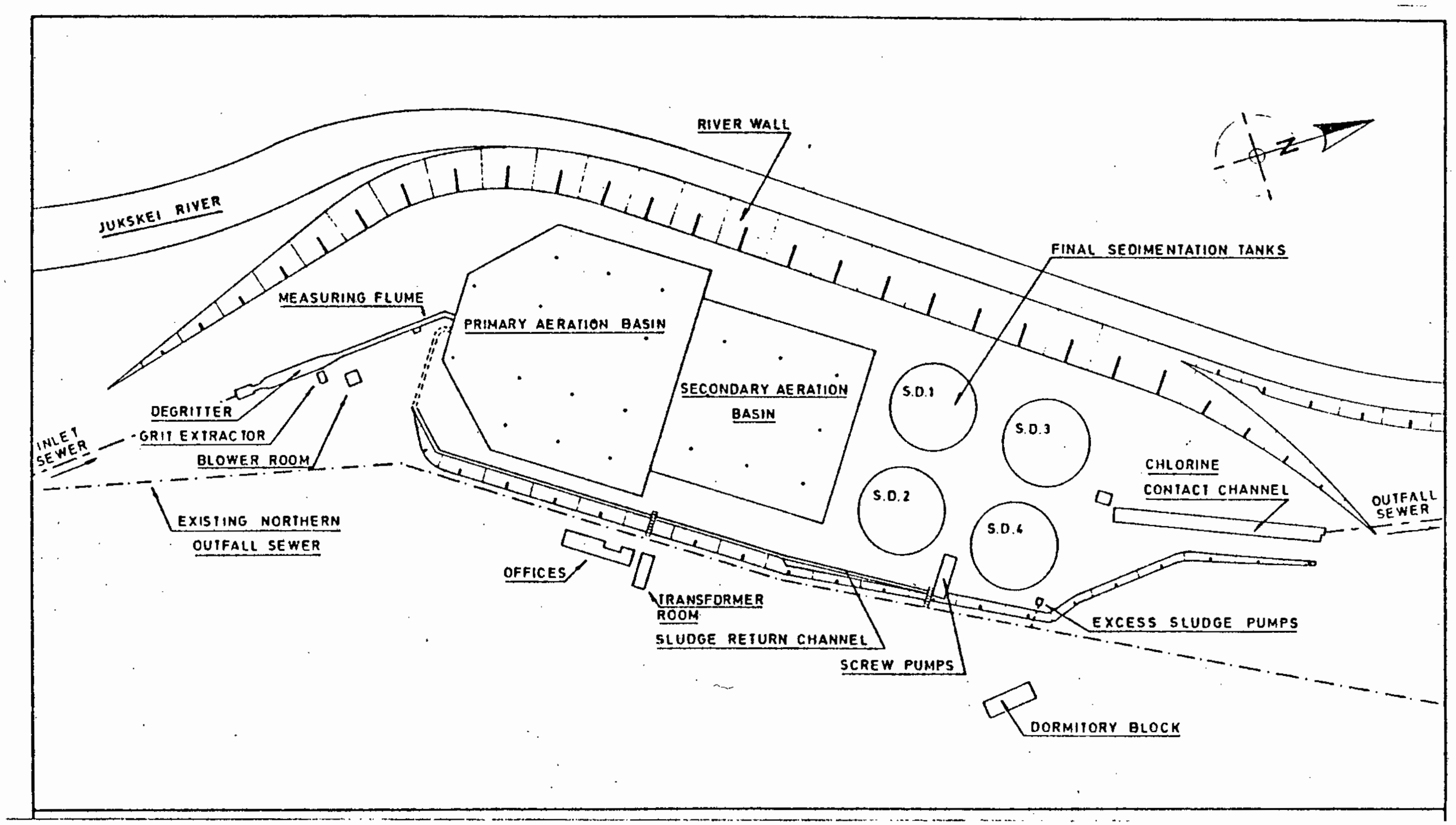


Fig. 3.3. Johannesburg Alexandra Plant design layout

## Table 3.1.

## ALEXANDRA PLANT DESIGN DATA

| | | | |
|---|---|---|---|
| Flow D W F | | (Ml/d) | 27 |
| Raw sewage composition | BOD | (mg/l) | 350 |
| | TKN | (mg N/l) | 35 |

**Aeration Basin**

| | | | |
|---|---|---|---|
| Volume (both basins) | $(m^3)$ | 33 500 | |
| Retention period at design flow | (h) | 28 | |
| Oxygenation capacity | $(kg\ O_2/h)$ | 1562 | |
| Mixed liquor suspended solids | (mg/l) | 3 500 - 5 000 | |
| Water depth in tank | (m) | 4,57 | |
| Basin number | | 1 | 2 |
| Volume | $(m^3)$ | 20 450 | 13 050 |
| Number of aerators | | 14 | 9 |
| Power per aerator at design flow | (kW) | 37 | 30 |
| Energy density at design flow | $(W/m^3)$ | 27 | 21 |

**Secondary Sedimentation Tanks**

| | | |
|---|---|---|
| Number | | 4 |
| Diameter | (m) | 26,7 |
| Side water depth | (m) | 3,73 |
| Surface loading at D W F | (m/h) | 0,5 |
| Volume | $(m^3)$ | 2 350 |
| Retention time at D W F | (h) | 8,3 |

**Returned Sludge Pumps**

| | | |
|---|---|---|
| Number | | 2 |
| Power per pump | (kW) | 11 |
| Maximum pumping capacity | $(m^3/sec/pump)$ | 0,24 |
| Head | (m) | 2,1 |

The rotational direction of the aerators is shown in Fig. 3.4.

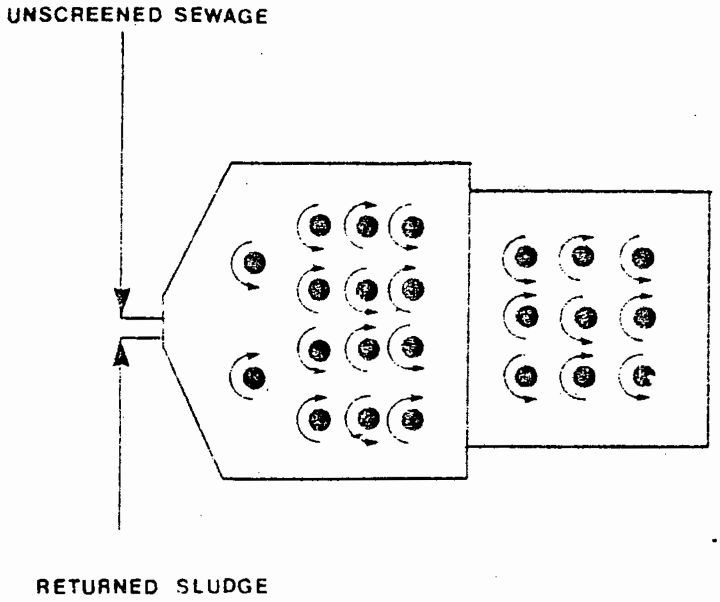


Fig. 3.4. Johannesburg Alexandra Plant

Direction of rotation of surface aerators.

Specific control features were provided as follows:

2.1. <u>Dissolved oxygen control</u>

Two methods were provided:

(i) A manual system accomplished by changing the depth of immersion of the mechanical aerators by raising or lowering a level control weir at the discharge end of the second aeration basin.

(ii) A semi-automatic system involving the connection of 12 aerators in the first aeration basin to a time switch which allowed the appropriate number of aerators to be switched in or out in accordance with a predetermined load pattern.

## 2.2. Sludge age control

The utilitarian design made no provision for measuring the mass of sludge wasted per day. Consequently in the initial stages of plant operation it was not possible to determine accurately the sludge age. Limited control of sludge age was imposed by endeavouring to keep the mixed liquor suspended solids (MLSS) at a constant value. Initially the best concentration was established by changing the MLSS until a sludge with optimal settling properties was obtained. However, because the actual sludge age was indeterminate, it was virtually impossible to operate the plant in a scientific manner and data obtained during this period is of little value.

In 1976 improved control of the sludge age was made possible by the installation of a pump to discharge a preselected volume of mixed liquor from the aeration basin. With this method the sludge age could be maintained at any selected value by simply adjusting the flow to be abstracted for wastage each day, the sludge age, $R_s$ , being defined by

$$R_s = \frac{\text{plant reactor volume}}{\text{volume wasted per day}}$$

The minimum sludge age for nitrification, $R_{sm}$ was calculated from the formula derived by Downing _et al_ (1964):

$$1 / R_{sm} = \mu_{nm20}^{(T - 20)} \qquad (2)$$

where

$U_{nmT}$ = specific growth rate of the nitrifiers at T °C

In the absence of any information on $\mu_{nmT}$ it was decided to accept a very conservative, low value, $\mu_{nm20} = 0{,}3$ . The lowest mean water temperature expected during winter was approximately 12 °C .

Substituting $\mu_{nm20} = 0{,}3$ and $T = 12$ in equation (2), $R_{sm}$ was estimated at 7,8 days. For efficient nitrification, i.e. 95% conversion, the sludge age must be greater than $R_{sm}$; Ekama and Marais (1978) found that if a safety factor of 1,25 is applied to $R_{sm}$ the plant will always nitrify efficiently even under cyclic flow conditions. Applying this factor of safety, the sludge age was specified at $1{,}25 \times 7{,}8 = 10$ days.

At the time the plant was put into operation it was already decided to utilise it as an experimental facility for testing denitrification behaviour. In order to allow for the effect of an anoxic zone of up to 1/3 total volume, the sludge age was increased to $10/(1 - 1/3) = 15$ days.

## 3. EXPERIMENTAL INVESTIGATION INTO NITROGEN REMOVAL AND RESULTS

The objective of the experimental investigation was to determine the effect of anoxic conditions on the performance of the plant. Anoxic conditions were to be imposed by switching off one, two or more aerators in the first or primary basin adjacent to the discharge point of the raw sewage and underflow return. The investigation consisted of four experiments, with zero, one, two and three aerators switched off respectively.

When one, two or more aerators were switched off in the primary basin, correspondingly an anoxic zone of increasing size was created. Nitrates produced in the remaining aerated section of the primary basin cycled through the artificially created anoxic zone by the strong pumping action of the remaining aerators (as illustrated in Fig. 3.5. (a) and (b) ) and were denitrified in the anoxic zone.

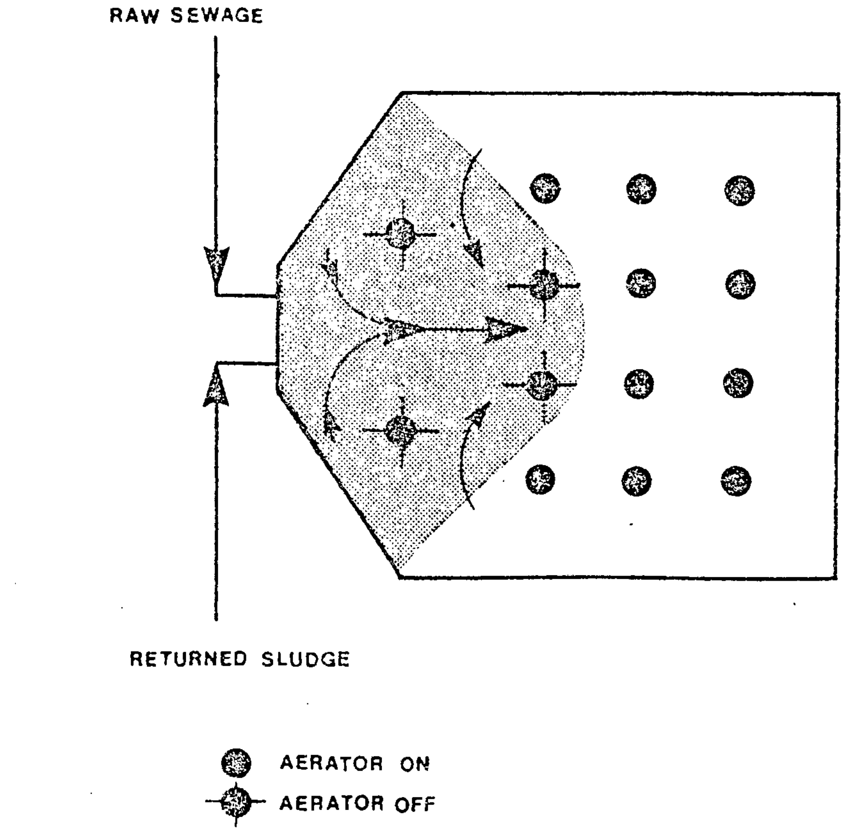


Fig. 3.5.(a) First aeration basin depicting the surface wave pattern and the current patterns obtained with aerators off

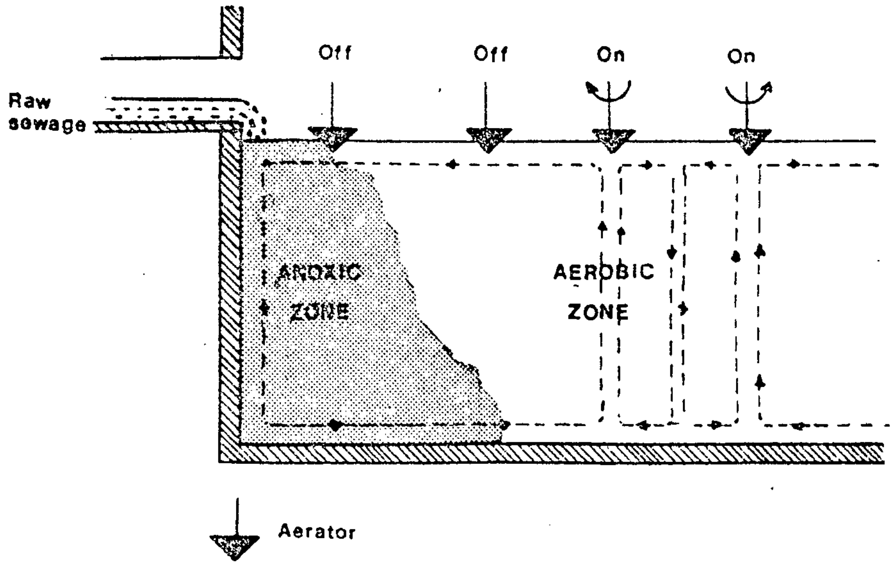


Fig. 3.5.(b) Flow pattern with four aerators off

Johannesburg Alexandra Plant

Preliminary tests, when operating the plant near the design load conditions and at a sludge age of 15 days, showed excessively high oxygen concentrations in the mixed liquor, particularly in the second aeration basin. Partial disruption of the activated sludge flocs was observed, resulting in fine colloidal particles in the effluent, higher than allowed by regulations promulgated under the Water Act No 54 of 1956. Since the plant effluent must comply with these regulations, corrective measures were taken by reducing the oxygenation input to the second basin by switching off three aerators; the dissolved oxygen concentration in the second aeration zone reduced to 1 - 2 mg/l, flocculation improved and the effluent quality fell below the minimum required. However, during the test in which three aerators were to be switched off in the primary basin the oxygen level reduced to zero in the second basin and it became necessary to switch in two of the three aerators i.e. only one remained off in the second basin.

## 3.1. Sampling procedure

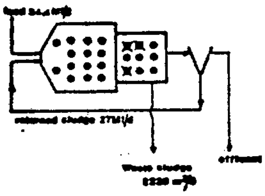
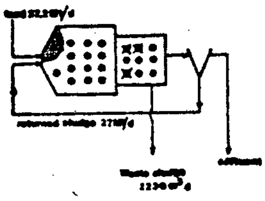
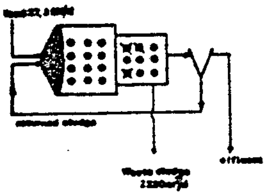
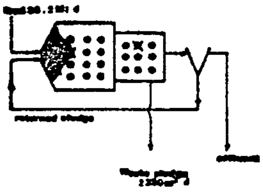
Sampling in each of the four experiments commenced only after the plant had been operated in the particular mode for a period of one month i.e. two sludge ages. Snap samples of influent just before the discharge into the plant, and effluent just before discharge into the river were taken hourly and compounded in equal proportions at the end of a 24 hour sampling period. Simultaneously hourly samples of mixed liquor were taken from a site adjacent to one of the aerators near the centre of the first basin and subsequently compounded to determine an average MLSS value. When the plant was sampled over weekends the samples were preserved by the addition of 1 ml of 0,85 per cent mass/mass mercuric chloride.

## 3.2. Results

A summary of the aerators which were switched in or out for each test run is given in Table 3.2. together with the summarised mean data for the feed and effluent during the test period. The raw data obtained during the various experiments are to be found in Appendix A2 .

Table 3.2.

Performance data for the Alexandra Plant with 0,1,2 and 3 aerators switched out in the first basin

| | | Total Nitrogen mg/l | Ammonia as N mg/l | Nitrate as N mg/l | Alkalinity as $CaCO_3$ mg/l | Total COD mg/l | Soluble COD mg/l | Suspended solids mg/l | pH |
|---|---|---|---|---|---|---|---|---|---|
|  | Feed | 39,9 | 20,3 | nil | 240 | 590 | 230 | 290 | 7,6 |
| | Effluent | 32,3 | 4,9 | 23,5 | 150 | 74 | 52 | 25 | 7,5 |
| | | No aerators off in first basin | | | MLSS 2 600 mg/l | | | | |
|  | Feed | 38,4 | 22,4 | nil | 240 | 520 | 270 | 230 | 7,4 |
| | Effluent | 24,4 | 4,4 | 16,5 | 120 | 82 | 58 | 31 | 7,2 |
| | | One aerator off in first basin | | | MLSS 2 560 mg/l | | | | |
|  | Feed | 39,2 | 18,9 | nil | 240 | 480 | 220 | 290 | 7,4 |
| | Effluent | 16,7 | 3,9 | 8,8 | 150 | 65 | 53 | 30 | 7,5 |
| | | Two aerators off in first basin | | | MLSS 2 260 mg/l | | | | |
|  | Feed | 38,0 | 20,1 | nil | 220 | 590 | 280 | 310 | 7,2 |
| | Effluent | 12,4 | 3,0 | 6,6 | 130 | 56 | 43 | 21 | 7,3 |
| | | Three aerators off in first basin | | | MLSS 3 100 mg/l | | | | |

# 4. DISCUSSION

## 4.1. MLSS concentration

The MLSS provided an opportunity to check the theoretical predictions of the model of Marais and Ekama (1976) . A sample calculation of the concentration of the various sludge fractions of the MLSS is shown in Appendix A3 . A summary of the calculated and observed mixed liquor concentrations is listed in Table 3.3.

Table 3.3.

Average experimental and theoretical MLSS concentrations during nitrogen removal experiments

| | Experiment no. | | | | Ave |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | |
| Aerators off first basin | 0 | 1 | 2 | 3 | |
| Sludge age (d) | 15 | 15 | 15 | 15 | 15 |
| Theoretical MLSS (mg/l) | 2695 | 1878 | 1740 | 2759 | 2268 |
| Experimental MLSS (mg/l) | 2620 | 2560 | 2260 | 3100 | 2635 |
| % Difference | +3 | -27 | -23 | -11 | -14 |

The calculated and observed concentrations consistently show that the calculated concentrations were less than the observed. It is not possible to check the validity of the results because in 1974 when these tests were done the importance of the oxygen utilisation rate had not been realised and this measurement was not undertaken. Consequently it is not possible to do an energy or electron balance on the carbonaceous material i.e. check if the daily (mass of COD in the effluent) + (mass of COD in the sludge wastage) + (mass of oxygen utilised) equals the daily (mass of COD in the influent) . Without a check on the COD balance it is not possible to make a comparison between the theoretical prediction and the observed MLSS. In addition the mean daily influent sample was obtained from grab samples, not compounded according to the flow at the time the sample was taken. This can have a serious effect when calculating the mass of COD that passes through the plant each day. Ekama and Marais estimated that, depending on the cyclicity of both flow and load, the mass of COD determined in the manner employed here, can result in underestimation of the load by up to 20% . On this basis the apparent underestimation of 14% is not unexpected.

## 4.2. Nitrification and denitrification

The introduction of an anoxic zone into the process configuration did not affect final effluent quality detrimentally. Both organically bound nitrogen and ammonia contained in the influent sewage will pass through the anoxic zone unaffected, except for dilution, to enter the downstream aerobic area where the organic nitrogen is converted to ammonia. At the sludge age provided (15 days) the major proportion of the bound and free saline nitrogen should be oxidised biologically to nitrate.

In particular the ammonia should be reduced to below 1 mg/l . However the ammonia concentrations in the last basin and effluent were in the range 3 - 5 mg N/l; no acceptable explanation for these high values can be advanced.

The mass of nitrate removed per day for each experiment is listed in Table 3.4.

Table 3.4.

Johannesburg Alexandra Plant

Mass of nitrogen removed per mass of incoming COD

| | Experiment number | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| Number of aerators off in first basin | 0 | 1 | 2 | 3 |
| Mass N removed (kg/d) | 261 | 380 | 514 | 901 |
| Mass N removed / Mass COD (% removed) | 1,4 | 3,0 | 5,3 | 4,6 |
| Total N (mg N/l)<br>Influent<br>Effluent | <br>39,9<br>32,3 | <br>38,4<br>24,4 | <br>39,2<br>16,7 | <br>38,0<br>12,4 |
| Drop in alkalinity (mg/l $CaCO_3$) | 90 | 120 | 90 | 90 |

It is clear that as an increasing number of aerators were switched off, so the mass of nitrate removed increased. The degree of nitrate removal from the system is dependent upon how much of the nitrate enters the anoxic zone and to what degree it is then denitrified. The nitrate entering the anoxic zone depends on the direction of rotation of the aerators, the recycle flow rate, the number and position of rotation of decommissioned aerators; whereas the degree of denitrification depends on the fraction of nitrate entering the anoxic zone and the concentration of COD in the influent. No reliable estimation of the mixing into the anoxic zone was possible so that no quantitative prediction of the concentration of nitrate entering the zone could be made. The only positive statement that appears to be valid is that as the anoxic zone increased, the concentration of nitrate in the effluent decreased. Consequently it would appear that the factor that limited denitrification was the size of the anoxic zone created. This was too small to denitrify all the nitrates entering the zone - as the zone increased so the nitrate removal increased correspondingly, as indicated in Table 3.4.

Surprisingly, from Table 3.4. , with one exception, there was no significant change in the loss in alkalinity through the process. It is to be expected that with nitrification and denitrification there will be a loss of alkalinity and this loss should decrease as the denitrification effect increases.

## 4.3. Settling properties of the sludge

The inclusion of a non-aerated zone into the original process configuration did not appear to produce any observable effects on on the settling properties of the sludge. At that time comparative measurements on sludge settling rates were not appreciated so that little can be said quantitatively with regard to the effect of the anoxic zone on settling. Other effects were visible; over periods in which anoxic zones were present a dark brown scum formed during the cold weather on the surface of the aeration tank. Initially it was believed to be due to the presence of oil or fat but later was found to be due to floating accumulations of an organism Nocardia Spp. The reason why this particular organism should flourish in anoxic/aerobic systems, particularly in winter, has not yet been established, but without doubt the possibility of generation of this organism is a factor to be considered in these plants.

## 5. OPERATION OF THE PLANT IN A NITROGEN AND PHOSPHORUS REMOVAL MODE

Barnard (1974) , in testing the Bardenpho system, noted that on occasions when an anoxic reactor contained no nitrate phosphorus release was observed in that reactor and excess phosphorus removal was obtained in the aerobic reactor. From these observations it can be suggested that anaerobic conditions could be established by placing such a reactor at the head of the system to receive the influent flow and the underflow recycle - Fig. 2.8. This reactor, because of the low nitrate concentration in the underflow conceivably would utilise the mass of nitrate entering the reactor and establish an anaerobic condition sufficiently intense to cause release of phosphorus. This hypothesis was tested at the Alexandra plant by making due modifications to the operation of the plant.

Before modifying the Alexandra plant so that it would reduce phosphorus removal, it was necessary to examine a number of options whereby it may be possible to create 'anaerobic conditions' such that phosphorus will be released. Three options were investigated:

(i) Switch out more than three aerators around the influent point of the main basin

(ii) Store the sludge in the secondary clarifier

(iii) Store the sludge on the floor of the main aeration basin.

It was not possible to monitor the system as extensively as deemed necessary; provision was not available on site for research investigations, only for essential monitoring required by law. Because of these difficulties only the bare minimum testing, to determine if denitrification and phosphorus removal took place, could be undertaken.

## 5.1. Switching out of aerators

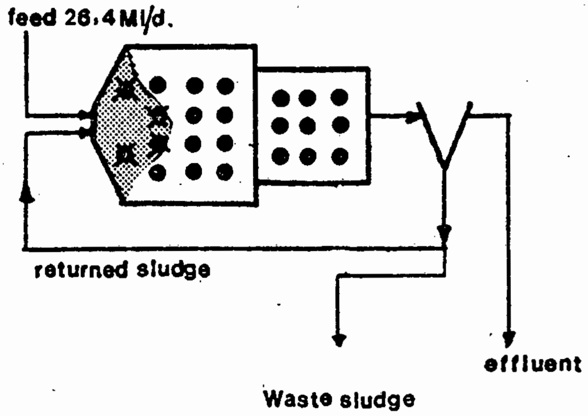
The plant was operated in the same manner as for the denitrification experiments except that four and later six aerators were switched out around the influent point.

Consider the experiment in which four aerators were switched out; the configuration of aerators switched in and out are shown in Table 3.5. , also the effluent response to the plant.

Table 3.5.

Johannesburg Alexandra Plant

Summary of operating parameters and chemical analysis under conditions where 4 aerators at the start of the aeration basin were off



| | Concentration | |
|---|---|---|
| | Feed | Effluent |
| Total nitrogen (mg N/l) | 42,5 | 6,5 |
| Ammonia as N (mg N/l) | 25,0 | 2,5 |
| Nitrate as N (mg N/l) | nil | 1,9 |
| Alkalinity as $CaCO_3$ (mg/l) | 220 | 140 |
| Total COD (mg/l) | 690 | 85 |
| Suspended solids (mg/l) | - | 7,0 |
| pH | 7,1 | 7,4 |
| O - phosphate (mg P/l) | 5,5 | 5,0 |

Nitrate removal was excellent, the effluent concentrations ranged around 1,9 mg N/l. Phosphorus removal was relatively minor, indicating that the required anaerobic conditions for phosphorus release had not been attained. Nitrification was unaffected by the anoxic zone. This was indicated by the low ammonia nitrogen value of 2,5 mg N/l .

Notwithstanding the fairly large unaerated volume there was no significant deterioration of the settling properties. A typical settling velocity curve over this period is depicted in Fig. 3.6.

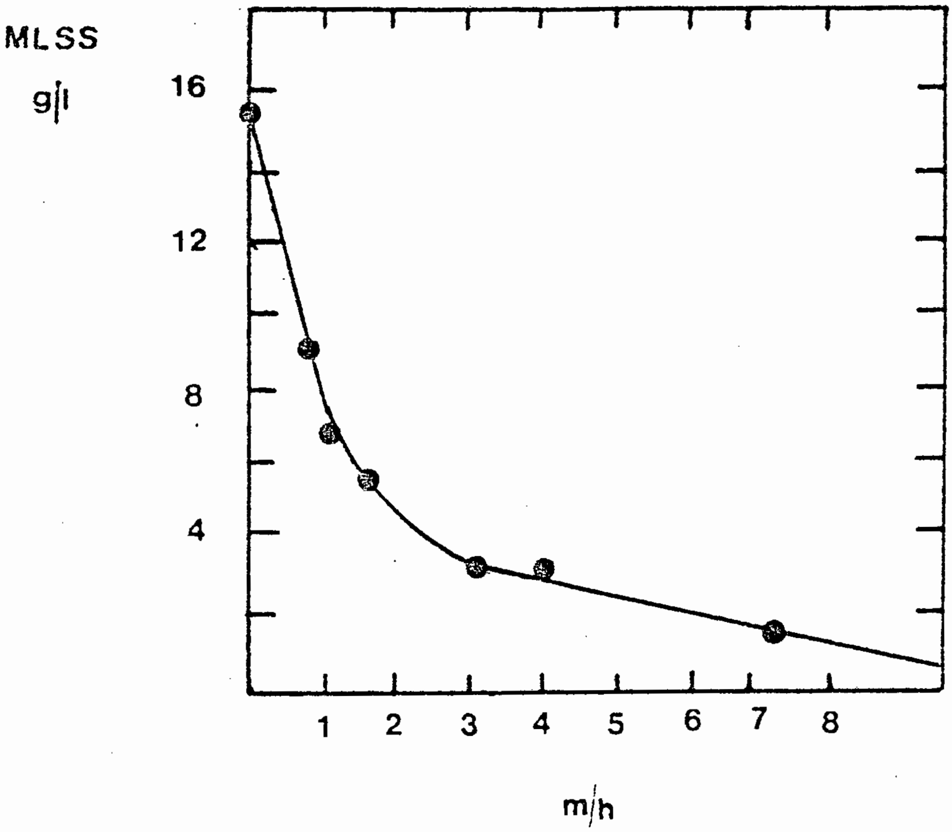


Fig. 3.6. Johannesburg Alexandra Plant

Relation between settling velocities of sludge and sludge concentration.

In order to increase the probability of anaerobic conditions six aerators were switched off around the inlet point - see Fig 3.7. This operational modification gave excess phosphorus removal sporadically. The plant was operated in this mode for four months; the influent and effluent phosphorus over this period is shown in Fig. 3.8.

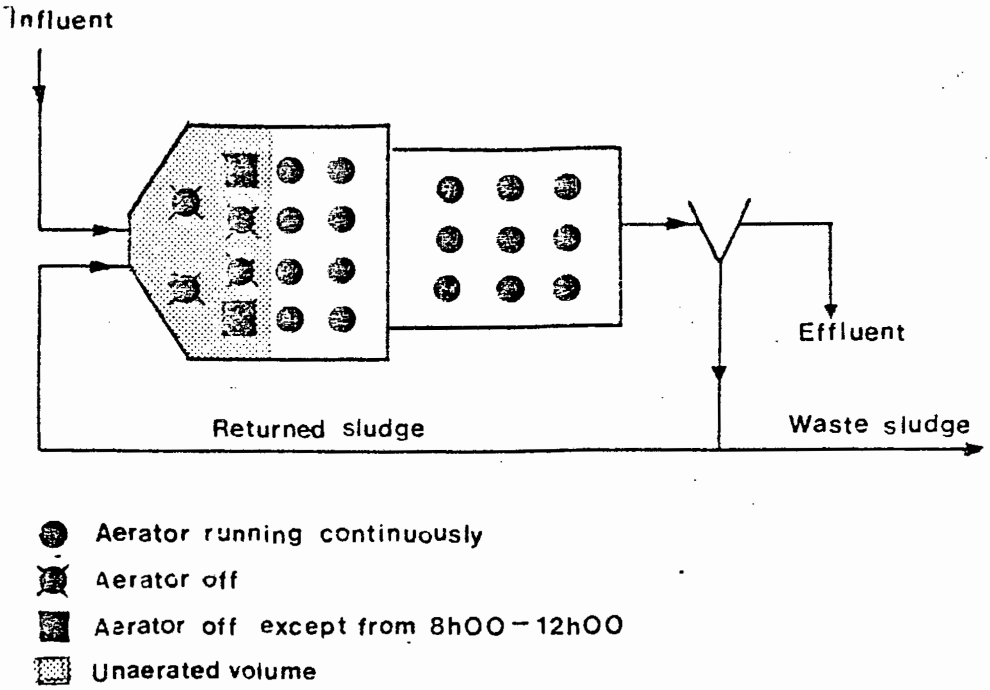


Fig. 3.7. Creation of an enlarged anaerobic zone at the head of the first aeration basin

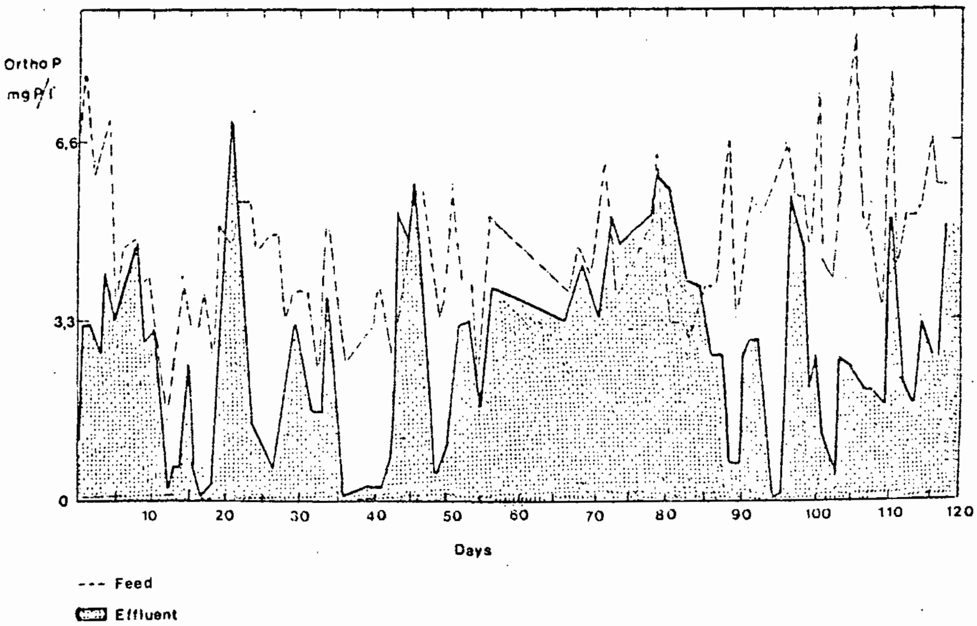


Fig. 3.8. Phosphorus removal data associated with an enlarged anaerobic zone (6 aerators off) at the head of the first aeration basin

Johannesburg Alexandra Plant

Over this period the average removal of ortho-phosphorus was approximately 1,9 mg P/l. Nitrification efficiency deteriorated slightly - compare the ammonia effluent concentration in Table 3.5. with that in Table 3.6.

Table 3.6.

Average analysis of feed and effluent when 6 aerators were off at the head of the aeration basin

| | | Feed | Effluent |
|---|---|---|---|
| COD | (mg/l) | 540 | 58 |
| TKN | (mg N/l) | 38 | - |
| Ammonia as N | (mg N/l) | 17 | 6,1 |
| Nitrate as N | (mg N/l) | - | 1,9 |
| O- phosphate as P | (mg P/l) | 4,7 | 2,8 |
| Suspended solids | (mg/l) | | 23 |
| MLSS | (mg/l) | 3 900 | |

## 5.2. Accumulation of sludge in the secondary clarifier

The sporadic nature of the phosphorus removal, when six aerators were switched off in the main basin highlighted the unstable nature of the conditions created in the anoxic zone. It was then hypothesized that if a fixed quantity of sludge could be brought into a state of 'deep anaerobiosis' a more consistent phosphorus removal might be accomplished. To induce such a continuous state of anaerobiosis the underflow recycle was reduced so that sludge accumulated in the settling tank. By regulating the recycle appropriately the settling tank could be maintained approximately half full of sludge - Fig. 3.9.

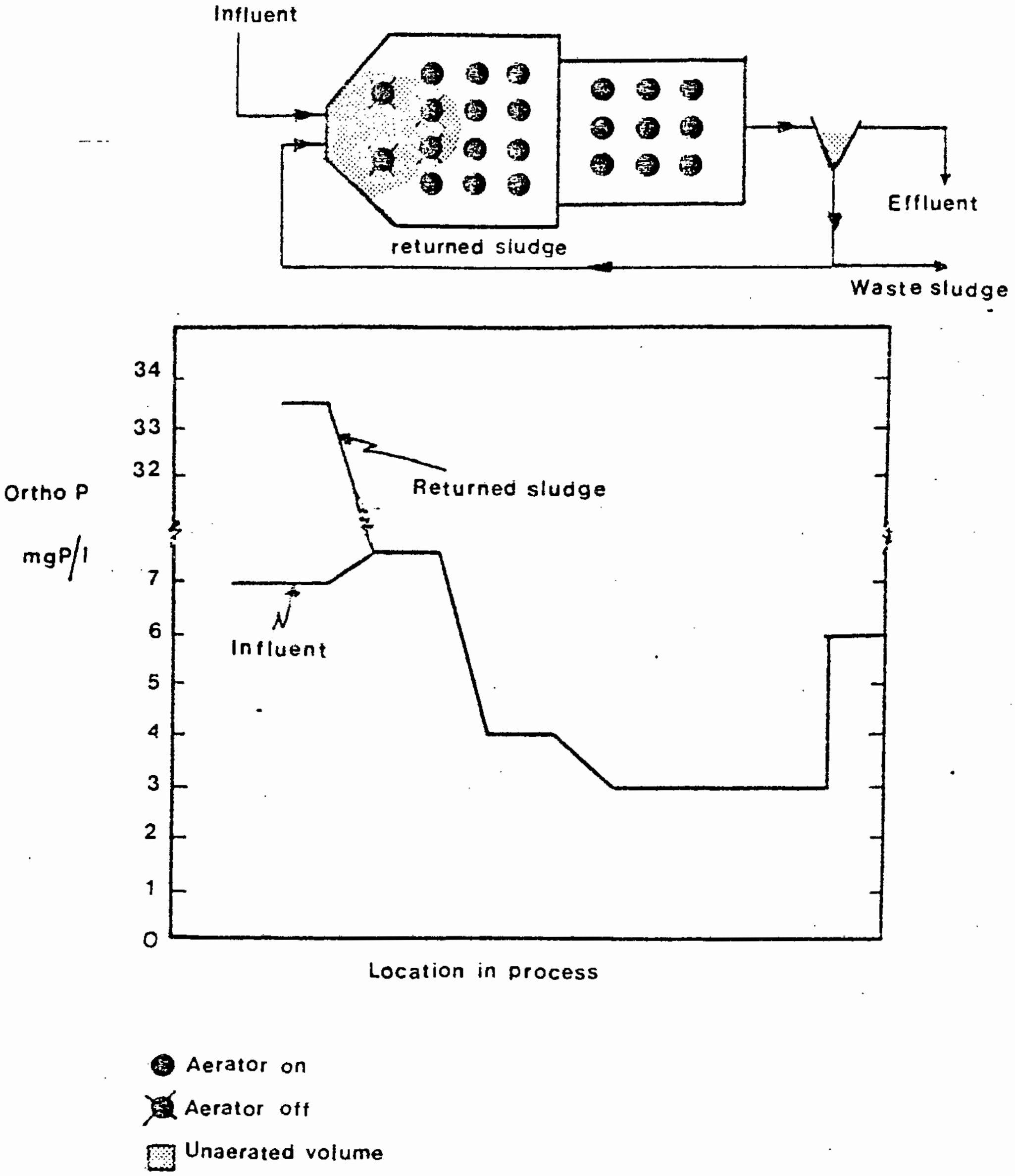


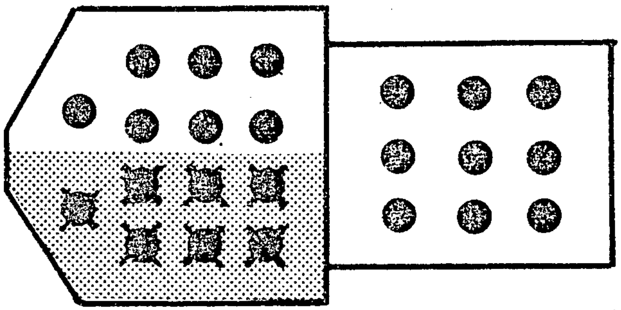
Fig. 3.9. Johannesburg Alexandra Plant Phosphorus profile when sludge stored temporarily in final clarifier

In monitoring the plant while operating in this mode a series of phosphorus determinations on filtered samples was carried out along the centre line of the plant and in the recycle (i.e. equivalent to the bottom of the settling tank) . The results are shown in Fig. 3.9. It is clear that whereas very little release had taken place in the anoxic zone per se , significant release did take place in the settling tank. It is also evident that the stress condition caused substantial excess uptake of phosphorus in the aerobic region of the plant. Indeed 4 mg/l of phosphorus was taken up. Unfortuneately in the settler the phosphorus was again partially released so that the effluent phosphorus was only 1 mg/l less than the influent. The mode of operation therefore did not provide for a significant removal of phosphorus.

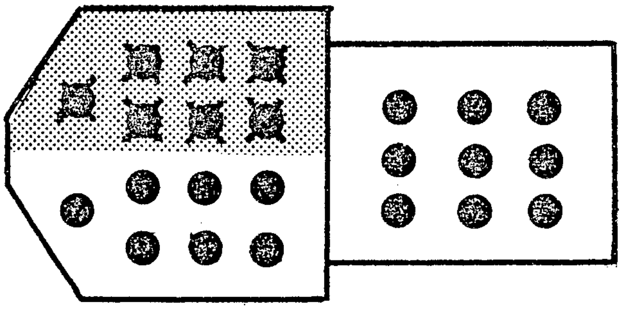
## 5.3. Storage of sludge on the floor of the aeration basin

It was hypothesised that release of phosphorus in the sludge could be induced by allowing accumulation of sludge to form on the base of the tank by switching off some of the aerators for a fixed period to test this approach. All the aerators on one side of the first aeration basin were switched off to encourage settlement of sludge on the floor. Sludge accumulated for 24 hours, after which it was resuspended by switching on the aerators, at the same time switching off those in the other half of the basin (see Fig. 3.10.) This procedure was repeated daily.

The response of the plant, for phosphorus and nitrate, as measured along the centre line of the plant, is plotted in Fig. 3.11.



First day's operation



Second day's operation

● aerator on
☒ aerator off
▨ unaerated volume

Fig. 3.10. Johannesburg Alexandra Plant

Creation of an anaerobic zone in each half of the first aeration basin by sequential turning off of aerators

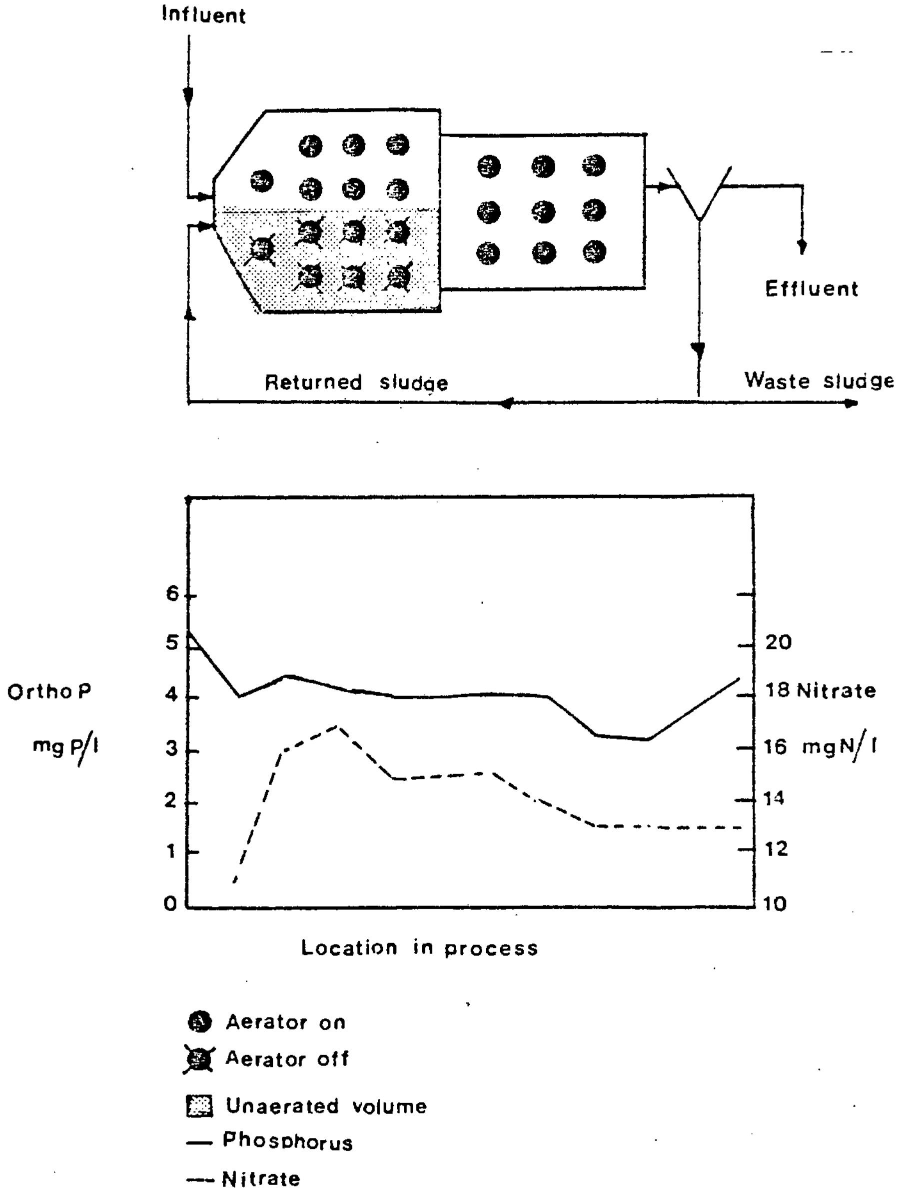


Fig. 3.11. Johannesburg Alexandra Plant

Phosphorus profile across plant with anaerobic zone on side of first basin

Clearly phosphorus removal was negligible and the nitrate in the effluent was considerably higher than when aerators were switched off around the influent point. From observation it would appear that when the aerators were switched off on one side of the plant the intermixing of the aerated and unaerated sections was relatively minor and this possibly was the reason for the low nitrate removal. It is evident that this mode of operation has little to recommend it both for nitrogen and phosphorus removal.

## 6. GENERAL CONCLUSIONS

The work on the Alexandra plant points to the following conclusions:

(i) By switching off aerators around the point of entry of the influent and recycle flows denitrification is readily achieved.

(ii) The mass of nitrate removed appears to increase as the number of aerators that are switched off is increased. The number of aerators that can be switched off can be increased only to that number where the nitrification becomes affected. In the Alexandra plant when 6 aerators were switched off nitrification efficiency commenced to decline. On any plant this limit will need to be determined by trial and error because of the difficulty in quantifying the fractional volume of the plant that becomes anoxic when one or more aerators are switched off.

(iii) If sufficient aerators are switched off (6 in the Alexandra plant) apparently an anaerobic region can be developed of such intensity that phosphorus release will be observed and some excess phosphorus removal obtained. Again the anaerobic region can not be defined and appears to fluctuate, resulting in very variable phosphorus uptake. In the Alexandra plant phosphorus release commenced with 6 aerators off, but at the same time the nitrification efficiency commenced to decline; phosphorus removal therefore may be constrained by the requirement that good nitrification must be maintained.

(iv) The operational modification in which sludge was stored in the settling tank, gave rise to phosphorus release but due to the fact that the settling tank also served as the final separator the phosphorus release to the effluent nullified the excess uptake in the plant. It would appear therefore that this method also has little value.

(v) Storage of sludge on the base of the aeration tank by switching off sections of the aerators did not appear to work - phosphorus removal was minimal and denitrification efficiency declined.

(vi) A general conclusion on the work on the Alexandra plant is that in most activated sludge plants it should be possible to achieve fair to excellent removal of nitrate by creating an unaerated region around the area where the influent and recycle flows meet. The degree of nitrogen removal needs to be found by experiment, the limiting size of the region being given either by the point at which nitrification efficiency commences to decline or, the reduced aeration capacity no longer can supply sufficient oxygen for carbonaceous energy degradation and nitrification.

# CHAPTER FOUR

# THE GOUDKOPPIE PLANT

## 1. INTRODUCTION

The Goudkoppie Works was proposed when it became apparent that the Klipspruit Works, the oldest in the City, could not be extended any further. The new works was to be constructed adjacent to the biological filter plant at Klipspruit, as shown in Fig. 1.1. At the same time a new tunnel sewer was to be constructed to replace two older sewers draining the central business area of Johannesburg. Most of the flow to the new works was of domestic origin, although some light industries and the City Gasworks also discharged into this line. Effluent from the Gasworks, although small in volume, was of very high organic strength and high in ammonia concentration.

The site chosen was sufficiently large to permit the construction of works ultimately to treat 650 Ml/d . Design objectives included the production of high quality effluent low in nitrogen content, readily amenable for reuse without further treatment. Treatment was to take place in three identical modules each with the capacity to treat 50 Ml/d . Each module was to be provided with adequate metering facilities to permit large scale experiments to be carried out on the plant in order to determine the optimum mode of operation. The concrete shell of a fourth 50 Ml/d unit also was to be constructed but not to be equipped with any aerators or other auxiliary appliances. The intention here was to modify and complete this unit at some later date depending on the outcome of the experimental program on the fully equipped units.

At the time of construction there was uncertainty regarding the best mode of treating the solids arriving at the works, i.e. by the normal anaerobic digester route or via an aerobic digestion route, the latter, if necessary, could be carried out in the fourth unfinished basin. Pending a final decision on sludge treatment it was decided that all sludge generated in the first 150 Ml/d stage would be pumped to the adjacent Klipspruit Works for treatment in existing digesters there.

It was during the period of construction that the National Institute for Water Research showed, at pilot plant scale, that enhanced biological uptake of phosphorus could be achieved in Bardenpho type plants provided that the activated sludge was exposed to some degree of anaerobiosis during the process. The experiments at the Alexandra plant and subsequently at Olifantsvlei Works (Venter, Halliday & Pitman, 1978) confirmed that phosphorus removal could take place on large plants provided that the active solids are passed through an anaerobic zone placed ahead of the main aeration basin. Based on this evidence, albeit somewhat meagre, a decision was taken to modify the Goudkoppie Works while under construction by providing an anaerobic zone at the influent end of the activated sludge plant. Physical constraints such as the presence of existing pipes limited the size of basin that could be added. This resulted in the construction of a zone having a retention time of one hour based on the ADWF of incoming sewage. In terms of the criteria available at that time the volume of the anaerobic reactor can be considered on the low side.* (Barnard, 1975, proposed a nominal retention time of $1\frac{1}{2}$ to 2 hours.)

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* The additional cost of this modification was about R250 000, compared to the total cost of the works of R10,7 million. This amounted to 2,4 per cent.

- By incorporating the anaerobic reactor the Goudkoppie plant became the first large plant in the world designed specifically for the biological removal of both nitrogen and phosphorus. It was only natural that the plant subsequently would be the subject of evaluation to determine the degree to which the plant fulfilled the design expectations.

## 2. DESIGN FEATURES

The plant, as constructed, provided for primary and secondary screening, degritting, primary sedimentation using six tanks, and flow balancing, these to serve three identical modules in parallel each designed in conformity with the Phoredox system. A diagrammatical sketch of the plant is shown in Fig. 4.1. , detailed design data are given in Table 4.1. Some of the design features are discussed in more detail detail below:

(i) Primary sedimentation followed by sludge digestion was required on this plant as the City Council was under contract to supply AECI with sludge gas from the adjacent Klipspruit Works for conversion to cyanide for use on the gold mines; this contract was likely to be extended to the Goudkoppie Works.

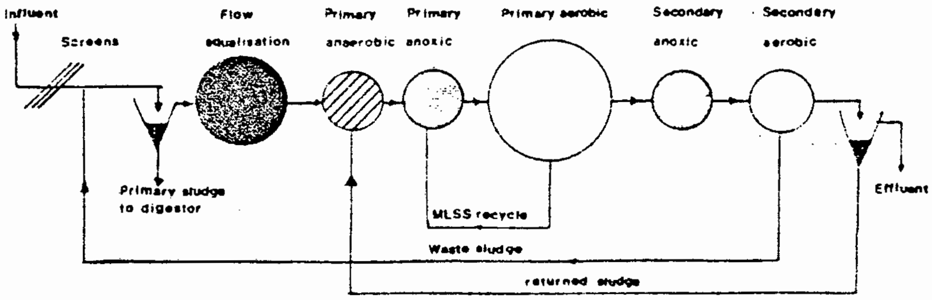


Fig. 4.1. Goudkoppie Works Basin Configuration

Table 4.1.

## GOUDKOPPIE PLANT DESIGN DATA

| | | | | | |
|---|---|---|---|---|---|
| Flow / module | | (Ml/d) | 50 | | |
| Raw sewage composition | BOD | (mg/l) | 400 | | |
| | TKN | (mg N/l) | 60 | | |
| Settled sewage composition | BOD | (mg/l) | 300 | | |
| | TKN | (mg N/l) | 50 | | |
| Sewage temperature | | (°C) | 16 | 15 | 12 |
| BOD loading | | (kg BOD/kg MLSS) | 0,16 | 0,15 | 0,11 |
| MLSS | | (g/m$^3$) | 3,5 | 3,7 | 5,1 |
| Sludge age | | (days) | 8,4 | 9,1 | 13,9 |

| | | | | |
|---|---|---|---|---|
| Volume | (1) | Anaerobic | (m$^3$) | 2 080 |
| | (2) | Primary anoxic | (m$^3$) | 4 800 |
| | (3) | Primary aerobic | (m$^3$) | 14 700 |
| | (4) | Secondary anoxic | (m$^3$) | 4 800 |
| | (5) | Secondary aerobic | (m$^3$) | 2 700 |
| | Total | | (m$^3$) | 29 080 |

| Basin number | | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| Nominal retention time | (h) | 1 | 2 | 7 | 2 | 1 |
| Number of aerators | | - | - | 12 | - | 2 |
| Power / aerator | (kW/aerator) | | | 110 | | 45 |
| Oxygenation capacity | (kg $O_2$/h per aerator) | | | 205 | | 74 |
| Oxygen transfer efficiency | | | | 1,8 | | 1,5 |
| Number of mixers | | 2 | 4 | - | 4 | - |
| Power per mixer | (kW) | 11 | 22,5 | - | 15 | - |
| Number per module | | 4 | | | | |
| Average nominal daily flow to secondary sedimentation tank (without recycle) | (m$^3$/h) | 520 | | | | |

Table 4.1. continued

## Secondary sedimentation

| | | |
|---|---|---|
| Peak factors based on nominal flow | | |
| Dry weather peak | | 1,0 |
| Wet weather peak | | 1,6 |
| Solid flux based on nominal flow | ($kg/m^2/h$) | |
| Winter | | 2,5 |
| Summer | | 3,5 |
| Solid inflow based on nominal flow | ($kg/m^3$) | |
| Winter | | 5,1 |
| Summer | | 3,5 |
| Surface loadings based on mean flow | (m/h) | |
| Winter | | 0,5 |
| Summer | | 1,0 |
| Surface area required per tank based on mean flow | ($m^2$) | |
| Winter | | 1 040 |
| Summer | | 832 |
| Diameter of tank | (m) | 36,2 |
| Volume of tank | ($m^3$) | 2 360 |
| Side wall depth | (m) | 2,4 |

(ii) The balancing tank was designed to minimise the cyclic variation in flow and load, and was located in line between the primary sedimentation tanks and the activated sludge process. Since the influent to this tank was to be settled sewage it was hypothesised that settlement of solids would be minimal, and by installing dwarf walls a flushing action would be induced at low flow ; this in turn should remove any solids which might have settled, hence, no mixers were installed. However, should it be found subsequently that settlement is a problem provision was made for sparges, positioned along the wall closest to the point of entry, to be switched on to resuspend the solids.

The balancing tank scheme was justified by the expected benefits. These were, smaller final settling tanks, smaller hydraulic connections and lower peak oxygen aeration capacity. The estimated saving was considerable, approximately R1 000 000 (Keay and Pitman, 1980)

(iii) The activated sludge process was based on the Phoredox system (Fig. 2.8.) It consisted of five completely mixed reactors in the sequence: anaerobic - primary anoxic - primary aerobic - secondary anoxic - secondary aerobic. Some of the more important features in the process design are:

* All the zones are physically separated by baffles containing suitable openings to permit flow continuity, the one exception being a solid wall with surface overflow between the primary aerobic and secondary anoxic reactors in order to allow for the installation of a movable weir for oxygen control.

- The MLSS is recycled from the effluent end of the primary aeration zone back to the influent point of the primary anoxic reactor at recycle ratios (recycled flow/ feed flow) that can be varied from zero to 16.
- The aerobic reactors are aerated using 12 X 110 kW surface aerators in the primary aeration basin and 2 X 45 kW aerators in the secondary aeration basin.
- The sludge age is controlled by wasting a fixed volume of mixed liquor each day from the secondary aeration zone i.e. hydraulic control of the sludge age is applied.

(iv) <u>Final clarifiers</u> , of which there are four per module, each with a diameter of 36,2 m and a very shallow side wall depth of only 2,4 m . Sludge removal is by means of a rotating bridge carrying five syphons.

(v) <u>Flow metering</u>

This plant has metering facilities at the following points:

- <u>Feed flow</u> from the balancing tank to the process is automatically controlled to a selected flowrate by activation of a Rotork valve. The flowrate is monitored by a flume type flow meter. Provided the balancing tank does not empty during the day or overflow, a fixed volume of feed passes into the process each day.

- Underflow sludge from the final clarifiers to the anaerobic zone is measured by a flume type flow meter and controlled by means of a valve which in turn adjusts the volume of sludge syphoned from the clarifier floor.
- Waste sludge control from basin 5 is exercised through a hand operated valve and the volume measured by means of a flow meter similar to that for the underflow

The built in meters were checked against a portable standardised meter and found to be accurate to within 10 percent of the indicated value.

(vi) Dissolved oxygen control

Two forms of control are available:

- Manual control achieved by switching aerators in and out as required.
- Automatic control can be activated by any one of a number of dissolved oxygen probes in the primary aeration basin. The oxygen input is increased or decreased by raising or lowering a level control weir at the end of this basin, thereby increaseing or decreasing the depth of immersion of the aerators. Experience with this system has shown that it is not effective or reliable; for the series of experiments hereafter it was necessary to use only the manual control method.

## 3. PLANT PERFORMANCE EVALUATION

### 3.1. Objectives

The objectives of the experimental programme were:

(1) To trace the response of a set of selected parameters in each reactor under the conditions of flow and load set on the process

(2) To compare the observed performance with predictions by the general activated sludge model developed at the University of Cape Town.

### 3.2. Conditions of test

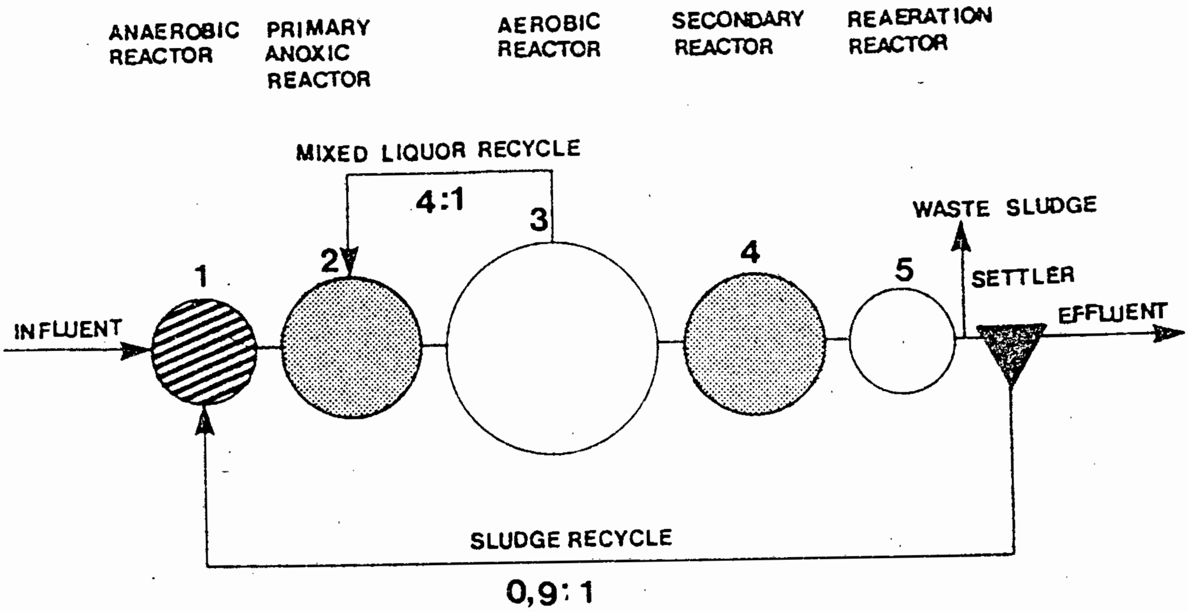
(i) Flow to the experimental module was to be constant and limited to 30 Ml/d. Compared with mean design flow - 50 Ml/d the flow to the plant was still well below the design flow.

(ii) Sludge age was to be maintained in the range 20 - 25 days which, according to Pitman (1974) , was likely to give rise to a rapidly settling sludge. Notwithstanding this provision immediately prior to the commencement of this experiment, the sludge volume index (S V I ) was in the range 200 - 300, so that the value of this provision is to be questioned.

(iii) Physical details of the process layout are given in Fig. 4.2.(a) and Table 4.2.

(iv) The MLSS recycle (s) ratio was fixed at 6:1 .

(v) The underflow recycle sludge recycle was fixed at 0,9 :1 .



Temperature 20°C

Sludge age 72 d

Fig. 4.2.(a) The process layout of the Goudkoppie plant during the experimental investigations

Table 4.2.

Physical details of the Goudkoppie plant during the experimental investigations

| | Anaerobic | Primary Anoxic | Primary Aerobic | Secondary Anoxic | Secondary Aerobic |
|---|---|---|---|---|---|
| Reactor number | 1 | 2 | 3 | 4 | 5 |
| Volume ($m^3$) | 2 060 | 4 800 | 14 700 | 4 800 | 2 700 |
| Nominal retention time (d) | 0,069 | 0,160 | 0,490 | 0,160 | 0,090 |
| Mass fraction | 0,072 | 0.165 | 0,505 | 0,165 | 0,093 |

(vi) Dissolved oxygen concentrations in both aerobic reactors were to be maintained in excess of 2 mg/l . Under the proposed conditions of low flow and load this concentration could be achieved with only half the total number of aerators operational, as shown in Fig. 4.2.(b)

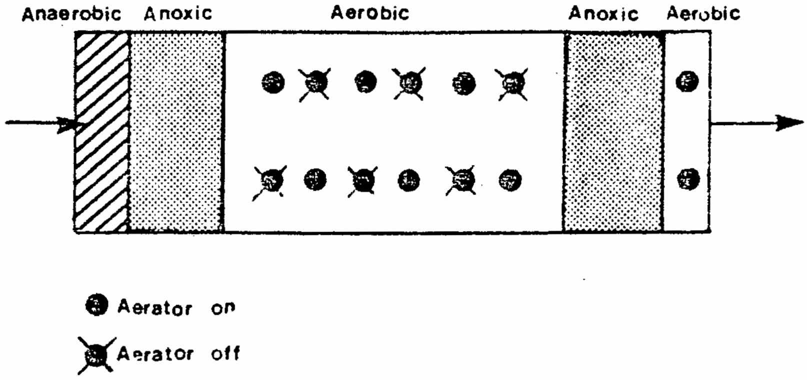


Fig. 4.2.(b) Operational aerators during experimentation on Goudkoppie Works

(vii) Sampling: In each reactor "grab" samples were to be taken near the end of the reactor because these would reflect the concentrations passing into the subsequent reactor. The samples were processed by filtering immediately through coarse filter paper into a bottle containing 1ml of 0,85% (mass/mass) mercuric chloride to inhibit further bacterial action. Samples were stored at ambient temperature and collected daily for laboratory analysis. Sampling of the feed and effluent were done by automatic samplers. The sampling pipework was flushed with the liquid being sampled immediately prior to collecting the sample. The influent samples were to be collected immediately prior to the inlet point. The effluent samples were to be taken at the confluence point of the effluent from all four clarifiers. Individual one litre samples were taken, treated with mercuric chloride and stored in separate plastic bottles until analysed.

(viii) Oxygen utilisation measurements: Preliminary tests on oxygen utilisation taken along the longitudinal centre line of the reactors, at each reactor, indicated an oxygen utilisation rate profile high at the influent end of the reactor and falling to lower values at the effluent end, indicating that completely mixed conditions were not present in the reactors. The profile varied as the flow and load on the reactor varied. Eventually it was decided that the most representative assessment of the mean behaviour of the reactors would be achieved by testing at three points along the centre line of the reactors; between the first and second, third and fourth, and fifth and sixth, and averaging the results. The detailed procedure followed during a utilisation rate test is set out in Appendix A4 .

## 4. PERFORMANCE DATA

Sampling of the feed, effluent and contents of each zone was carried out at two - hourly intervals for a period of one week and samples analysed for COD, TKN, ammonia, nitrate and phosphorus. Oxygen utilisation rate tests were also taken at the same time. Unfortuneately the results of three of the seven days had to be discarded due to the malfunction of one of the samplers.

The results from the remaining four days, at each time point, were averaged and are listed in Appendix A5 . Plots of these averages are shown in Figs. 4.3. to 4.10. as follows:

| | |
|---|---|
| Fig. 4.3. | Unfiltered COD concentration in the feed and filtered effluent and reactor contents. |
| Fig. 4.4. | Unfiltered TKN concentration in the feed and filtered effluent |
| Fig. 4.5. | Total phosphorus concentration in the unfiltered feed and filtered effluent |
| Fig. 4.6. | Oxygen utilisation rate in the main aeration basin |
| Fig. 4.7. | Soluble COD concentration in filtered samples in each basin |
| Fig. 4.8. | Soluble ammonia concentration in filtered samples in each basin |
| Fig. 4.9. | Nitrate concentration in filtered samples in each basin |
| Fig. 4.10. | Soluble total phosphorus concentration in filtered samples in each basin |

The consolidated daily average results over 24 hours of the above data are given in Table 4.3.

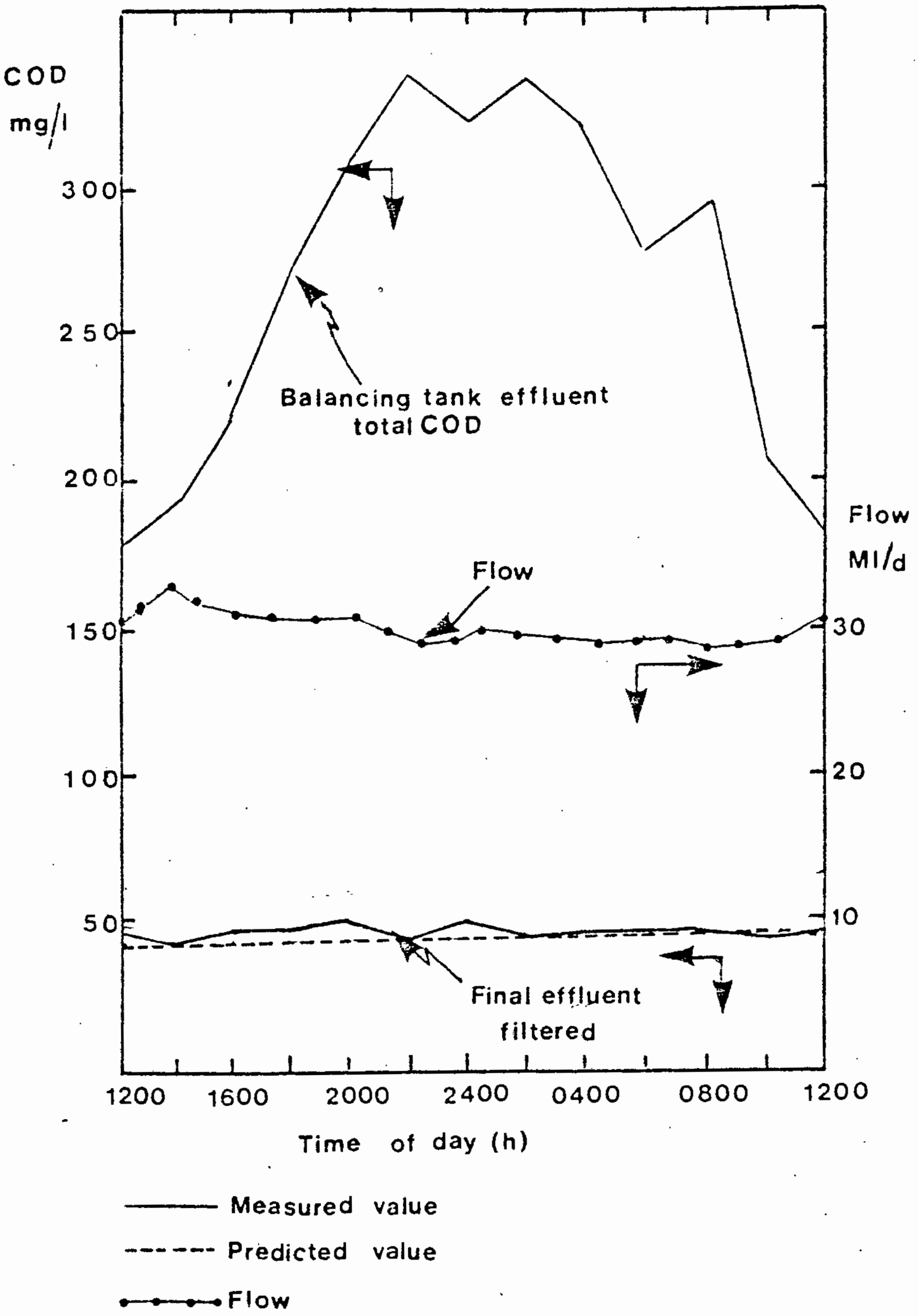


Fig. 4.3. Goudkoppie Plant

Total COD concentrations in the feed and filtered COD in the effluent together with predicted values.

In addition the flow to the process during the test period is shown

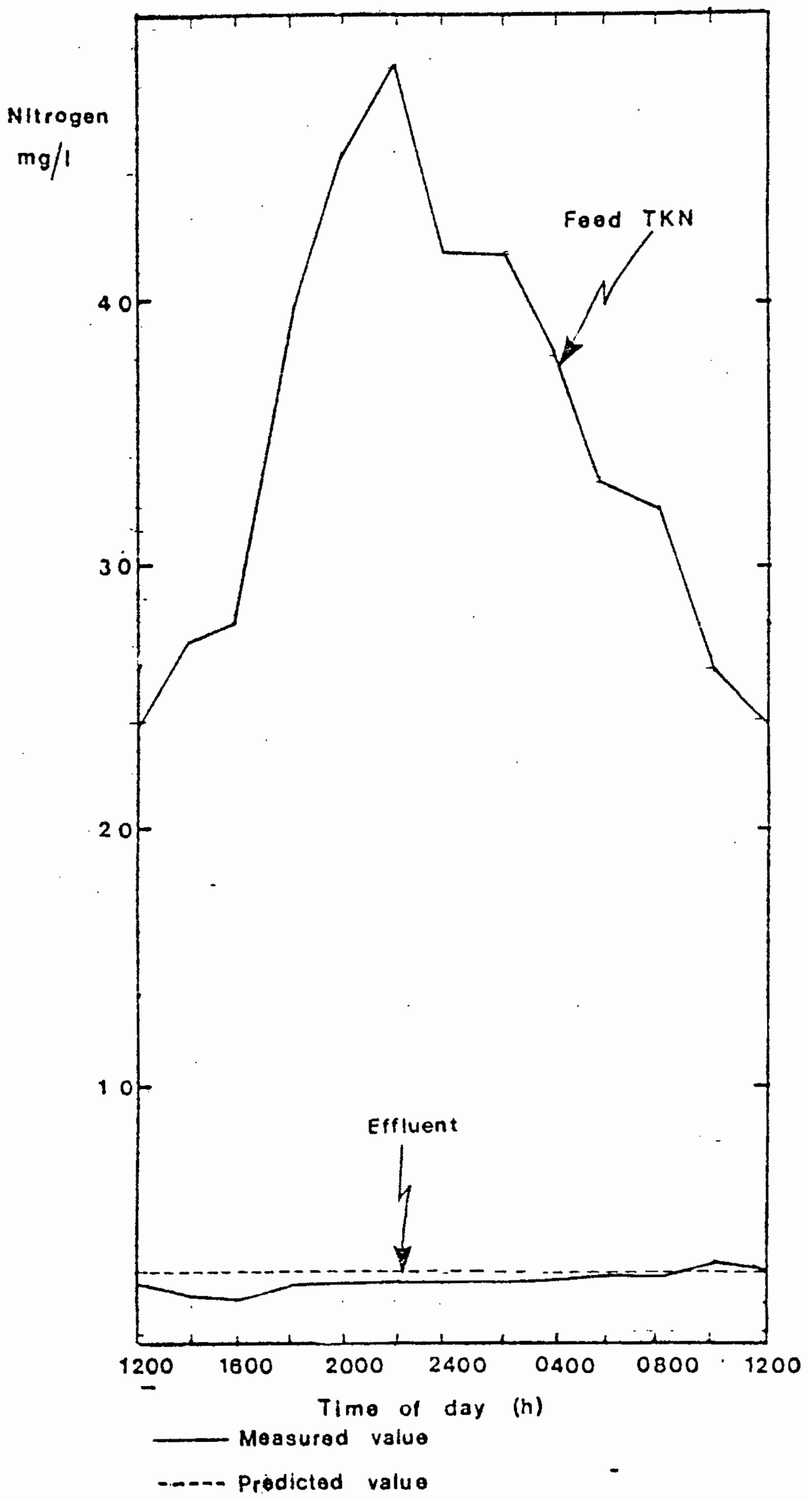


Fig. 4.4. Goudkoppie Plant

TKN concentration in the feed and filtered TKN in the effluent together with predicted values for the effluent

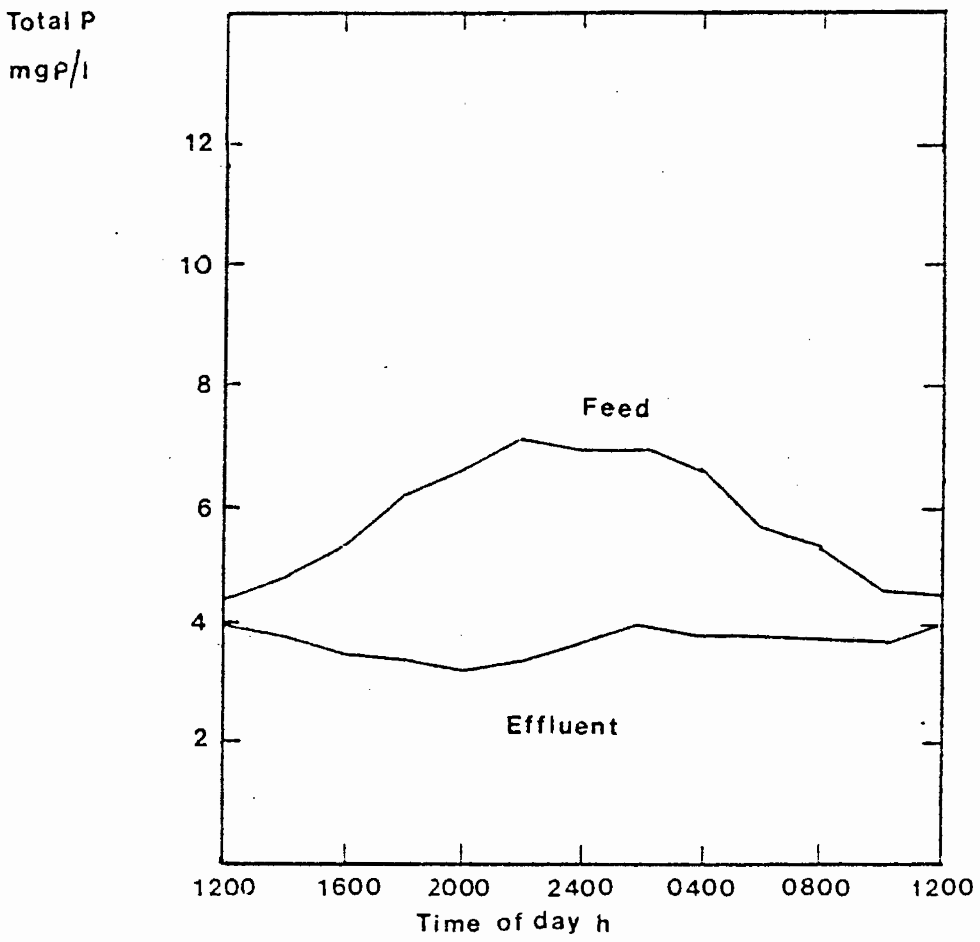


Fig. 4.5. Goudkoppie Plant

Total phosphorus concentrations in the feed and filtered effluent

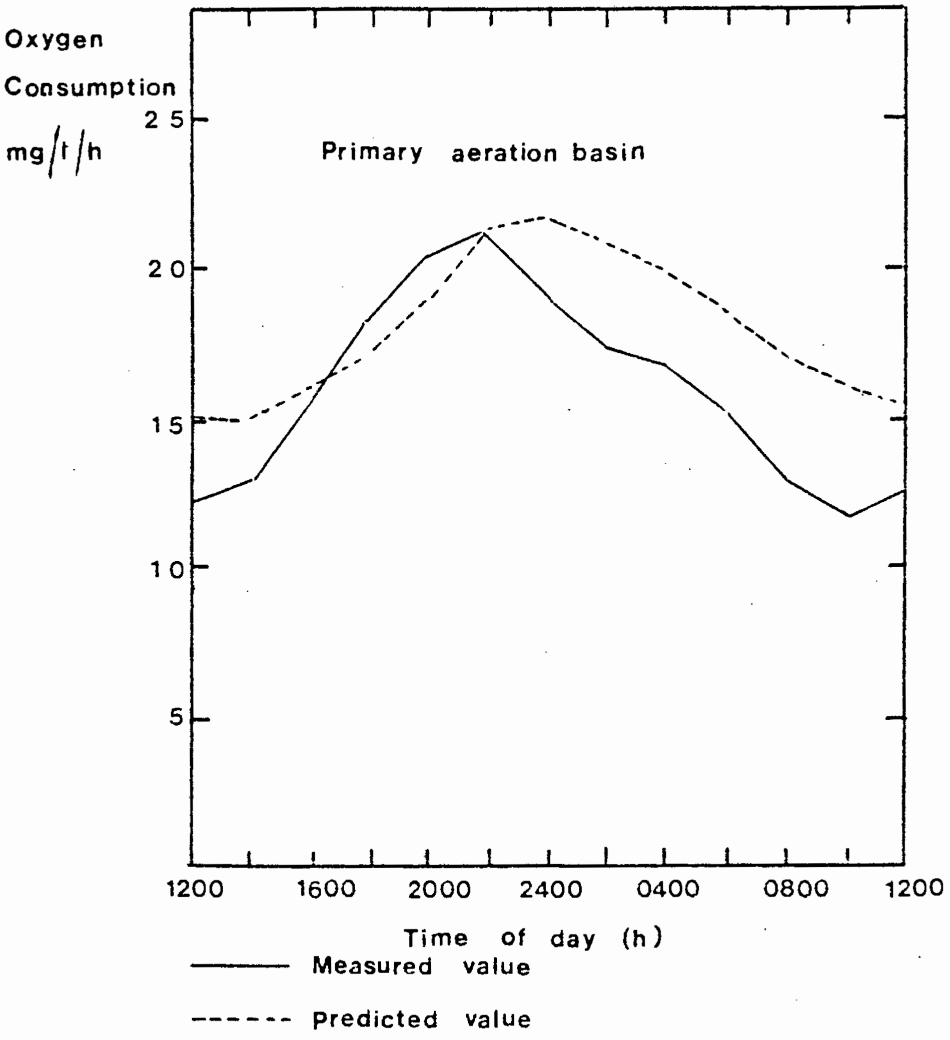


Fig. 4.6. Goudkoppie Plant

Predicted and measured oxygen consumption rates in the primary aeration basin

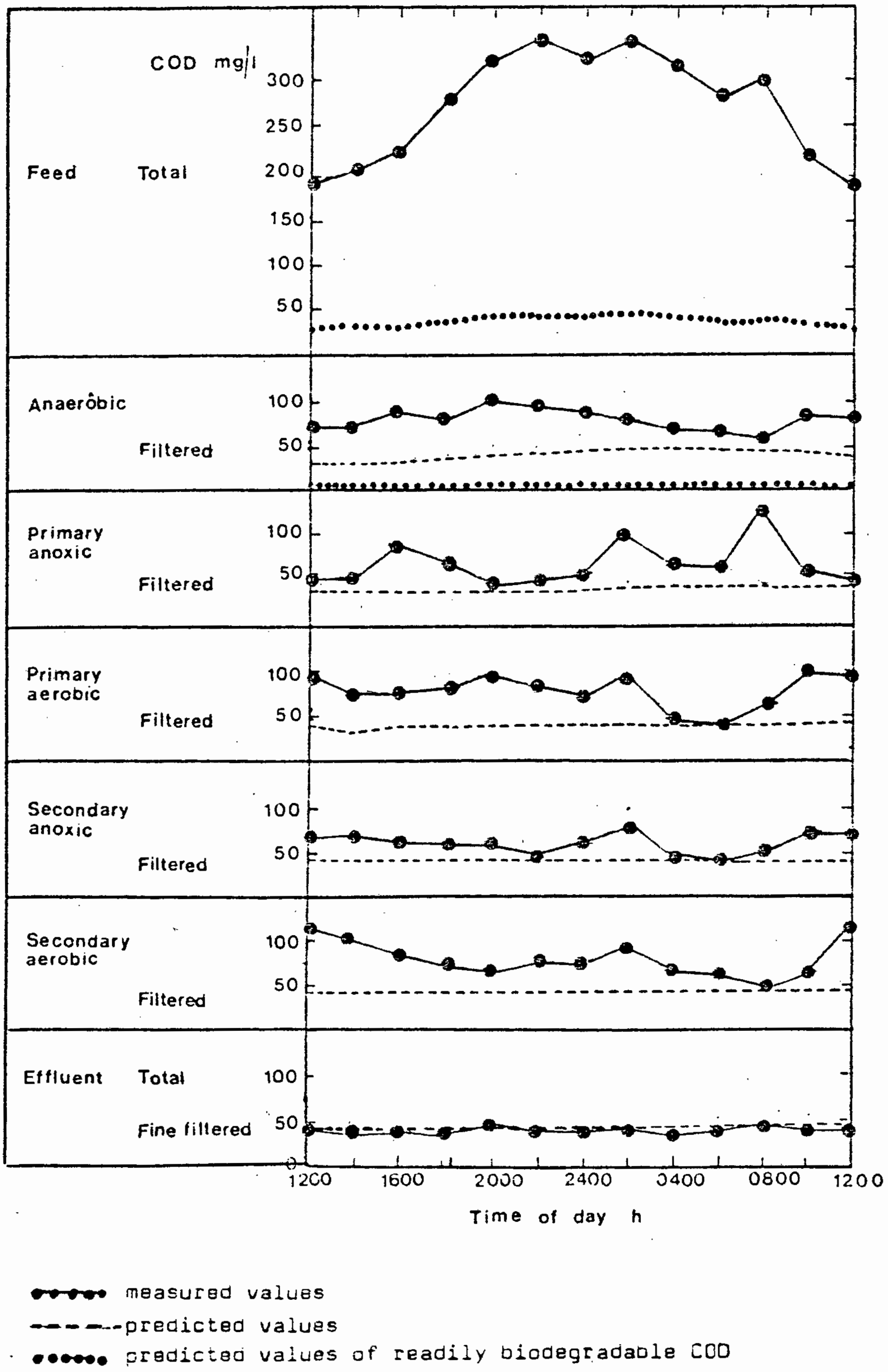


Fig. 4.7. Goudkoppie Plant

Measured filtered COD and predicted soluble COD concentrations in each reactor of the system

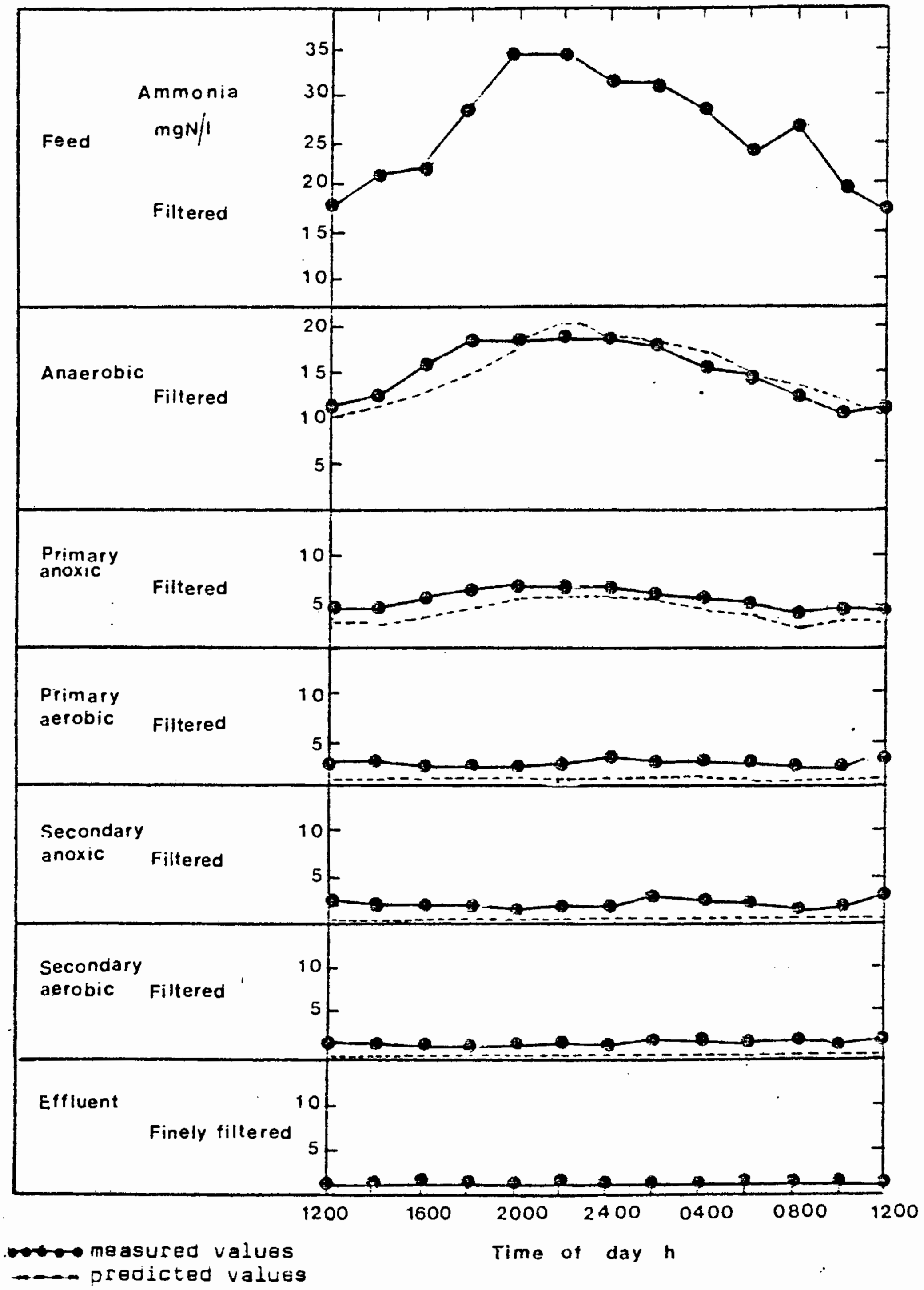


Fig. 4.8. Goudkoppie Plant

Measured filtered and predicted ammonia concentrations in each reactor of the system

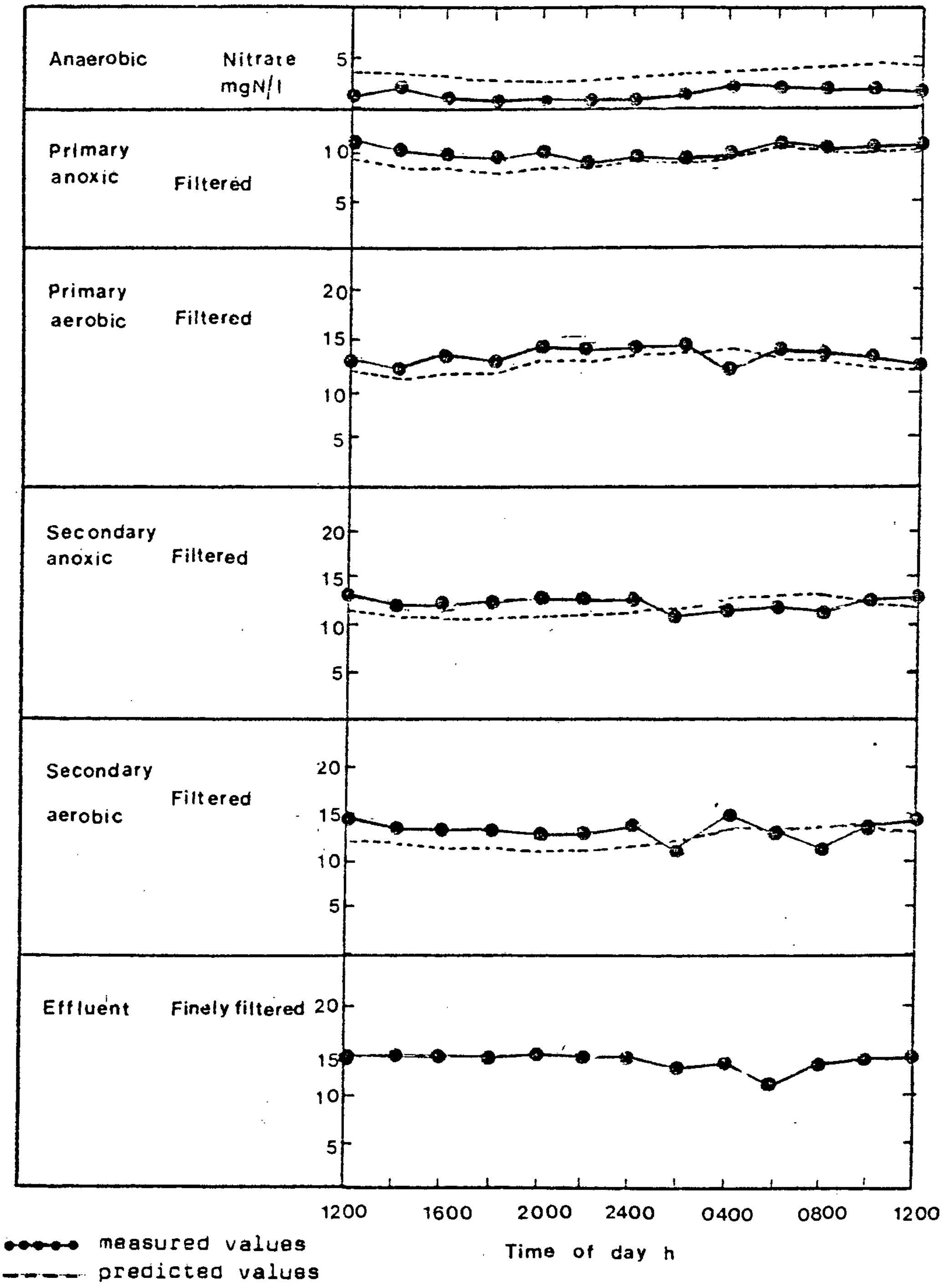


Fig. 4.9. Goudkoppie Plant

Measured filtered and predicted nitrate concentrations in each reactor of the system

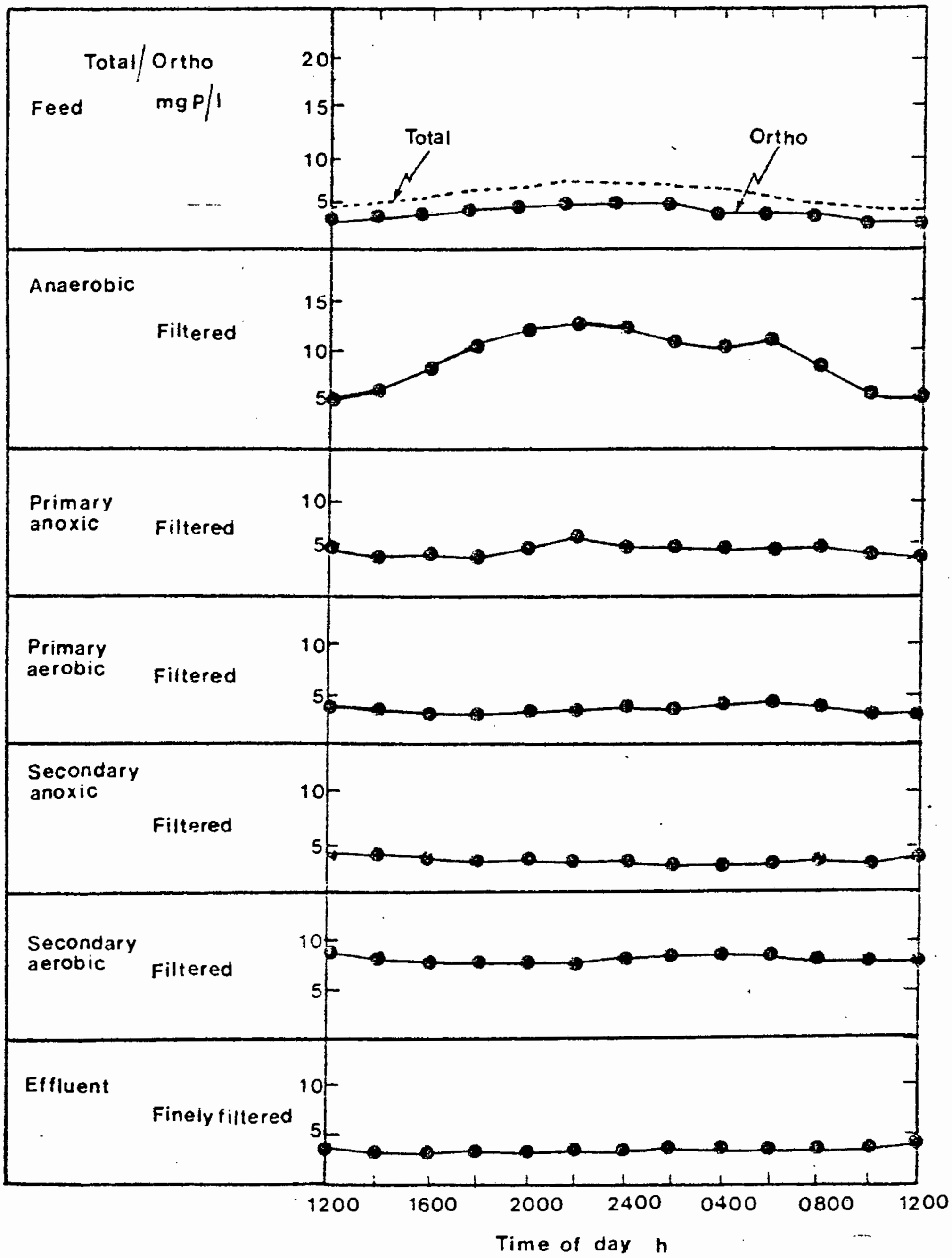
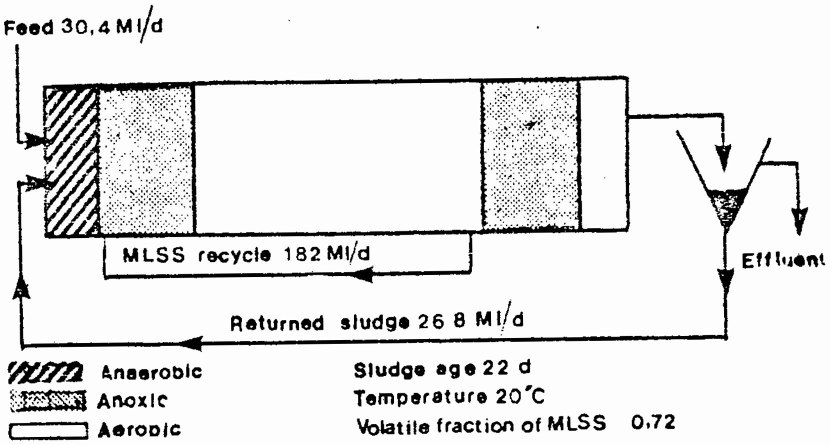


Fig. 4.10. Goudkoppie Plant

Unfiltered total phosphorus concentration in influent and filtered orthophosphate concentrations in the reactors and effluent

## Table 4.3.

The average performance of the Goudkoppie Plant during the experimental period



| | Feed | Anaerobic | Primary Anoxic | Primary Aerobic | Secondary Anoxic | Secondary Aerobic | Effluent * |
|---|---|---|---|---|---|---|---|
| Total COD | 270 | | | | | | 63 |
| Soluble COD | 170 | 77 | 67 | 73 | 55 | 72 | 43 |
| $S_{bs}$ | 29 | | | | | | |
| TKN as N | 35 | | | | | | 2,0 |
| Ammonia as N | 25 | 15 | 5,1 | 1,9 | 1,6 | 1,5 | 1,5 |
| Nitrate as N | | 1,1 | 9,8 | 13,4 | 12,5 | 13,3 | 13,5 |
| Total P | 5,8 | | | | | | 3,7 |
| Soluble P | 3,6 | 10 | 5,0 | 3,9 | 3,6 | 3,2 | 3,6** |
| Suspended solids | | | | 1 940 | | | |
| Oxygen consumption mg/l/h | | | | 16,2 | | | |

Unless otherwise stated all results expressed as mg/l

* Effluent samples were filtered through Whatman 542 filter paper while the reactor samples were filtered through coarse filter paper

** Reactor samples were filtered and test by means of the orthophospnate test

$S_{bs}$ = readily biodegradable COD concentration mg/l

## 4.1. Data validity

Before testing the plant data against model predictions it is necessary to check if the data is acceptable. A powerful check is to verify if mass balances over the plant, of the COD and nitrogen, are achievable within reasonable limits. Ekama and Marais (1978) concluded from a number of investigations that balances are acceptable if these fall within the range 96 to 104 percent. Their investigations, however, were on laboratory and pilot scale facilities where close control was exercised over the input to the plant and its operation. Clearly control over a large scale plant can never be of the level attainable on a laboratory or pilot scale plant. At the Goudkoppie plant every endeavour was made to achieve as high a level of control as possible, by having an equalization tank and setting a consistent flow rate to the test modules. Even so the masses of COD and TKN did fluctuate from day to day. These fluctuations can be smoothed out by testing the plant over a number of days and averaging out the results, to obtain a mean behaviour. It was for this reason that the experimental period extended over 7 days (of which, we have seen, four days were acceptable)

Utilising the averaged daily values over the days of acceptable readings , the mass balances achieved on the COD and nitrogen were 99,8 and 107 percent recoveries respectively.* These balances very likely are as good as can be expected on such a large plant and indicate inter alia that the sampling procedure was consistent and the testing accuracy acceptable.

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*For details of the procedures followed to make these balances, see Appendix A6 .

## 5. MODEL PREDICTIONS

To test the validity of the bisubstrate death - regeneration model, as developed in its final form by van Haandel, Ekama and Marais (1981), it is necessary to establish values for certain parameters utilised in the model. These are, firstly, the sewage charateristics which are specific to the particular waste flow, and secondly, the kinetic parameters; the latter in turn being subdivided into two groups:

(i) those that change with different waste water sources

(ii) those that are constant from one waste source to another

### 5.1. Sewage characteristics

Parameters defining the physical and chemical characteristics of the particular waste flow are the following:

(1) Total influent COD $S_{ti}$ (mg O/l) and total influent TKN (mg N/l) together with the total flow.

(2) Temperatures in the reactors

(3) Magnitudes of various influent COD fractions:

(a) Soluble unbiodegradable COD $f_{us}$ i.e.

$$S_{us} = f_{us} \cdot S_{ti}$$

(b) Particulate unbiodegradable COD, $f_{up}$ i.e.

$$S_{upi} = f_{upi} \cdot S_{ti}$$

(c) Biodegradable COD , $f_{bi}$ defined by

$$f_{bi} = (1 - f_{usi} - f_{upi})$$

$$\text{i.e. } S_{bi} = f_{bi} \cdot S_{ti}$$

(d) The biodegradable COD $S_{bi}$ in turn is subdivided into two fractions, easily biodegradable COD , $f_{bsi}$ defined by

$$S_{bsi} = f_{bsi} \cdot S_{bi}$$

$$= f_{bsi} \cdot f_{bi} \cdot S_{ti}$$

$$= f'_{bsi} \cdot S_{ti}$$

and particulate biodegradable COD $f_{fpi}$ i.e.

$$S_{bpi} = f_{bpi} \cdot S_{bi}$$

$$= (1 - f_{bsi}) S_{bi}$$

$$= f_{bpi} \cdot f_{bi} \cdot S_{ti}$$

$$= f'_{bpi} \cdot S_{ti}$$

(4) Magnitudes of various TKN influent fractions

(a) Soluble unbiodegradable TKN $f_{nui}$

$$N_{ui} = f_{nui} \cdot N_{ti}$$

(b) Free and saline ammonia $f_{nai}$

$$N_{ai} = f_{nai} \cdot N_{ti}$$

(c) Organic nitrogen

$$N_{orgi} = (1 - f_{nui} - f_{nai}) N_{ti}$$

With regard to the various fractions above, these are not all independent for example, once $f_{nu}$ and $f_{na}$ are known $f_{orgi}$ can be determined from $(1 - f_{nai} - f_{nui})$ and so on.

One parameter that can be of crucial importance, the Total Alkalinity, was not measured. Total alkalinity is the principal parameter forming the precipitate in an activated sludge plant. If the alkalinity in the reactor drops below 35 mg/l $CaCO_3$ then the pH becomes unstable and may either drop permanently to values below pH = 7 or fluctuate between 6 and 7,5 depending on nitrification.

Nitrification abstacts alkalinity and if it is reduced to less than 35 mg/l $CaCO_3$ the pH may drop below 7 which in turn inhibits nitrification causing the pH to rise again, hence the fluctuation. At Goudkoppie the alkalinity was relatively high ( 100 mg/l $CaCO_3$) in the reactors, consequently, the pH remained stable between 7 and 8 (mean 7,4) and nitrification was not affected. Hence alkalinity measurements were not essential.

We shall now consider briefly the measurement of the key parameters on the Goudkoppie plant.

### 5.1.1. Influent COD and TKN concentration and reactor temperature

The influent COD and TKN concentrations were measured at 2 hourly intervals over the entire period of the investigation. At the same time the temperature was measured in the main aeration basin because in this basin nitrification takes place and the nitrification rate is most sensitive to temperature.

### 5.1.2. Soluble unbiodegradable COD fraction ($f_{usi}$)

For a plant operating at long sludge ages, the filtered effluent COD concentration (provided a fine filter is used) is virtually identical to the soluble unbiodegradable COD concentration. From the average data over the day (Table 4.3.) the average soluble COD in the effluent was 42 mg/l ; the total influent COD , 272 mg/l . Therefore, $f_{usi}$ = 42/272 = 15 percent. This value normally is approximately 10 percent of the raw sewage COD value but at Goudkoppie an appreciable fraction of the particulate COD is removed in the primary settler, and a further fraction is removed in the balancing tank ; in contrast, the soluble unbiodegradable fraction, $f_{us}$ , is not affected. Consequently the unusually high $f_{us}$ was not unexpected.

### 5.1.3. Unbiodegradable particulate COD fraction ($f_{upi}$)

To determine $f_{upi}$ reliably requires an extensive series of tests on the same waste over a number of sludge ages. The value of $f_{upi}$ is then determined by fitting the equation for MLVSS / unit COD against the observed data. In doing this fit the specific yield constant (Y) and endogenous respiration rate constant (b) are assumed to remain at their standard values for the temperature in the plant (these appear to maintain their values for widely divergent waste characteristics). The best fit then is obtained by inserting a series of values for $f_{upi}$ in the equations describing the process, the final equation being that describing the MLVSS / unit COD . The value of $f_{upi}$ giving the best overall fit over all the sludge ages forms an estimate of $f_{upi}$ . This value is then checked by utilising it to predict the oxygen utilisation rate and comparing it with the observed rates at different sludge ages. This procedure has been found to give very good estimates of $f_{upi}$ when tested on influents (glucose) where it is known that $f_{upi}$ equals zero.

In the investigation of Goudkoppie it was not possible to do the series of tests necessary to determine $f_{upi}$ reliably. The only procedure possible was to accept the concentration of MLVSS in the plant, and knowing the mass COD feed/day , the value of $f_{upi}$ found by trial and error to give the best prediction of the MLVSS in the plant. This value was verified to a degree by the close correspondence between the simulated mean OUR against the mean observed OUR .

### 5.1.4. Easily biodegradable COD fraction ($f_{bs}$)

The value of $f_{bs}$ can differ depending on the source of the sewage. At Goudkoppie a further complication is that the biological action of the sludge layer in the balancing tank may either enhance $f_{bs}$ (by solubilisation of particulate COD) or deplete it by fermentation. The only reliable approach was to conduct a test to determine the value of $f_{bs}$ directly. At the time this investigation was undertaken the test for the estimation of $f_{bs}$ had not yet been developed. Subsequently Dold, Ekama and Marais (1980) provided an experimental procedure by means of which $f_{bs}$ could be determined. (The reader is referred to van Haandel and Marais (1981) for a detailed account on how to conduct such a test.) A summary of this test is given in Appendix A7 . When the test became available, a series of tests to determine $f_{bsi}$ was undertaken on the balancing tank effluent.

The readily biodegradable COD was found to be approximately 29 mg COD/l . Taking into account the $f_{usi}$ and $f_{upi}$ fractions the biodegradable COD equals $(1 - f_{usi} - 1{,}48\ f_{upi})\ S_{ti} = 0{,}67\ S_{ti}$ $= 0{,}67 \cdot 272 = 182$ mg COD/l . Hence $S_{bs} = 29/182 = 0{,}16$ Since the operation and influent conditions had remained very stable for a long period the value for $S_{bsi} = 0{,}16$ was accepted to have applied also over the period the plant was evaluated.

### 5.1.5. Fraction of TKN in ammonia form ($f_{na}$)

This fraction may differ between waste flows from different sources. Long sewer lines and any other conditions allowing degradation of the proteinaceous material will increase the fraction. For a particular Works it is determined by measuring the free and saline ammonia and TKN of the unfiltered influent. From such tests $f_{na}$ was found to be approximately 0,72 for the effluent from the equalisation tank.

## 5.2. Constants specific to a waste flow

The magnitude of the maximum specific growth rate of the nitrifiers, $\mu_{nm}$ , although a kinetic "constant" can differ greatly in value between sewage sources. Van Haandel, Dold and Marais (1982) have measured values for $\mu_{nm}$ at 20 C in the range 0,33 to 0,65 $d^{-1}$ ; this reange is ascribed in part to the magnitude of the industrial component in the waste flow, usually the larger the component the lower the value of the constant. Accurate determination requires a specialised series of test (Sehayek 1981) . However, by curve fitting to the observed TKN and nitrate (and to the alkalinity response) quite good estimates of $\mu_{nm}$ can be obtained. Fortuneately when the sludge age is very long (i.e. 22 days), the conversion to nitrate is near completion at 20 C even for $\mu_{nm} = 0,33$ , and the nitrate concentration becomes relatively insensitive to $\mu_{nm}$ . Under such conditions any reasonable value can be utilised in the simulation model. This was checked in the simulations on Goudkoppie, for $\mu_{nm}$ values ranging from 0,33 to 0,5 . All the simulations indicated very little difference in the effluent ammonia behaviour.

Eventually a value of $\mu_{nm20}$ = 0,5 was selected, primarily because it was felt that the industrial component in the waste flow to Goudkoppie would not have affected the $\mu_{nm}$ adversely.

The values of the influent characteristics specified for the waste water at Goudkoppie at the time of the investigation are listed in Table 4.4.

Table 4.4.

Influent characteristics specific to the balancing tank effluent at the time of investigation at Goudkoppie Works

| Name | Symbol | Units | Value |
|---|---|---|---|
| Fraction of soluble unbiodegradable COD | $f_{us}$ | mg COD/mg COD | 0,15 |
| Fraction of particulate unbiodegradable COD | $f_{up}$ | mg VSS/mg COD | 0,12 |
| Fraction of easily biodegradable COD | $f_{bs}$ | mg COD/mg bio-degradable COD | 0,16 |
| Easily biodegradable COD concentration | $S_{bs}$ | mg COD/l | 29 |
| Fraction of TKN of feed in ammonia form | $f_{na}$ | mg N/mg N | 0,72 |
| Specific growth rate constant for nitrifiers | $\mu_{nm}$ | $d^{-1}$ | 0,5 |

## 5.3. Constants invariant for different waste flows

The constants in this group are listed in Table 4.5. Experience in simulating response of processes indicates that these constants do not vary in any significant way and have been used unaltered by Marais and his groups for all their simulations.

## Table 4.5.

## Kinetic constants invariant for different waste flows

| Name | Symbol | Units | Value |
|---|---|---|---|
| Substrate adsorption rate coefficient | $K_{a20}$ | 1/mg VSS/d | 0,135 |
| Maximum specific growth rate coefficient for heterotrophic organisms utilising stored particulate substrate | $K_{mp20}$ | mg COD/mg VSS/d | 3,00 |
| Maximum specific growth rate coefficient for heterotrophic organisms utilising soluble substrate | $K_{ms20}$ | mg COD/mg VSS/d | 20,00 |
| Saturation coefficient for heterotrophic cell synthesis from stored particulate substrate | $K_{sp20}$ | mg COD/l | 0,04 |
| Saturation coefficient for heterotrophic cell synthesis from soluble substrate | $K_{ss20}$ | mg COD/l | 5,0 |
| Specific endogenous respiration rate for heterotrophic organisms | $b_{h20}$ | /d | 0,62 |
| Yield coefficient for heterotrophic organisms | $Y_{h20}$ | mg VSS/mg COD | 0,45 |
| Unbiodegradable fraction of the active organisms | $f$ | mg VSS/mg VSS | 0,08 |
| Nitrogen content of the sludge | $f_n$ | mg N/mg VSS | 0,10 |
| COD equivalent of volatile solids | $p$ | mg COD/mg VSS | 1,48 |
| Fraction of nitrogen released through endogenous respiration in the organic form | $f_{oe}$ | - | 1,00 |
| Fraction of nitrogen required for cell synthesis in the organic nitrogen form | $f_{os}$ | mg N/mg VSS | 0,00 |
| Maximum fraction of stored solids with respect to active mass | $f_{ma}$ | mg VSS/mg VSS | 1,00 |
| Organic nitrogen to ammonia conversion rate coefficient | $K_{r21}$ | /mg VSS/d | 0,015 |
| General parameter for pH dependency coefficients | | | |
| adsorption on heterotrophic organisms | $h_a$ | | 1,200 |
| synthesis by heterotrophic organisms | $h_s$ | | 1,100 |
| endogenous respiration by heterotrophic organisms | $h_e$ | | 1,029 |
| Saturation coefficient for *Nitrosomonas* | $K_{n20}$ | mg N/l | 1,00 |
| Specific endogenous rate for nitrifiers | $b_{n20}$ | /d | 0,04 |
| Yield coefficient for nitrifiers | $Y_{n20}$ | mg VASS/mg N | 0,10 |
| General parameter for pH dependency coefficients | | | |
| synthesis by *Nitrosomonas* | ns | | 1,123 |
| endogenous respiration by *Nitrosomonas* | ne | | 1,029 |

## 5.4. Simulated results

The simulated results of the Goudkoppie plant were obtained using the constants listed in Tables 4.4. and 4.5. and the input data , flow COD and TKN as listed in Table 4.6.

Table 4.6.

Goudkoppie Works

Input flow and COD and TKN concentrations used in the model predictions

| Time | Flow $m^3/d$ | COD mg/l | TKN mg N/l |
|---|---|---|---|
| 1200 | 31 500 | 180 | 24,0 |
| 1300 | 32 100 | 188 | 26,0 |
| 1400 | 32 700 | 195 | 27,3 |
| 1500 | 32 200 | 209 | 27,8 |
| 1600 | 31 800 | 222 | 28,3 |
| 1700 | 31 500 | 244 | 32,0 |
| 1800 | 31 600 | 273 | 39,3 |
| 1900 | 31 600 | 290 | 43,6 |
| 2000 | 31 700 | 310 | 46,1 |
| 2100 | 30 800 | 320 | 47,7 |
| 2200 | 29 500 | 342 | 47,8 |
| 2300 | 29 800 | 330 | 46,0 |
| 2400 | 30 300 | 320 | 42,0 |
| 0100 | 30 200 | 330 | 41,8 |
| 0200 | 30 200 | 337 | 41,5 |
| 0300 | 29 800 | 327 | 39,8 |
| 0400 | 29 800 | 320 | 38,0 |
| 0500 | 29 100 | 305 | 35,7 |
| 0600 | 29 100 | 278 | 32,5 |
| 0700 | 29 200 | 284 | 32,2 |
| 0800 | 29 300 | 295 | 32,0 |
| 0900 | 29 400 | 250 | 30,0 |
| 1000 | 29 700 | 207 | 26,0 |
| 1100 | 30 200 | 193 | 25,0 |
| 1200 | 31 500 | 180 | 24,0 |

The simulated results are shown plotted in Figs. 4.3. and 4.4. and 4.6. to 4.9. and listed in tabular form in Tables 4.7. to 4.9.

## Table 4.7.

## Goudkoppie Plant

Comparison of predicted and experimental COD concentrations in each reactor

| Time of Day | Feed | | POSITION WITHIN PLANT | | | | | | | | | | Effluent | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Anaerobic | | Primary Anoxic | | Primary Aeration | | Secondary Anoxic | | Secondary Aeration | | | |
| h | Total | Soluble | Soluble | | Soluble | | Soluble | | Soluble | | Soluble | | Total | Soluble |
| | | | E | P | E | P | E | P | E | P | E | P | | |
| 1200 | 180 | 110 | 73 | 36 | 40 | 41 | 98 | 42 | 63 | 42 | 110 | 42 | 69 | 46 |
| 1400 | 190 | 110 | 72 | 35 | 56 | 39 | 76 | 40 | 63 | 41 | 100 | 41 | 63 | 41 |
| 1600 | 220 | 130 | 84 | 37 | 83 | 39 | 72 | 39 | 55 | 40 | 89 | 40 | 61 | 45 |
| 1800 | 270 | 150 | 74 | 41 | 69 | 39 | 76 | 39 | 54 | 39 | 66 | 39 | 58 | 43 |
| 2000 | 310 | 170 | 100 | 46 | 45 | 39 | 88 | 39 | 55 | 39 | 57 | 39 | 60 | 50 |
| 2200 | 340 | 190 | 94 | 49 | 49 | 40 | 79 | 40 | 45 | 39 | 73 | 39 | 68 | 39 |
| 2400 | 320 | 210 | 90 | 49 | 52 | 41 | 67 | 41 | 56 | 40 | 69 | 40 | 63 | 48 |
| 0200 | 340 | 210 | 76 | 49 | 91 | 42 | 89 | 41 | 79 | 41 | 86 | 41 | 56 | 39 |
| 0400 | 320 | 210 | 67 | 49 | 61 | 43 | 43 | 42 | 42 | 42 | 56 | 41 | 57 | 41 |
| 0600 | 280 | 210 | 67 | 47 | 62 | 43 | 37 | 43 | 37 | 43 | 51 | 42 | 63 | 43 |
| 0800 | 300 | 170 | 58 | 46 | 110 | 43 | 56 | 43 | 47 | 43 | 43 | 43 | 68 | 44 |
| 1000 | 210 | 180 | 74 | 41 | 65 | 42 | 95 | 43 | 58 | 43 | 61 | 43 | 60 | 41 |
| Ave. | 270 | 170 | 77 | 44 | 67 | 41 | 73 | 41 | 55 | 41 | 72 | 41 | 63 | 43 |

Notes:

1. All results expressed in mg O/l
2. E denotes experimental value obtained
3. P denotes predicted values
4. All reactor samples were filtered through coarse filter paper
5. Effluent samples were filtered through Whatman 542 filter paper

## Table 4.8.

## Goudkoppie Plant

Comparison of predicted and experimental ammonia concentrations in each reactor. In addition the TKN of the feed is given

| Time of Day | Feed | | POSITION WITHIN PLANT | | | | | | | | | | Effluent | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Anaerobic | | Primary Anoxic | | Primary Aeration | | Secondary Anoxic | | Secondary Aeration | | | |
| h | TKN | $NH_3$ | Soluble | | Soluble | | Soluble | | Soluble | | Soluble | | TKN | $NH_3$ |
| | | | E | P | E | P | E | P | E | P | E | P | | |
| 1200 | 24 | 18 | 11 | 10 | 4,3 | 3,0 | 2,1 | 0,3 | 2,0 | 0,5 | 1,7 | 0,1 | 1,9 | 1,7 |
| 1400 | 27 | 21 | 12 | 11 | 4,2 | 3,2 | 2,0 | 0,3 | 1,7 | 0,6 | 1,5 | 0,1 | 1,7 | 1,5 |
| 1600 | 28 | 22 | 15 | 12 | 5,1 | 3,3 | 1,9 | 0,4 | 1,7 | 0,6 | 1,4 | 0,1 | 1,6 | 1,4 |
| 1800 | 39 | 29 | 18 | 14 | 5,9 | 3,6 | 1,4 | 0,4 | 1,5 | 0,6 | 1,2 | 0,1 | 1,9 | 1,2 |
| 2000 | 46 | 34 | 18 | 18 | 6,4 | 4,7 | 1,5 | 0,6 | 1,1 | 0,8 | 1,4 | 0,1 | 1,8 | 1,4 |
| 2200 | 48 | 34 | 18 | 19 | 6,3 | 5,2 | 1,6 | 0,7 | 1,4 | 0,9 | 1,4 | 0,1 | 1,9 | 1,4 |
| 2400 | 42 | 37 | 18 | 18 | 6,4 | 5,1 | 2,8 | 0,7 | 1,5 | 0,9 | 1,4 | 0,1 | 1,8 | 1,4 |
| 0200 | 42 | 31 | 17 | 17 | 5,5 | 4,7 | 2,1 | 0,6 | 1,3 | 0,9 | 1,6 | 0,1 | 2,0 | 1,6 |
| 0400 | 38 | 28 | 15 | 16 | 3,0 | 4,4 | 2,4 | 0,6 | 1,9 | 0,8 | 1,7 | 0,1 | 1,9 | 1,7 |
| 0600 | 33 | 24 | 14 | 14 | 4,9 | 4,1 | 2,0 | 0,5 | 1,5 | 0,7 | 1,5 | 0,1 | 2,4 | 1,5 |
| 0800 | 32 | 26 | 12 | 13 | 3,7 | 4,0 | 1,8 | 0,4 | 1,3 | 0,6 | 1,7 | 0,1 | 2,1 | 1,7 |
| 1000 | 26 | 20 | 10 | 11 | 4,0 | 3,3 | 1,8 | 0,4 | 1,4 | 0,6 | 1,6 | 0,1 | 2,8 | 1,6 |
| Ave. | 35 | 26 | 15 | 14 | 5,0 | 4,0 | 2,0 | 0,5 | 1,5 | 0,7 | 1,5 | 0,1 | 2,0 | 1,5 |

Notes:
1. All results expressed as mg N/l
2. E denotes experimental value
3. P denotes predicted value
4. Reactor samples were filtered through coarse filter paper
5. Effluent samples were filtered through Whatman 542 filter paper

## Table 4.9.

## Goudkoppie Plant

Comparison of predicted and experimental nitrate concentrations in each reactor

| Time of Day | Feed | POSITION WITHIN PLANT | | | | | | | | | | Effluent |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Anaerobic | | Primary Anoxic | | Primary Aeration | | Secondary Anoxic | | Secondary Aeration | | |
| h | | Soluble | | Soluble | | Soluble | | Soluble | | Soluble | | |
| | | E | P | E | P | E | P | E | P | E | P | |
| 1200 | | 1,3 | 3,2 | 10,0 | 9,2 | 12,5 | 12,0 | 13,0 | 11,6 | 13,8 | 12,6 | 14,0 |
| 1400 | | 1,5 | 3,0 | 9,8 | 8,8 | 12,0 | 14,6 | 12,0 | 11,3 | 12,8 | 12,1 | 14,0 |
| 1600 | | 0,7 | 2,7 | 9,6 | 8,5 | 13,0 | 11,3 | 11,4 | 10,9 | 12,8 | 11,8 | 14,0 |
| 1800 | | 0,6 | 2,5 | 9,5 | 8,3 | 13,3 | 11,2 | 12,3 | 10,8 | 13,0 | 11,5 | 13,6 |
| 2000 | | 0,5 | 4,7 | 9,7 | 8,2 | 14,0 | 11,4 | 12,8 | 10,9 | 13,3 | 11,5 | 14,0 |
| 2200 | | 0,7 | 4,1 | 9,2 | 8,6 | 14,3 | 12,1 | 12,8 | 11,5 | 13,3 | 11,9 | 14,0 |
| 2400 | | 0,5 | 4,4 | 9,9 | 9,1 | 13,8 | 12,8 | 12,8 | 12,2 | 13,5 | 12,6 | 14,0 |
| 0200 | | 0,7 | 2,7 | 4,6 | 9,6 | 16,0 | 13,3 | 10,7 | 12,7 | 11,0 | 13,2 | 12,0 |
| 0400 | | 1,3 | 2,9 | 9,1 | 9,9 | 8,7 | 14,4 | 11,5 | 14,9 | 14,4 | 13,5 | 13,6 |
| 0600 | | 1,4 | 3,1 | 10,5 | 10,5 | 14,3 | 13,3 | 12,0 | 12,9 | 13,3 | 13,6 | 10,6 |
| 0800 | | 1,7 | 3,2 | 10,6 | 9,9 | 13,8 | 13,0 | 8,7 | 12,6 | 9,7 | 13,4 | 13,0 |
| 1000 | | 1,7 | 3,2 | 10,1 | 9,6 | 13,5 | 12,6 | 13,0 | 12,3 | 13,8 | 13,0 | 14,0 |
| Average | | 1,1 | 3,0 | 9,4 | 9,1 | | 12,3 | 12,5 | 11,9 | 13,3 | 12,6 | 13,5 |

Notes:
1. All results expressed as mg N/l
2. E denotes experimental value
3. P denotes predicted value
4. Nitrate is absent from feed
5. Reactor samples were filtered through coarse filter paper
6. Effluent samples were filtered through Whatman 542 filter paper

# 6. DISCUSSION

## 6.1. Model predictions

In comparing the observed and predicted response one can proceed by examining the daily mass response and the cyclic response separately.

### 6.1.1. Daily mass response

The response of the plant, averaged over the day, observed and predicted are shown in Table 4.10.

Table 4.10.

Goudkoppie Works

Comparison of average predicted effluent results, oxygen consumption rate and MLSS concentration, with those obtained experimentally

| Test | | Average Model prediction | Average Measured value |
|---|---|---|---|
| COD | (mg O/l) | 40,8 | 43,0 |
| TKN | (mg N/l) | 3,0 | 2,0 |
| Ammonia | (mg N/l) | 0,1 | 1,5 |
| Nitrate | (mg N/l) | 12,6 | 13,5 |
| Oxygen consumption main basin | (mg/l/h) | 17,7 | 16,2 |
| MLSS | (mg/l) | 1950 | 1940 |

Examining Table 4.10., the agreement is remarkably close, the maximum relative difference occurring in the oxygen uitlisation rate (OUR) in the main aeration basin where the predicted exceeds the observed by (17,7 - 15,8) ≐ 1,9 mg/l/h i.e. about 11 percent. With such a small difference, it is indeed difficult to identify any single significant source of error, but the most likely source is the experimental measurement of OUR ; it is sensitive to the location of the sampling point because the basin is not completely mixed ; although this was countered by taking the average from three locations the likelihood of obtaining the true average is small.

### 6.1.2. Cyclic response

Again the predicted and observed response appears to be excellent. The first, and main difference, arises in the oxygen utilisation rate (Fig. 4.6.) where the two curves are slightly out of phase. This, very likely, could be the result of the fact that the model treats the main aeration basin as a single completely mixed unit. More likely, the basin should be treated as a semi - plug flow system by, for example, subdividing the unit into two reactors in series with perhaps a recycle between them. However it is doubtful if any further refinement in the prediction is of real value.

A second and less important difference between the predicted and experimental values is to be noted in Table 4.7. The observed COD concentration leaving the second aeration tank appears to be higher than that leaving the final clarifier, whereas one would expect these values to be almost identical.

Furthermore, the predicted COD concentration is virtually identical to that observed on the effluent from the clarifiers. The higher value in the aeration tank is attributed to the use of a different filter paper ; the tank samples were filtered through coarse filter paper whereas the effluent samples were filtered through Whatman 542 . The latter paper is a very fine one that will remove additional fine particulate material to that by the coarse paper. Consequently the fine paper gave COD concentrations lower than that using a coarse paper. The fine filter paper can be expected to be nearer the soluble COD fraction predicted by the model, and this indeed is the case in Fig. 4.7. It would appear that in future research, for the estimation of the soluble COD fraction in the reactor contents and the effluent, fine filter paper is mandatory, or, the sample should be centrifuged. However even if the fine filter paper is used, the filtered fraction in the sample from the aerobic reactor is unlikely to conform to the predicted value, for in this reactor an appreciable fraction of the soluble COD may consist of larger molecules or colloids that can pass through a fine filter paper.

With the exception of the above two differences, which are not considered serious, the simulated response by the model under the input data is in very good agreement with that observed. The general model, therefore, appears to provide a reliable means for predicting the behaviour of plants at the design stage, to obtain a rapid assessment of operating plants and to investigate the effect on the response if the flow and load conditions on an existing plant are changed.

## 7. NITROGEN REMOVAL

Nutrient removal from the Goudkoppie plant was poor. From Table 4.3. the average total nitrogen in the feed of 35 mg N/l was reduced to 15,5 total nitrogen ($NO_3$-N plus $NH_3$-N), and the average total phosphorus in the feed of 5,8 mg P/l to 3,7 mg P/l . The question arises as to whether this poor performance was due to inadequate design, or whether the process was working at maximum efficiency but the input of nutrients was so high that it was not possible to remove them substantially.

To resolve these questions it is useful to refer to the theories on which nitrification / denitrification and excess phosphorus removal are based. From the work of van Haandel, Ekama and Marais (1981) the mass of nitrate formed (nitrification capacity), is approximately proportional to the influent TKN concentration. The concentration of nitrate denitrified (denitrification capacity), for any specific influent is approximately proportional to the influent COD concentration. Consequently, very roughly, the TKN/COD ratio provides an approximate assessment of the ratio of nitrification to denitrification capacities. The TKN/COD ratio therefore forms a useful reference parameter against which the likelihood of complete nitrogen removal of a specific plant can be estimated. It can be readily appreciated that if the COD is fixed, then for a specific configuration and sludge age, the denitrification capacity is fixed, and the process will have the capability of reducing the nitrate formed only if the TKN/COD ratio does not exceed an upper critical limit. For example, van Haandel et al (1981) showed that, for raw sewage, an optimal Bardenpho design can not attain complete denitrification if the TKN/COD ratio exceeds about 0,09 and in the Phoredox process, an optimal design can not give complete denitrification if the TKN/COD ratio is equal to or greater than about 0,07 to 0,08 . These ratios refer to raw sewage. For settled sewage the ratios are slightly different principally because in primary settling, the easily biodegradable COD is only slightly affected, and magnitude of this fraction has a significant effect on denitrification. It is also evident from the work of van Haandel et al (1981) that the primary anoxic reactor is significantly more efficient in nitrate removal per unit volume than the secondary anoxic reactor. Consequently, for a specified TKN/COD the primary anoxic reactor should be increased in volume at the expense of the second anoxic reactor until zero nitrate is attained, the total anoxic mass fraction remaining constant. When the TKN/COD ratio attains a particularly high value this procedure will show that the volume of the second anoxic reactor eventually becomes zero. At any higher TKN/COD ratio it will be impossible to achieve complete nitrate removal for the fixed total anoxic mass fraction. Consequently in a particular plant, if nitrate is present in the effluent and that plant has a second anoxic reactor, the removal of nitrate could have been improved by increasing the primary anoxic reactor at the expense of the secondary anoxic reactor.; to express it differently, in an existing plant, if nitrate is present in the effluent and a second anoxic reactor is present, then the plant has not been optimally designed. The Goudkoppie plant, judged in terms of this criterion can be taken to have a design not optimal for the influent as received.

The relatively poor reduction in nitrate achieved in the second anoxic reactor is evident from the nitrate data in Table 4.3. The difference between the influent and effluent in this reactor is 5,9 ($NO_3$-N)/l . With respect to the influent doing a mass balance the removal is 0,9 . Total flow / nominal flow = 0,9 (30,4 + 26,8)/30,4 = 1,7 mg ($NO_3$-N) . A similar balance on the primary anoxic reactor gives (13,5 . 26,8 + 182 . 13,4) - (30,4 + 182 + 26,8) . 9,8 / 30,4 = 15,0 mg ($NO_3$-N) removed.

Was the design optimal with regard to the assumed influent characteristics (Table 4.1.) ? To test this, the plant response was simulated using the general model taking as sewage inputs the COD and TKN values assumed in the original design, and the same flow value to the modules as for the experimental investigations, 30 Ml/d . (COD was obtained from the ratio BOD : COD = 1 : 2 ) . The results of this simulation are summarised in Table 4.11.

Table 4.11.

The predicted performance of the Goudkoppie Plant under design load conditions

| | Feed | Anaerobic | Primary Anoxic | Primary Aeration | Secondary Anoxic | Secondary Aeration |
|---|---|---|---|---|---|---|
| COD | 600 | 150 | 91 | 90 | 90 | 90 |
| TKN as N | 50 | 32,6 | 10,9 | 3,8 | 5,6 | 2,9 |
| Ammonia as N | | 30,9 | 8,6 | 1,4 | 3,1 | 0,5 |
| Nitrate as N | | 0 | 1,9 | 7,6 | 1,2 | 3,4 |
| Oxygen consumption rate mg/l/h | | | | 47,5 | | |
| MLSS | | | | 6 500 | | |

Note: Flow 30 Ml/d

An inspection of Table 4.11. indicates that nitrate removal would have been virtually complete, and in terms of the theory for excess phosphorus removal, high removals would have been achieved.

However, the influent TKN to COD ratio assumed in the design was completely uncharacteristic of the value to be expected in settled sewage. The assumed TKN/COD ratio is 50/600 = 0,083, whereas more characteristically this ratio should be 0,1 or higher. The COD concentration assumed in the design appears to be on the high side - it would indicate that the designers expected an influent COD of approximately 800 mg/l .

The analysis above points to an important conclusion: An appropriate design can be made only if the sewage characteristics, in particular the TKN/COD ratio, are known within reasonable limits. Should the TKN/COD ratio be more adverse than that assumed in the design, the process may fail in its objective.

These comments apply particularly to the Phoredox process. Once the process cannot fulfill its design objectives by virtue of a high TKN/COD ratio there is, in fact, no operational procedure whereby it is possible to make the plant operate in an improved fashion, with regard to phosphorus removal for a specific sewage characteristic under which it has shown failure.

## 8. PHOSPHORUS REMOVAL

Siebritz, Ekama and Marais (1982) concluded that the mass of phosphorus removed by a Phoredox process is dependent upon three factors:

(i) The magnitude of the readily biodegradable COD in excess of 25 mg/l in the anaerobic reactor.

(ii) The actual retention time in the anaerobic reactor

(iii) The fractional mass of sludge in the system that is recycled through the anaerobic reactor each day.

Of these three factors the first only is related to the influent COD, but the concentration of readily biodegradable COD ($S_{bsa}$) in the anaerobic reactor depends also on the nitrate recycled to this reactor via the underflow recycle. For every 1 mg/l nitrate entering the anaerobic reactor 8,6 mg/l of $S_{bsa}$ are used.

Taking these criteria into account there are two reasons why the phosphorus removal is so low ; .

(i) The high nitrate concentration (13,5 mg N/l) in the underflow would remove 116 mg/l of easily biodegradable COD . The influent readily biodegradable COD concentration $S_{bs}$ is 29 mg/l (see Table 4.4.) and consequently no $S_{bsa}$ would be present in the anaerobic reactor and no excess phosphorus removal could be expected.

(ii) Even if the nitrate in the recycle was zero this plant would still not have removed phosphorus, for the concentration in the anaerobic reactor with a 0,9:1 underflow recycle would be 29 / (0,9 + 1) = 15,3 which is still less than the critical 25 mg/l required for excess phosphorus removal. It would appear therefore that the Phoredox process is inappropriate to give excess phosphorus removal for this influent. This conclusion is borne out by a study of the past history of the plant over the two and a half years of operation prior to this investigation - excess phosphorus removal was observed only sporadically (see Fig. 4.11.) even though the plant was operated with deficient oxygen input so that nitrification was only partial (the average recycle nitrate concentration was 4,5 mg N/l)

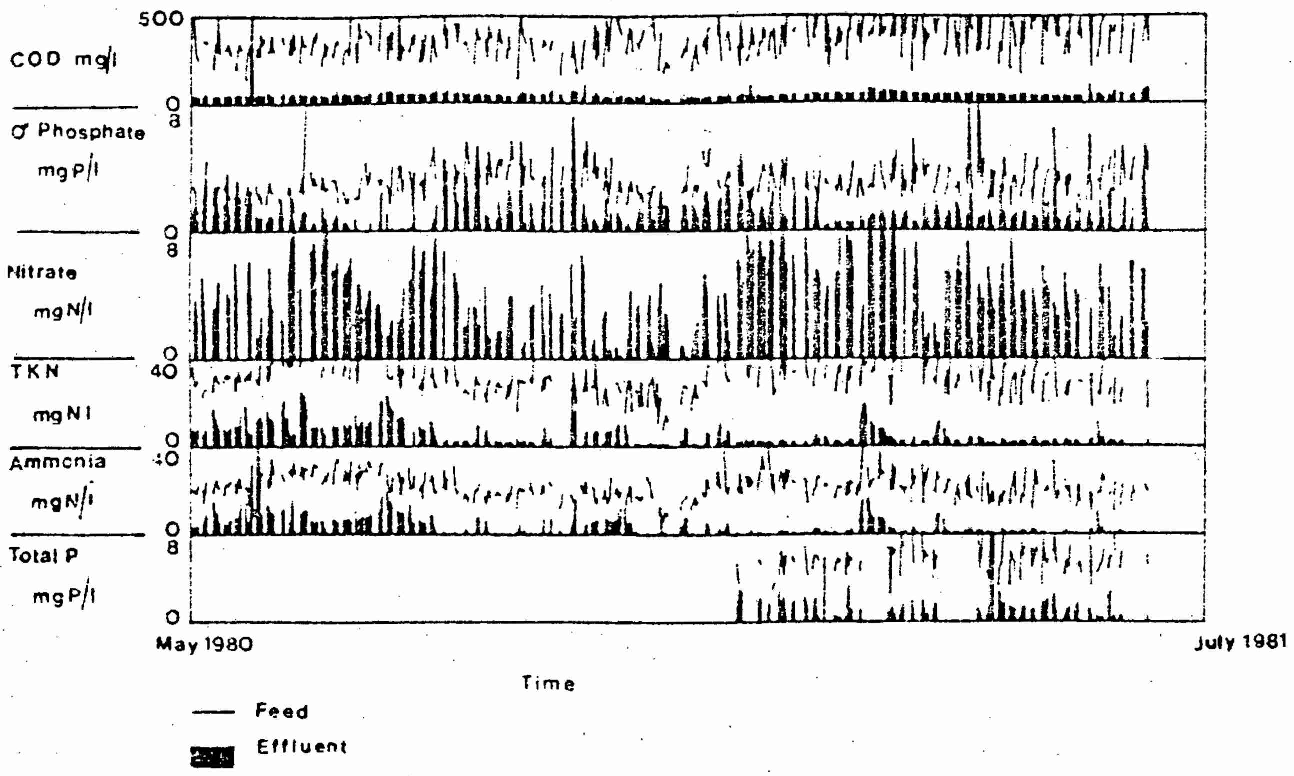

Fig. 4.11. The Goudkoppie plant

The feed and effluent concentrations of some of the main parameters from the start up of the plant until the balancing strategy was applied.

## 9. POSSIBLE MODIFICATION TO THE GOUDKOPPIE PLANT TO IMPROVE NUTRIENT REMOVAL UNDER THE EXISTING FLOW AND LOAD

In view of the poor nitrogen and phosphorus removal attained in the Goudkoppie plant it was decided in July 1980 to investigate possible ways of improving plant performance. Two approaches to the problem of improving plant performance were considered :

(i) Changing process configuration from a Phoredox to a Modified UCT process

(ii) Bypassing the equalisation tanks

(iii) Changing the operating mode of the equalisation tank

In each case the process model was utilised in the analysis of the effects of different changes on plant performance. The model serves a very useful purpose in this respect because the accuracy of predictions obtained from the model can be regarded with confidence ; this aspect has become apparent from the very close correspondence between observed and predicted results presented in the previous section.

## 9.1. Changing to a Modified UCT Process configuration

Siebritz, Ekama and Marais (1980) have recommended the use of the Modified UCT process to a single sludge system where, firstly nutrient removal is required, and secondly the feed TKN/COD ratio is high. It would appear that the process would lend itself to the conditions which exist at the Goudkoppie plant provided the sewage characteristics were more favourable ; the $S_{bsi}$ of the feed to the process is so low that it is doubtful whether any process modification would significantly improve the mass of phosphorus removed. Nevertheless in this section the feasibility of modifying the Goudkoppie plant from a Phoredox process to a Modified UCT process was investigated.

For optimal nitrogen removal in the Modified UCT process, Siebritz et al (1980) have recommended the anoxic mass fraction and recycled flows given in Fig. 4.12. The Goudkoppie plant could be changed to incorporate these recommendations but it would require certain expensive modifications. The main modification would be to increase the size of the primary anoxic reactor by converting the existing secondary anoxic reactor into a new second primary anoxic reactor. With this change the mass fractions of the various zones then would be approximately within practical limits, the desired values given in Fig. 4.12. (see Table 4.12.)

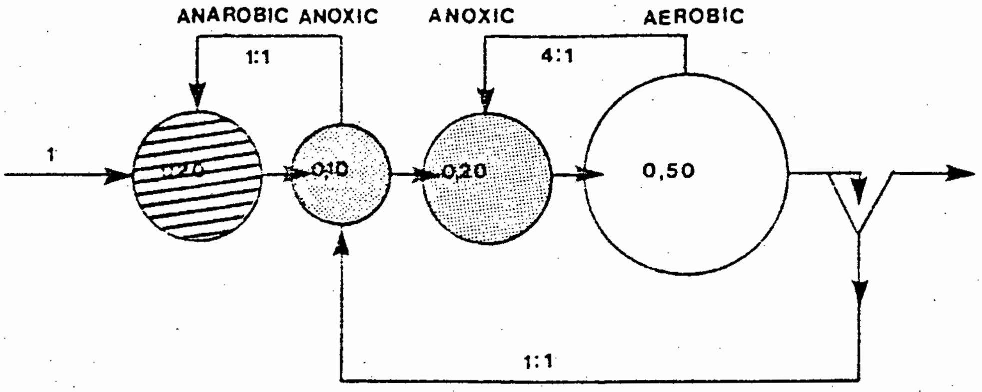

Fig. 4.12. Layout of the Modified UCT Process

Note: Values given inside reactor denote mass fraction

Table 4.12.

The mass fractions of the various zones when the secondary anoxic reactor is converted into a primary anoxic reactor

| | Bardenpho Goudkoppie | UCT Goudkoppie |
|---|---|---|
| Anaerobic | 0,07 | 0,20 |
| Primary anoxic 1 | 0,17 | 0,10 |
| 2 | 0,17 | 0,20 |
| Aerobic | 0,51 | 0,50 |
| Secondary anoxic | 0 | 0 |
| Re aeration | 0,09 | 0 |

A more detailed explanation of the changes required to convert the Goudkoppie plant from a Bardenpho to a UCT process is given below :

(i) With relatively minor changes the primary and secondary anoxic reactors could be interconnected using the existing MLSS recycle channels; the activated sludge could be made to flow by gravity from the existing primary anoxic to the existing secondary anoxic reactors. Using a new recycle pump the sludge from the former secondary anoxic reactor could be pumped back to the primary anoxic reactor. In this manner the two reactors would be interconnected.

(ii) The MLSS recycle ratio could be controlled by allowing the desired proportion of effluent to flow from the main aeration basin into the newly created primary anoxic reactor. (Since there would be a head loss between these two reactors no pumping would be required.) The remainder of the effluent from the main aeration basin could bypass the new primary anoxic reactor and flow into the old reaeration reactor. Again no pumping is required as there is a head loss between the two reactors, but a new pumping main is required.

(iii) The Modified UCT process requires that the returned sludge be returned to the primary anoxic reactor and not to the anaerobic reactor as is the case at present. Such a modification would necessitate additional pipework ; no additional pumping would be required.

(iv) The MLSS in the first primary anoxic reactor should be recycled back to the anaerobic reactor; one of the redundant

- MLSS recycle pumps could be used for this purpose in conjunction with a new pumping main.

A summary of the suggested modifications is depicted in Fig. 4.13. together with the relative mass fractions of each reactor.

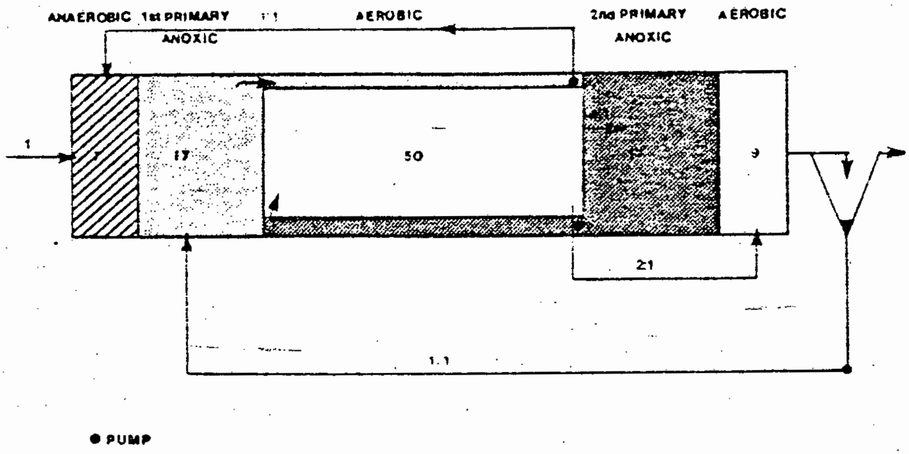

Fig. 4.13. Proposed modification of the Goudkoppie Plant to a Modified UCT Process

Such modifications as proposed above would involve considerable expense and to establish whether such expenditure is justified the data obtained during the intensive test period discussed earlier is used in the model to predict the performance of the plant incorporating the Modified UCT process. The constants used in the model prediction were the same as those used in the initial test run - see Tables 4.4. and 4.5. , and the input flow , COD and TKN data the same as given in Table 4.6.

- The average results predicted by the model for the Goudkoppie plant when operating a modified UCT mode are given in in Table 4.13. and the dynamic predictions of soluble COD, ammonia and nitrate in each reactor are given in Figs. 4.14. , 4.15. and 4.16. respectively.

Table 4.13.

Predicted performance of Goudkoppie plant when changed to a Modified UCT Process and fed with balancing tank effluent

| Test | Feed | Anaerobic | First Primary Anoxic | Second Primary Anoxic | First Aerobic | Second Aerobic |
|---|---|---|---|---|---|---|
| Total COD | 270 | 53 | 42 | 41 | 41 | 41 |
| Soluble easily biodegradable COD | 29 | 11,7 | 0,8 | 0 | 0 | 0 |
| TKN as N | 35 | | | | | |
| Ammonia as N | 25 | 19,9 | 13,3 | 4,9 | 0,5 | 0,1 |
| Nitrate as N | 0 | 0 | 1,1 | 7,0 | 11,2 | 11,8 |
| MLSS | | | | | 1 740 | |
| Oxygen consumption rate mg O/l/h | | | | | 18,1 | |

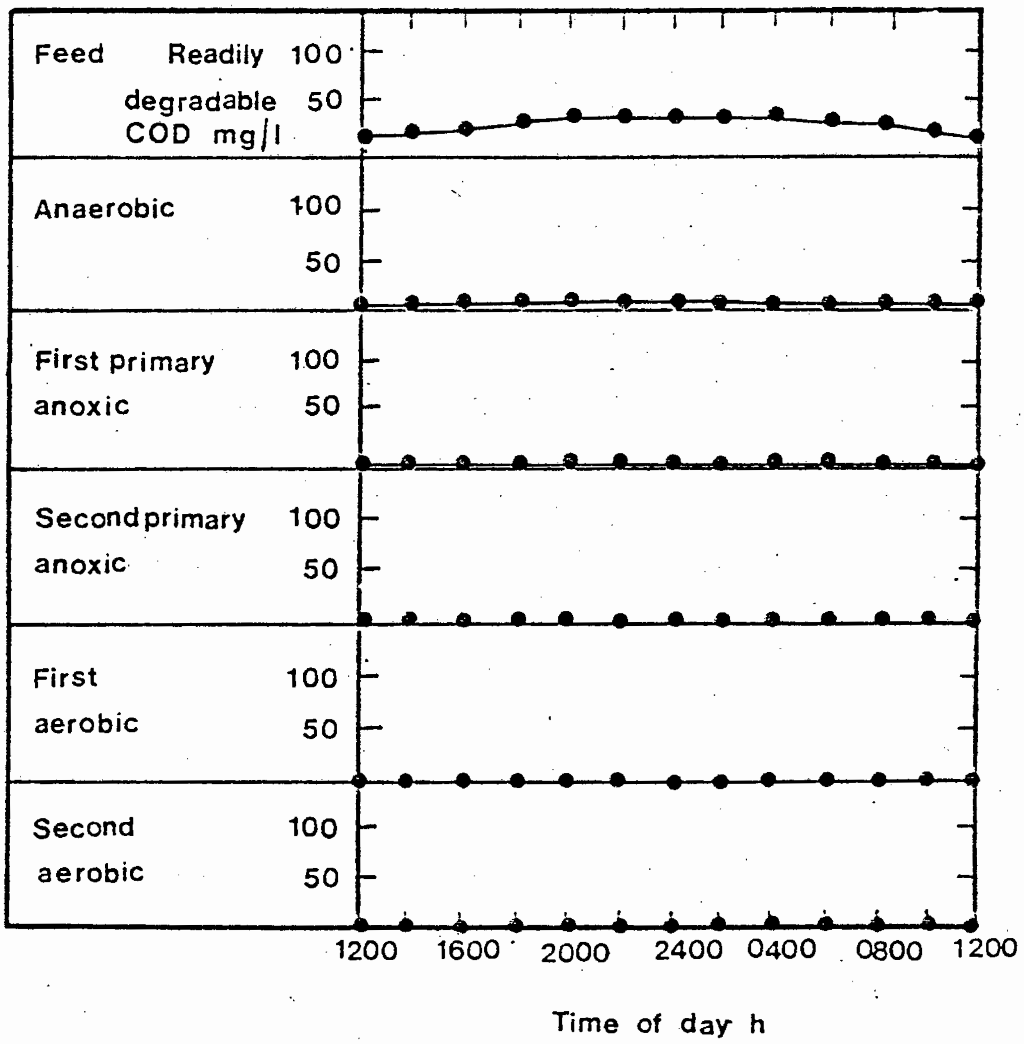

Fig. 4.14. Process configuration : Modified UCT

The predicted readily biodegradable COD concentrations when the plant is fed with balancing tank effluent

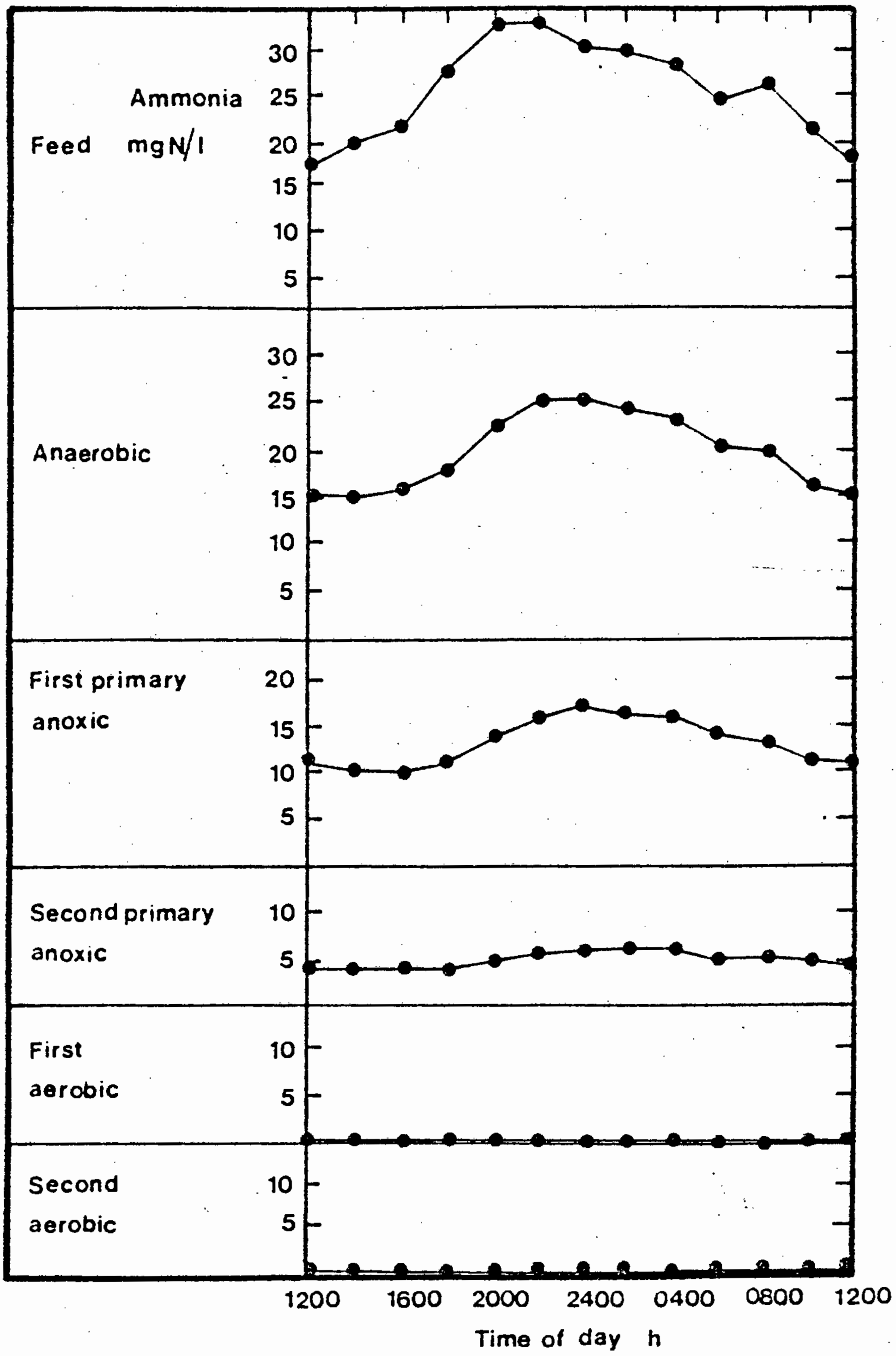

Fig. 4.15. Process configuration : Modified UCT

The predicted ammonia concentrations when the plant is fed with balancing tank effluent

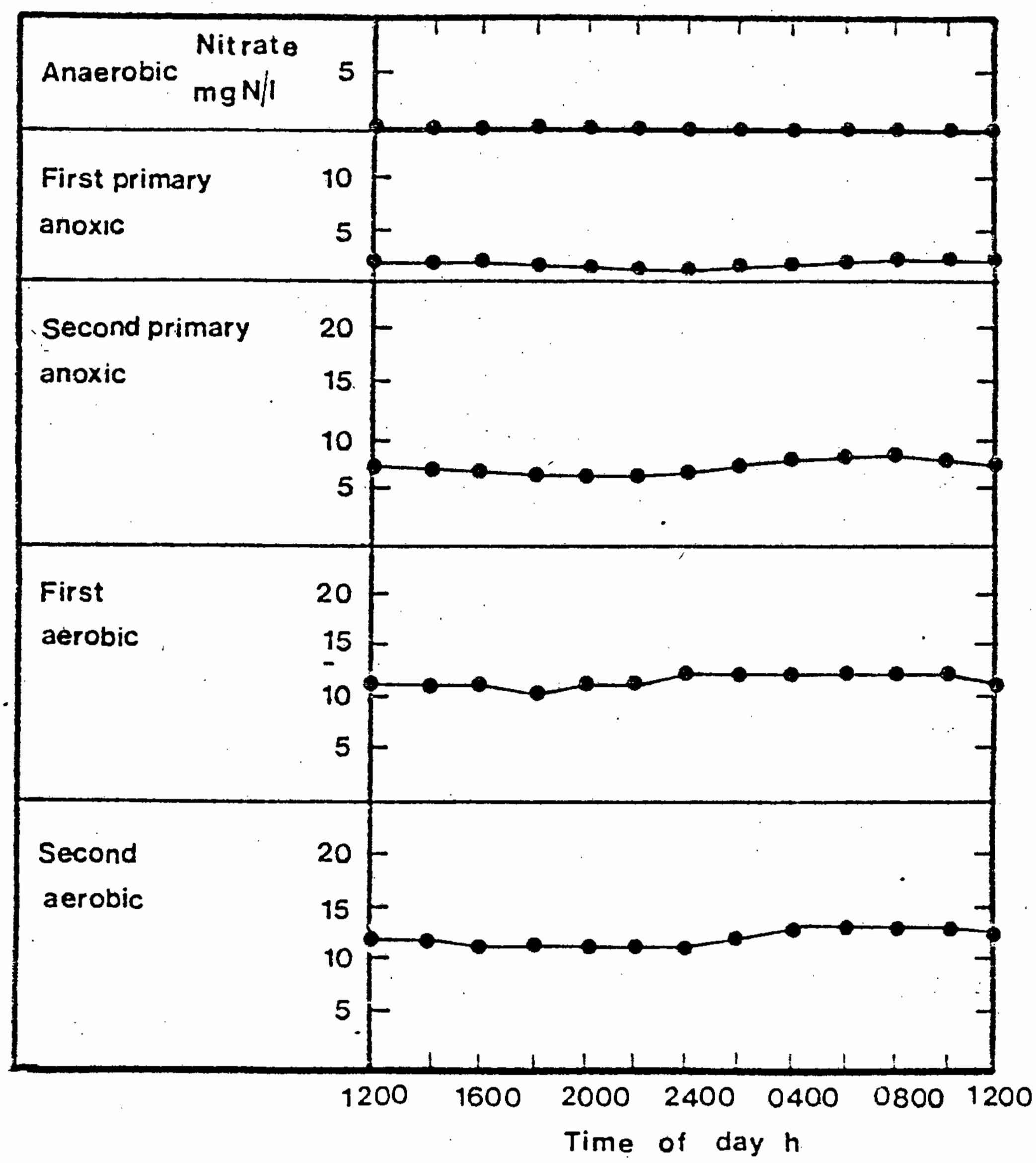

Fig. 4.16. Process configuration : Modified UCT

The predicted nitrate concentrations when the plant is fed with balancing tank effluent

### 9.1.1. Discussion

From the analysis above it was apparent that ;

(i) The nitrate concentration in the first and second anoxic reactors is 1,1 and 7,0 mg N/l respectively, which is not acceptable both from a nitrogen and phosphorus removal point of view. This lack of removal may be attributed to:

- the high TKN/COD ratio
- the low readily biodegradable COD concentration of the feed to the process, 29 mg/l

(ii) As the average readily biodegradable COD concentration in the anaerobic reactor is estimated to be approximately 12 mg COD , no release of phosphorus is expected, with the result that no or little excess phosphorus uptake is likely to occur.

Both the above factors show clearly that, for this particular situation, there is no merit in considering changing the process configuration from that of the Phoredox to the Modified UCT process. With regard to nitrogen removal, performance with the Modified UCT process would be marginally only better than that attained with the present Phoredox configuration. The cost of implementing the change in configuration (in the region of R300 000) would definitely not be justified in the light of the slight improvement in effluent quality.

Comparison of the performance of the Goudkoppie plant (either in a Phoredox or Modified UCT configuration) with the performance of other plants clearly showed that the principal cause of poor nutrient removal was the low fraction of easily biodegradable COD entering the process. An investigation into the causes for the relatively low value led to the second approach to improving plant performance i.e. changing the mode of operation.

## 9.2. Bypassing the settling tank

A schematic representation of the flow entering the plant is shown in Fig. 4.1. Raw sewage after screening and grit removal enters the primary sedimentation where approximately 45% of the influent COD is removed in an underflow stream which constitutes only two percent of the inflow. Overflow from the primary sedimentation tank passes to the biological process via the balancing tank.

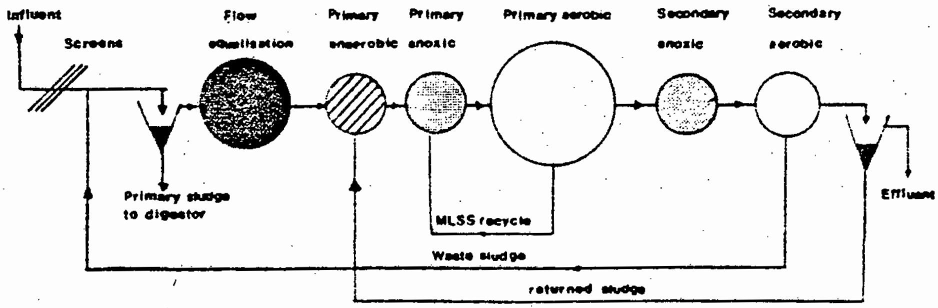

Fig. 4.1. Goudkoppie Plant
Basin configuration

Measurement over a period of time of the sewage characteristics of the unsettled (raw) , settled and equalised flows are given in Table 4.14. The concentration of easily biodegradable COD $S_{bsi}$ can be expressed as a fraction of the biodegradable COD $f_{bs}$ by taking due account of $f_{us}$ and $f_{up}$ in these influents. The $S_{bs}$ was estimated and is also given in Table 4.14.

## Table 4.14.

Sewage characteristics of raw, settled and equalised flows at the Goudkoppie plant.

| | Symbol | Raw Sewage | Settled Sewage | Balancing tank effluent |
|---|---|---|---|---|
| Fraction of readily biodegradable COD (mg COD/mg biodegradable COD) | $f_{bs}$ | 0,19 | 0,36 | 0,16 |
| Fraction of particulate unbiodegradable COD (mg VSS/mg COD) | $f_{up}$ | 0,10 | 0,08 | 0,12 |
| Fraction of soluble unbiodegradable COD (mg COD/mg COD) | $f_{us}$ | 0,06 | 0,08 | 0,16 |
| Easily biodegradable COD concentration (mg COD/mg COD) | $S_{bs}$ | 114 | 114 | 29 |

The following should be noted regarding the results given in Table 4.14.

(i) Influent raw sewage had a $f_{bs}$ value of 0,19 mg COD/mg COD. This is only marginally less than that encountered at other works in South Africa ; usually $f_{bs} \approx 0,24$ .

(ii) Approximately 45% of the raw influent COD was removed in the primary sedimentation tanks; and the COD removed consisted principally of particulate matter; however this mass of COD is removed in only 2% of the flow. Therefore it can be expected that the readily biodegradable fraction with respect to the total COD in settled sewage should be almost double that of the raw waste water. This was borne out by the results which showed that $f_{bs}$ increased from 0,19 to 0,36 mg COD/mg biodegradable COD in passing through the primary sedimentation tank.

(iii) The value of $f_{bs}$ for settled sewage and for balancing tank effluent should be similar i.e. very little change in the value of $f_{bs}$ should be expected because the function of the unaerated balancing tank merely is to attenuate cyclic flow and load rate variations. However, the results show that the value of $f_{bs}$ was reduced considerably (by 56 percent). In addition, it was found that there was approximately a 20 percent mass loss of COD across the balancing tank. These aspects were a direct consequence of the operational procedure applied to the balancing tank, and merit further discussion.

The Goudkoppie balancing tank is unmixed ; therefore settlement of sewage solids on the base of the tank is to be expected. If the tank is not drained regularly there will be a large accumulation of solids in the tank. In practice, this was found to be the case ; in fact, the accumulation of solids was so large that plant operators specifically avoided draining the tank because, if this happened, the COD concentration in the stream leaving the tank rose to as high as 6 000 mg/l . This led to operational problems in the down stream process. This operational approach had severe consequences as regards the performance of the Goudkoppie Plant:

- The accumulation of solids on the tank floor led to a substantial degree of anaerobic activity in this sludge. Evidence of this was the gas bubbles which rose to the surface of the balancing tank together with masses of sludge. The net result was that the $f_{bs}$ reduced significantly*. In addition the TKN/COD ratio was increased from 0,10 to 0,13 because there was only a marginal loss of TKN across the tank. The consequence of both the above phenomena was the poor nitrogen and phosphorus removal in the subsequent activated sludge plant discussed earlier.

To avoid the reduction in $f_{bs}$ so as to enhance plant performance two approaches were considered:

(i) Bypassing the balancing tank

(ii) Operating the balancing tank so as to ensure no accumulation of solids on the floor.

The first approach was unlikely to be practical at the Goudkoppie plant. Firstly, considerable expense would be required to bypass the balancing tank, and secondly the plant was designed to handle only the equalised (or mean) flow rate i.e. smaller final clarifiers, larger peak load concentration which would result in peak aeration capacities which could be greater than the maximum oxygen input allowed for in the design. In addition, operation under

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* At one stage it was thought that the anaerobic activity would, in fact increase $f_{bs}$ ; it was hypothesised that anaerobic degradation of particulate matter would increase the amount of readily biodegradable material which in turn would improve the phosphorus removal capacity. However, with the long retention time of the solids on the floor, the fermentation was more than likely taken to completion with methane and not volatile acids as the end product. The gas produced was not analysed because at that time methane fermentation was not suspected

unequalised inputs would lead to major operational and control problems. However to illustrate the effect which an increase in $f_{bs}$ would have on the performance, it was decided to simulate the behaviour of the plant having as input the settled sewage flow before entry into the balancing tank i.e. there would be no reduction in either the readily biodegradable fraction of COD or the mass of COD leaving the primary sedimentation tanks. The kinetic parameters used were the same as those used previously, given in Table 4.5. , while those kinetic parameters specific to this settled sewage are given in Table 4.15. The plant operating conditions are the same as discussed in section 3.2. with the exception of the flow to the process which would not be equalised. The input data with respect to flow, COD and TKN concentrations of the feed to the process (settled sewage) is listed in Table 4.16.

The results of this simulation are shown in Table 4.17. and in Figs. 4.17. , 4.18. and 4.19.

Table 4.15.

Kinetic parameters specific to settled sewage at Goudkoppie plant when balancing tank bypassed

| Name | Symbol | Units | Value |
|---|---|---|---|
| Fraction of soluble unbiodegradable COD | $f_{us}$ | mg COD/mg COD | 0,08 |
| Fraction of particulate unbiodegradable COD | $f_{up}$ | mg VSS/mg COD | 0,08 |
| Fraction of easily biodegradable COD | $f_{bs}$ | mg COD/mg bio-degradable COD | 0,36 |
| Easily biodegradable COD concentration | $S_{bs}$ | mg COD/l | 113 |
| Fraction of TKN of feed in ammonia form | $f_{nu}$ | mg N/mg N | 0,76 |
| Specific growth rate for nitrifiers | $_{nm}$ | $d^{-1}$ | 0,5 |

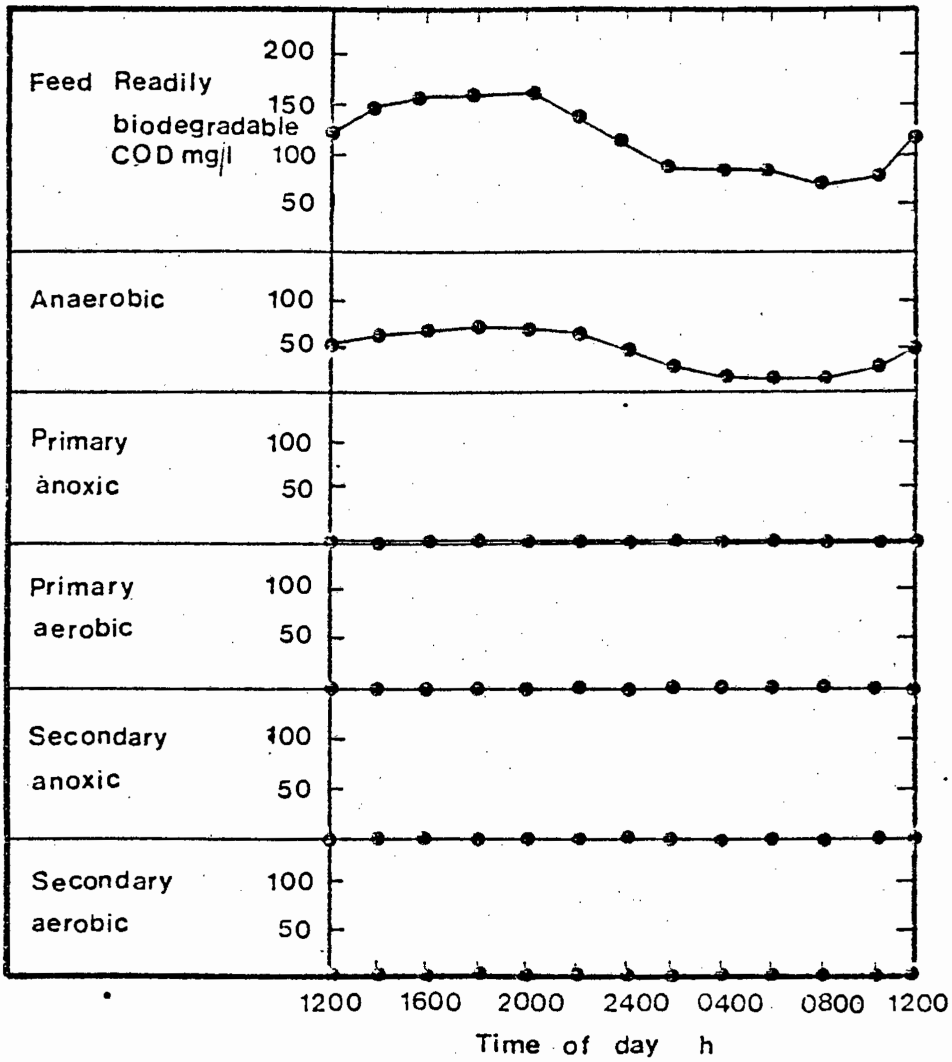


Fig. 4.17. Process configuration : Phoredox

Predicted readily biodegradable COD concentrations when the balancing tank is bypassed

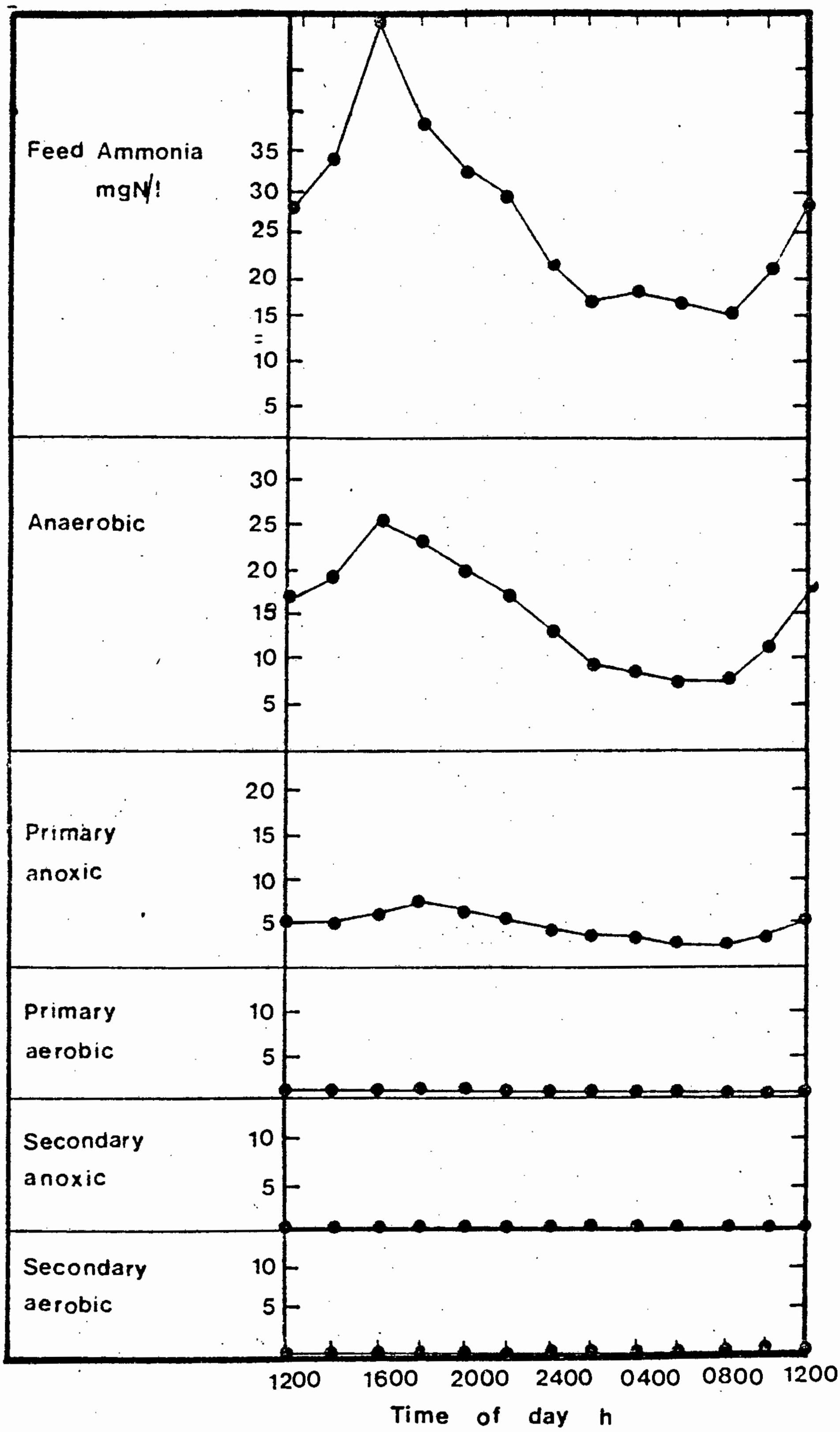


Fig. 4.18. Process configuration : Phoredox

Predicted ammonia concentration when the

balancing tank is bypassed

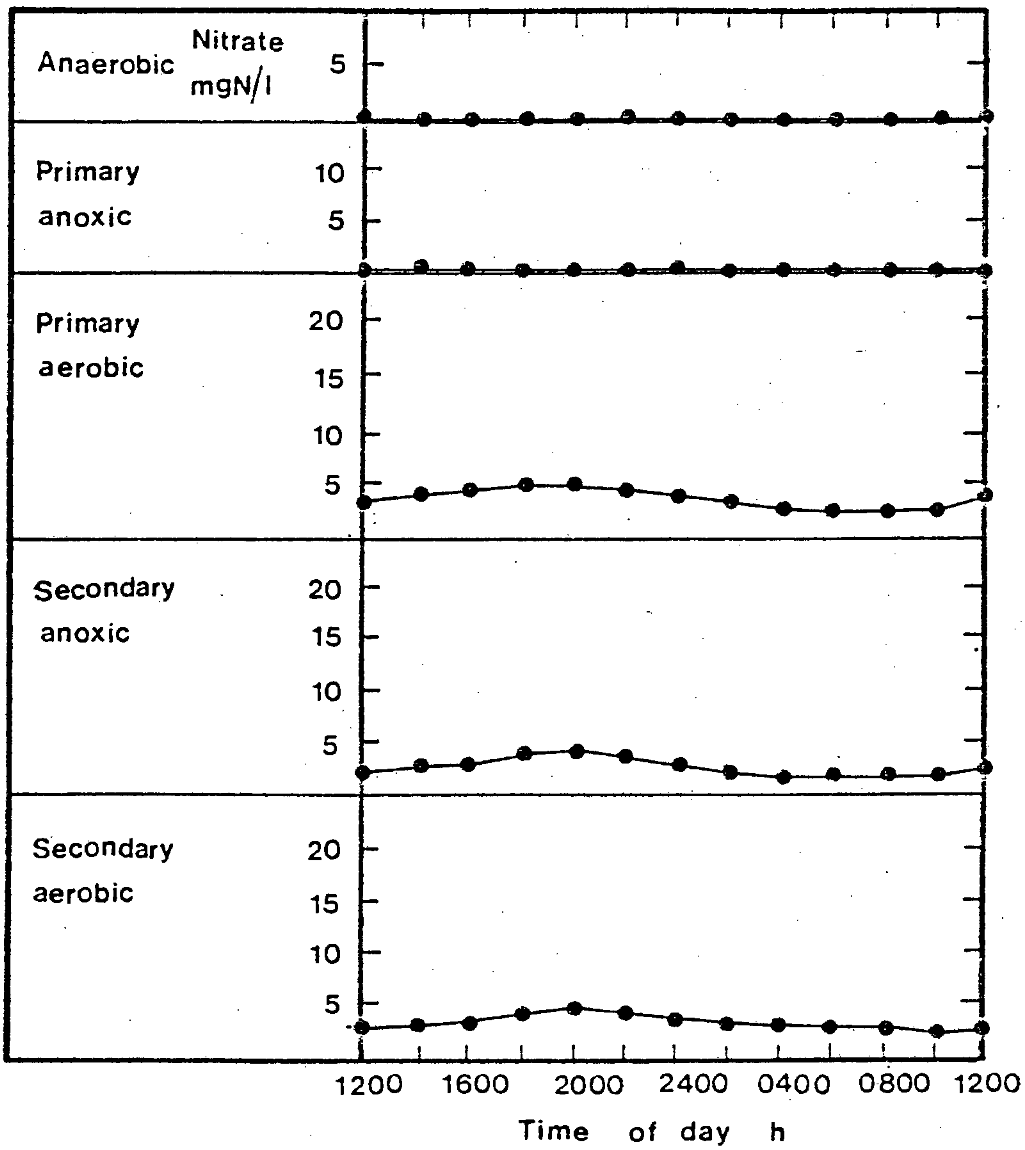


Fig. 4.19. Process configuration : Phoredox

Predicted nitrate concentration when the balancing tank is bypassed

Table 4.16.

Input flow and COD and TKN concentrations used in the model to predict the behaviour of the process if the balancing tank were bypassed

| Time | Flow $m^3/d$ | COD mg/l | TKN mg N/l |
|---|---|---|---|
| 1200 | 51 800 | 420 | 37 |
| 1300 | 46 100 | 460 | 41 |
| 1400 | 40 300 | 500 | 45 |
| 1500 | 40 300 | 515 | 43 |
| 1600 | 40 300 | 530 | 60 |
| 1700 | 43 200 | 530 | 45 |
| 1800 | 46 100 | 530 | 50 |
| 1900 | 41 800 | 545 | 46 |
| 2000 | 37 400 | 560 | 42 |
| 2100 | 37 400 | 520 | 41 |
| 2200 | 37 400 | 480 | 39 |
| 2300 | 33 100 | 430 | 32 |
| 2400 | 28 800 | 380 | 28 |
| 0100 | 25 900 | 330 | 25 |
| 0200 | 23 300 | 280 | 22 |
| 0300 | 20 600 | 280 | 23 |
| 0400 | 17 900 | 280 | 24 |
| 0500 | 17 600 | 285 | 23 |
| 0600 | 17 300 | 290 | 23 |
| 0700 | 22 200 | 255 | 21 |
| 0800 | 27 100 | 220 | 19 |
| 0900 | 38 000 | 240 | 24 |
| 1000 | 49 000 | 260 | 28 |
| 1100 | 50 400 | 340 | 32 |
| 1200 | 51 800 | 420 | 37 |

Table 4.17.

Predicted performance of the Goudkoppie Plant when the balancing tank is bypassed

| Test | Feed | Anaerobic | Primary Anoxic | Primary Aerobic | Secondary Anoxic | Secondary Aerobic |
|---|---|---|---|---|---|---|
| Total COD | 330 | 77,8 | 36,6 | 33,5 | 33,5 | 33,5 |
| Soluble easily biodegradable COD | 113 | 44,7 | 3,1 | 0 | 0 | 0 |
| TKN as N | 34 | | | | | 3,1 |
| Ammonia as N | 25,7 | 14,7 | 4,2 | 0,5 | 0,9 | 0,1 |
| Nitrate as N | 0 | 0 | 0 | 3,0 | 2,1 | 3,0 |
| MLSS | | | | 3 060 | | |
| Oxygen utilisation rate mg O/l/h | | | | 27,4 | | |

From these plots several factors are of interest. When the balancing tank is bypassed, the model predicts :

(i) Good nitrification in the primary aerobic reactor with ammonia concentrations of approximately 0,5 mg N/l leaving the reactor.

(ii) Denitrification improves dramatically ; the mean effluent nitrate declines from 13,5 mg N/l for the equalised effluent to approximately 3 mg N/l if the bypass is instituted.

(iii) Even with a recycle nitrate of 3 mg N/l discharging to the anaerobic reactor, the concentration of readily biodegradable COD ($S_{ba}$) in the anaerobic reactor increases ; zero when the balancing tank is in line to 45 mg/l when the balancing tank is bypassed. The latter concentration is well above that suggested by Siebritz <u>et al</u> (1980) (25 mg/l) necessary to cause good phosphorus release and effective phosphorus removal.

Since the model predictions do not consider the relatively high dissolved oxygen concentrations in the feed entering the process, the 45 mg/l readily biodegradable COD in the anaerobic reactor predicted by the model would be lower than that hypothesised. If, for example, the feed contained 4 mg/l dissolved oxygen, then 2,86 X 4 = 11,4 mg/l of readily biodegradable COD would be utilised by this oxygen, thus reducing the readily biodegradable fraction to approximately 34 mg/l ; however this is well in excess of the limit suggested by Siebritz <u>et al</u> (1980) . Consequently appreciable phosphorus removal would be expected. Since bypassing the balancing tank was not a practical proposition, the discussion above is only hypothetical. However the results serve the useful purpose of illustrating the positive effect of ensuring no reduction in $f_{bs}$ .

## 9.3. Modification to operating the settling tank

An avenue to improve the phosphorus removal propensity would be to avoid the reduction of $f_{bs}$ in the balancing tank. It was hypothesised that if the operating mode of the balancing tank was changed such that solids would not accumulate on the floor of the tank, then possibly fermentation of the sludge might not take place, and the readily biodegradable COD concentration could preserve its value in the influent to the tank. At that time it became possible to test the validity of this hypothesis. An on-line microprocessor - based equalisation tank control strategy, developed by Dold, Buhr and Marais (1982) , was implemented at the balancing tank at Goudkoppie, and operated very successfully. Amongst the important desirable features achieved by the operation of on-line control balancing tank strategy were :

(i) The efficiency of equalisation attained under control strategy operation was far superior to that achieved when the balancing tank was operated manually. Previously, problems of balancing tank overflows were encountered almost weekly, whereas under the control strategy operation this did not occur. The improved equalisation performance also reduced operation and control problems on the downstream plant substantially e.g. aeration control, settling tank control etc.

(ii) Under control strategy operation , the problem of solids accumulation in the balancing tank was also overcome. This was achieved by a feature of the control strategy operation, that each day the tank level was regulated to drop sufficiently to ensure flushing of any accumulated solids. As a consequence, anaerobic degradation of the settled material no longer took place in the balancing tank, with the result

- that there was no significant decrease in the value of $f_{bs}$ across the tank and, during the hold up, the mass loss of the total COD did not exceed one percent (As opposed to a 20 percent mass loss encountered under manual balancing tank operation) ; the net effect of these two aspects was that there was no significant increase in the TKN/COD ratio across the balancing tank.

## 10. THEORETICAL EVALUATION OF THE EFFECT ON NUTRIENT REMOVAL WHEN THE BALANCING TANK CONTROL STRATEGY WAS APPLIED

The successful operation of the balancing tank under equalisation control strategy operation (Dold, Buhr and Marais, 1982) prompted a simulation investigation on the possible effects on the nutrient removal capacity of the plant. For the simulation the input data are listed below in Table 4.18.

Table 4.18.

Input data for simulation under equalisation control strategy

| Parameter | Symbol | Units | Value |
|---|---|---|---|
| Total COD | $S_{ti}$ | mg/l | 390 |
| TKN | $N_{ti}$ | mg N/l | 34 |
| Underflow recycle ratio | s | | 1:1 |
| Mixed liquor recycle ratio | a | | 4:1 |
| Sludge age | $R_s$ | d | 22 |
| Fraction of unbiodegradable particulate COD | $f_{up}$ | mg VSS/mg COD | 0,08 |
| Fraction of soluble unbiodegradable COD | $f_{us}$ | mg COD/mg COD | 0,08 |
| Fraction of readily biodegradable | $f_{bs}$ | mg COD/mg biodegradable COD | 0,36 |
| Flow | | Ml/d | 35 |
| Temperature | T | °C | 20 |

- The other required constants and physical parameters are the same as those listed in Tables 4.4. and 4.5. The process configuration and volume of reactors are listed in Fig. 4.2.a

The simulated results using the above input data are given in Table 4.19.

Table 4.19.

Input data for simulation under equalisation control strategy operation

| | Feed | Anaerobic | Primary Anoxic | Primary Aerobic | Secondary Anoxic | Secondary Aerobic | Effluent |
|---|---|---|---|---|---|---|---|
| Total COD | 390 | 77,8 | 36,6 | 35,5 | 33,5 | 33,5 | 33,5 |
| Soluble COD | 114 | | | | | | |
| $S_{bs}$ | 113 | 44,7 | 3,1 | 0 | 0 | 0 | 0 |
| TKN as N | 34 | | | | | 3,1 | 3,1 |
| Ammonia as N | 25,7 | 14,7 | 4,2 | 0,5 | 0,9 | 0,1 | 0,1 |
| Nitrate as N | 0 | 0 | 0 | 3,0 | 2,1 | 3,0 | 3,0 |
| Total P | | | | | | | |
| Soluble P | | | | | | | |
| Suspended solids | | | | 3 060 | | | |
| Oxygen consumption mg/l/h | | | | 27,4 | | | |

Unless otherwise stated all results expressed as mg/l

The theoretical concentration of phosphorus which could be expected to be removed by the plant when operating under the conditions above may be estimated as follows :

(i) Biodegradable COD concentration $S_{bi}$

$$S_{bi} = (1 - f_{us} - 1{,}48\ f_{up})\ S_{ti} \qquad (11)$$

$$= (1 - 0{,}08 - 1{,}48\ .\ 0{,}08)\ 394$$

$$= \underline{315 \text{ mg COD/l}}$$

(ii) - Readily biodegradable COD concentration in the anaerobic reactor $S_{bsa}$

$$S_{bsa} = (S_{bi} f_{bs} - 8{,}6\ S\ N_{nr}) / (1 + S) \qquad (13)$$

$$= (315 \,.\, 0{,}36 - 8{,}6 \,.\, 1 \,.\, 3{,}0) / (1 + 1)$$

$$= (113 - 25{,}8) / 2$$

$$= \underline{43{,}6 \text{ mg COD/l}}$$

(iii) The mass concentration of phosphorus that will be removed and the anaerobic mass fraction is expressed by the phosphorus removal propensity factor $P_f$ ;

$$P_f = (S_{bsa} - 25)\ f_{xa} \qquad (14)$$

$$= (43{,}6 - 25)\ 0{,}07$$

$$= 1{,}30$$

The propensity factor is related to the percentage concentration of phosphorus with respect to the volatile active suspended solids VASS , , as follows :

$$= 0{,}35 - 0{,}29\ e^{-0{,}242\ P_f}$$

$$= 0{,}35 - 0{,}29\ e^{-0{,}242 . 1{,}3}$$

$$= 0{,}14$$

Having estimated $\alpha$ the concentration of phosphorus which can be removed is estimated using equation (15)

$$\Delta P = S_{ti}\ ((1 - f_{us} - Pf_{up})\ Y_h\ (\alpha + f_p f b R_s)) / \left[(1 + bR_s) + f_p f_{up}/P\right] \qquad (15)$$

$$= 394\ \left[((1 - 0{,}08 - (1{,}48 \,.\, 0{,}08))\ 0{,}45\ (0{,}14 + (0{,}015 \,.\, 0{,}2 \,.\, 0{,}24 \,.\, 22))) / (1 + 0{,}24 \,.\, 22) + (0{,}015 \,.\, 0{,}08)/1{,}48\right]$$

$$= 394\ (0{,}009)$$

$$= \underline{3{,}5 \text{ mg P/l}}$$

Hence provided the influent characteristics are given in Table 4.18. under equalisation control strategy, the Goudkoppie plant could be expected to remove 3,5 mg P/l .

It is important to note that this removal is subject to the nitrate concentration in the effluent remaining at or below 3 mg N/l . If the nitrate concentration should increase the removal will decrease. In effect the plant performance will be critically affected by the nitrate concentration. Clearly such a situation may be tolerated, but is not desirable for stability in operation.

Based on the consideration expressed above that if the nitrate in the effluent could be limited to about 3 mg N/l , phosphorus removal is achievable, the plant was operated with some of the aerators switched off near the point discharging the flow from the primary anoxic reactor. The aeration capacity in the rest of the reactor was appropriately increased so that nitrification could proceed within this region.

During the experimental period the flow was 40 Ml/d and the sewage characteristics were as listed in Table 4.18. The mean observed effluent quality under these conditions is listed in Table 4.20. and the daily response of the plant shown in Fig. 4.20.

Table 4.20.

Feed and effluent concentrations when the Goudkoppie plant was operated with equalisation control strategy.

| Test | Feed | Effluent |
|---|---|---|
| Total COD | 300 | 50 |
| TKN as N | 32 | 9,5 |
| Ammonia as N | 21 | 8,5 |
| Nitrate as N | - | 1,0 |
| Total phosphorus as P | 6,1 | 1,0 |
| Readily biodegradable COD | 86 | - |

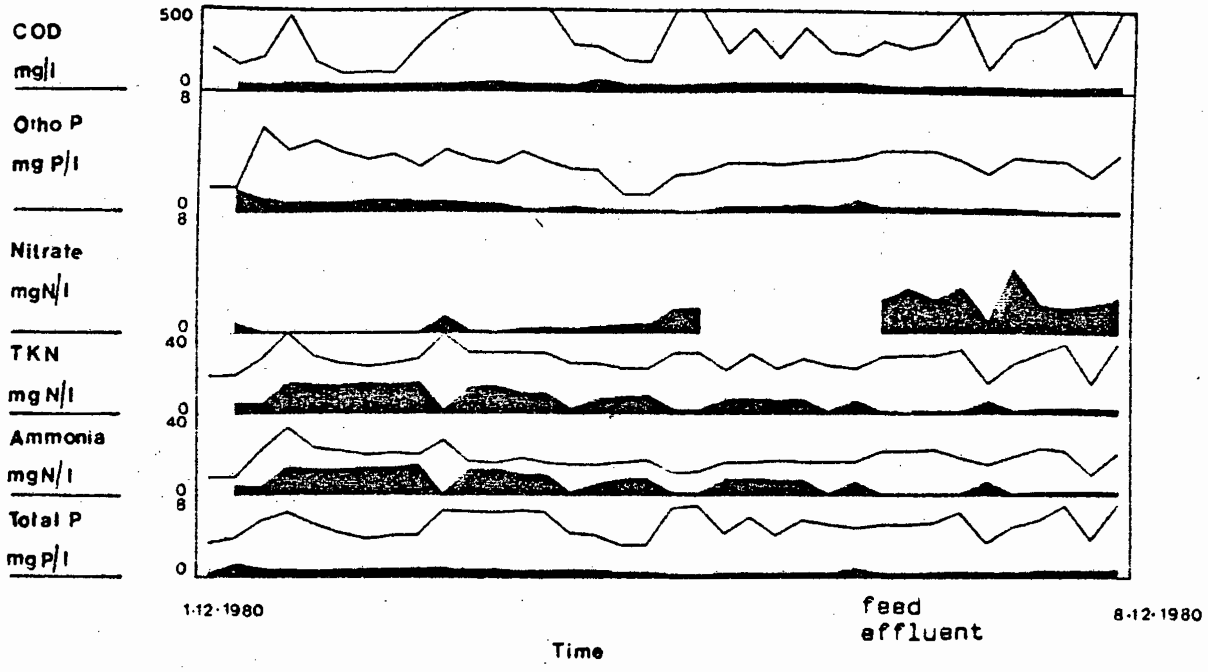


Fig. 4.20. Goudkoppie Works

The feed and effluent concentrations of the more important parameters when operating under equalisation control strategy

The theoretical phosphorus removal i.e. ( P =3,0 mg P/l) was lower than the mean removal observed ( P = 3,5 mg P/l) ; but because the plant was now no longer operated in a definable sense kinetically the removal could deviate from the predicted. At least the theory did indicate successfully the direction to be taken to achieve phosphorus removal. Examining Fig. 4.21. , the phosphorus removal remained relatively constant over the period of the experimentation. which replaced the unstable removal situation of before. Indeed, in as far as the phosphorus removal aspects on the Goudkoppie plant is concern concerned, the removal is probably near the maximum possible theoretically, and no other operational procedure is likely to improve it. However this efficiency was attained only by curtailing the aeration capacity at the beginning of the main aeration basin, thereby effectively increasing the anoxic zone. It was also possible to operate in this fashion because the remaining mass fraction was large enough to allow nitrification to take place. i.e. this mode of operation will be limited by the load to the plant.

# CHAPTER FIVE

## NORTHERN WORKS

### 1. INTRODUCTION

As the name implies, this plant treats the waste water discharged in the watershed draining the north of Johannesburg. Originally there were three waste water treatment plants serving this area ; Bruma, Cydna and Delta Works (see Fig. 1.1.) However by 1950 these plants were surrounded by residential areas and were overloaded. As a result a new treatment plant, the Northern Works, was constructed on the banks of the Jukskei river, approximately 25 km from the city centre (see Fig. 1.1.) . This plant is a metropolitan one treating, not only waste water that flowed to the old Bruma, Cydna and Delta plants, but also those derived from the satellite towns surrounding Johannesburg in the northern drainage basin.

The first Northern Works, commenced in 1961, comprised two identical units each with primary sedimentation, biological filtration and sludge digestion. The effluent from these plants discharged into the Jukskei river either directly or indirectly via Kelvin Power Station (where the effluent was used as cooling water). These discharges were high in nitrate and phosphate, and at times, caused severe eutrophication problems in Hartebeespoort Dam located downstream of the effluent discharge points.

By the late 1970's both these plants were overloaded and, as a result, Northern Works Unit 3 was designed, constructed and commissioned by the end of 1979. This new plant, located alongside the existing plants, is of a similar type to that at Goudkoppie, discussed in Chapter 4.

## Table 5.1

## NORTHERN WORKS DESIGN DATA

| | | | |
|---|---|---|---|
| Flow / module | | (Ml/d) | 50 |
| Raw sewage composition | BOD | (mg/l) | 380 |
| | TKN | (mg N/l) | 46 |
| Settled sewage composition | BOD | (mg/l) | 265 |
| | TKN | (mg N/l) | 30 |
| Sewage temperature | | (°C) | 13 |
| BOD loading | | (kg BOD/kg MLSS) | 0,401 |
| MLSS | | (g/m$^3$) | 5 250 |
| Sludge age | | (days) | 25 |
| Volume | (1) Anaerobic | (m$^3$) | 2 230 |
| | (2) Primary anoxic | (m$^3$) | 4 575 |
| | (3) Primary aerobic | (m$^3$) | 15 300 |
| | (4) Secondary anoxic | (m$^3$) | 4 575 |
| | (5) Secondary aerobic | (m$^3$) | 2 500 |
| | Total | (m$^3$) | 29 180 |

| Basin number | | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| Nominal retention time | (h) | 1 | 2 | 7 | 2 | 1 |
| Number of aerators | | - | - | 10 | - | 3 |
| Power / aerator | (kW/h) | | | 90 | | 22 |
| Oxygenation capacity | (kg $O_2$/h per aerator) | | | 186 | | 45 |
| Oxygen transfer efficiency | (kg $O_2$/kWh) | | | 2,03 | | 1,94 |
| Number of mixers | | 2 | 4 | - | 4 | - |
| Power per mixer | (kW) | 15 | 15 | - | 22 | - |
| Number per module | | 3 | | | | |
| Design nominal daily flow to secondary sedimentation tank (without recycle) | (m$^3$/h) | 700 | | | | |

## Table 5.1. continued

### Secondary sedimentation

| | | |
|---|---|---|
| Peak factors based on nominal flow | | |
| Dry weather peak | | 1,2 |
| Wet weather peak | | 1,2 |
| Solid flux based on nominal flow | ($kg/m^2/h$) | |
| Winter | | 4,6 |
| Summer | | 5,5 |
| Surface loadings based on mean flow | (m/h) | |
| Winter | | 0,61 |
| Summer | | 0,95 |
| Diameter of tank | (m) | 38 |
| Volume of tank | ($m^3$) | 3 740 |
| Side wall depth | (m) | 3,25 |

## 2. DESIGN FEATURES

The design of this plant provided for primary and secondary screens, degritting, primary sedimentation using 8 rectangular tanks, flow balancing tanks and 3 activated sludge modules in parallel, each designed as a Phoredox process. A diagrammatic sketch of the plant is shown in Fig. 5.1. and the details of the design data are given in Table 5.1.

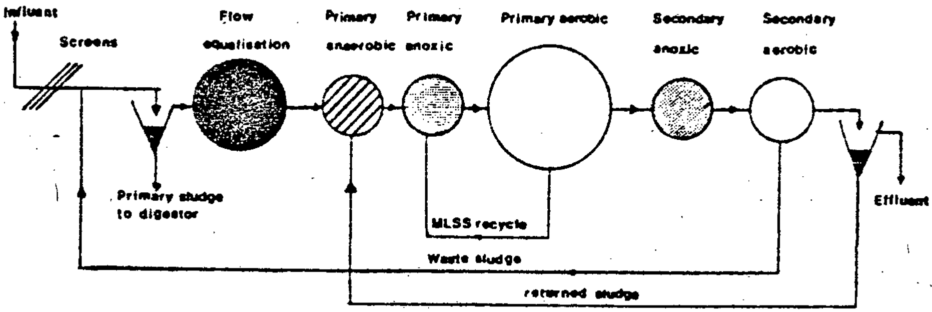


Fig. 5.1. Northern Works basin configuration

Some design features are discussed below, and, in particular, are compared with those at Goudkoppie.

(i) Primary sedimentation The tanks at Northern Works are rectangular whereas those at Goudkoppie are circular. The design upward velocity in these tanks on both plants is 1,5 m/h , However both plants were hydraulically underloaded during the experimental period and the upward velocities on both plants were lower.

(ii) Balancing tanks : the design includes three balancing tanks, one for each of the three modules, not interconnected in any way i.e. they are completely separate units, each balancing tank feeding to a specific module. (This differs from the design of the balancing facility at Goudkoppie Works where one balancing tank serves all four modules). At Northern Works the balancing tanks are designed as long rectangular basins with the floors sloping sharply to the longitudinal axis of the tank, to a channel running along the same axis of the tank. Any solids deposited while the tank is full are flushed out when the balancing tank empties.

(iii) Process units : The process units are identical and based on the Phoredox process. Each consists of five completely mixed reactors in sequence : anaerobic - primary anoxic - primary aerobic - secondary anoxic - secondary aerobic . The important features in the process design are very similar to those listed for the Goudkoppie plant with the following exceptions :

- The maximum MLSS recycle ratio is less than at Goudkoppie, i.e. 10 : 1 , compared with 16 : 1 of Goudkoppie.
- In the design of the oxygenation requirements at the Northern Works, cognizance was taken of the BOD utilised during denitrification, with the result that the overall available oxygenation capacity, per influent BOD in the primary aeration basin is less than that at the Goudkoppie plant i.e. 900/1 325 = 0,68 as against 1 320/1 410 = 0,94 kg O/kg BOD/day

(iv) Final clarifiers : There are three per module, each with a diameter of 38 m and a side wall depth of 3,25 m .

- Sludge is removed by means of 10 syphons located on a rotating bridge spanning the diameter of the clarifier. The mixed liquor enters the clarifier at the bottom, in the centre, in a tangential flow pattern. In the initial design no baffles, to reduce the kinetic energy of the incoming flow, were provided ; considerable shortcircuiting was observed . In order to counter this, horizontal and vertical baffles were fitted which effectively have reduced this problem.

(v) Flow metering : This plant has flow metering facilities at the following points :

* Feed flow to the process from the balancing tank is automatically controlled to a selected flow rate by a Rotork valve activated by a magnetic flow meter. Hence, provided the balancing tank does not empty over the day, an approximately fixed volume of flow should pass into the process each day.

* Sludge wastage, to control sludge age, is wasted directly from the secondary aeration basin. The volume wasted each day is metered by means of a magnetic flow meter.

No metering facility is provided in the returned sludge line consequently underflow sludge flow rate has to be measured indirectly by means of a solids mass balance across the secondary clarifier.

## 3. PLANT PERFORMANCE EVALUATION

### 3.1. Objectives

Once the plant operated under stable conditions for a period of approximately 3 sludge ages, it was planned to carry out a detailed investigation of the plant performance similar to that of the Goudkoppie plant :

* An indepth evaluation of the performance of each zone

* Estimation of oxygen consumption rates under different conditions in the primary aerobic reactor.

* Overall appraisal of nitrification / denitrification efficiency

* Assessment of phosphorus removal capability

* Comparison of actual performance data with predictions obtained making use of the mathematical model developed by the University of Cape Town.

### 3.2. Conditions of test

(i) Flow to the experimental module was fixed at a constant 40 Ml/d (compared with design flow 50 Ml/d) - the total flow to the plant was still below the design flow.

(ii) Sludge age was monitored at 27 days which, as for the Goudkoppie plant, was presumed to give rise to a rapid settling sludge.

(iii) Physical details of the process layout are given in Fig 5.2.(a) and Table 5.2.

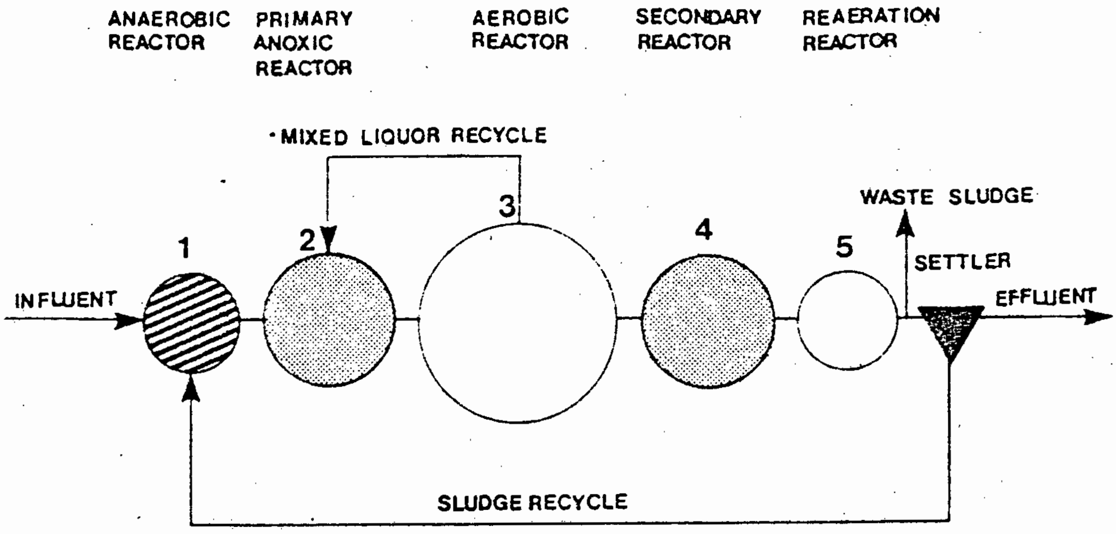


Fig. 5.2.(a) The process layout at Northern Works

Table 5.2.

Physical details of the process layout at the Northern Works

| | Anaerobic | Primary Anoxic | Primary Aerobic | Secondary Anoxic | Secondary Aerobic |
|---|---|---|---|---|---|
| Reactor number | 1 | 2 | 3 | 4 | 5 |
| Volume ($m^3$) | 2 230 | 4 575 | 15 300 | 4 575 | 2 500 |
| Nominal retention time (d) | 0,056 | 0,114 | 0,383 | 0,114 | 0,063 |
| Mass fraction | 0,076 | 0,157 | 0,524 | 0,157 | 0,086 |

Note 1. MLSS recycled from reactor 4 to reactor 2, ratio 4:1

2. Sludge return cycled from settler to reactor 1, ratio 0,4:1

(iv) <u>Dissolved oxygen concentration</u> in both aerobic reactors was maintained in excess of 2 mg/l . Under the existing conditions of low flow and load this concentration could be achieved with only half the total number of aerators operational, as shown in Fig. 5.2.(b) .

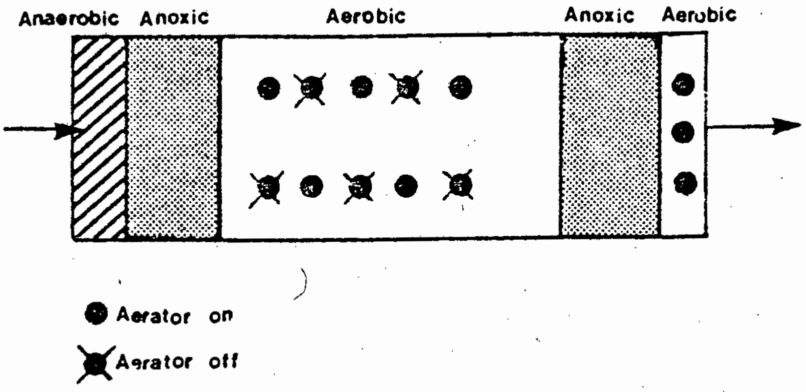


Fig. 5.2.(b) Operational aerators during experimentation

(v) <u>Sampling procedures</u> during this investigation were the same as those in the Goudkoppie experiment, with one important exception : The filter paper, when filtering the grab sample from each reactor, was Whatman 542 and not the coarse paper used in the Goudkoppie tests - it was evident from the Goudkoppie experimental results on the effluent that when fine filter paper was used, the fine filter filtrate corresponded more closely to the soluble COD than the filtrate of the rough filter paper.

(vi) <u>Measurements of the oxygen utilisation rate</u> were done by means of a respirometer identical to the type used at Goudkoppie (see Appendix A4) . During the experimental period the respirometers were positioned in the following positions ; between the first and second aerator bridges, in line with the third aerator bridge, and between the fourth and fifth bridges .

## 3.3. Performance data

Sampling of the influent, the effluent and the contents of each reactor was carried out at two hourly intervals over a period of four days, and samples analysed for COD, TKN, ammonia, nitrate and phosphate. The oxygen utilisation rates were measured at the same time. Unfortuneately the results of three of the seven days had to be discarded due to the malfunction of one of the respirometers. The results of the remaining data at each time point are listed in Appendix A8. These were averaged and are listed in Table 5.3. Plots of the average values are shown in Figs 5.3. - 5.10.

| | |
|---|---|
| Fig. 5.3. | Unfiltered COD concentration in the feed and filtered effluent and reactor contents |
| Fig. 5.4. | Unfiltered TKN concentration in the feed and filtered effluent |
| Fig. 5.5. | Total oxygen utilisation rate in the main aeration basin |
| Fig. 5.6. | Total phosphorus concentration in the unfiltered feed and filtered effluent |
| Fig. 5.7. | Soluble COD concentration in filtered samples in each basin |
| Fig. 5.8. | Soluble ammonia concentration in filtered samples in each basin |
| Fig. 5.9. | Nitrate concentration in filtered samples in each basin |
| Fig. 5.10. | Soluble phosphorus concentration in filtered samples |

The reliability of the data was checked, as discussed earlier, by conducting mass balances over the reactor on COD and nitrogen. (For details on the procedure see Appendix A9) .

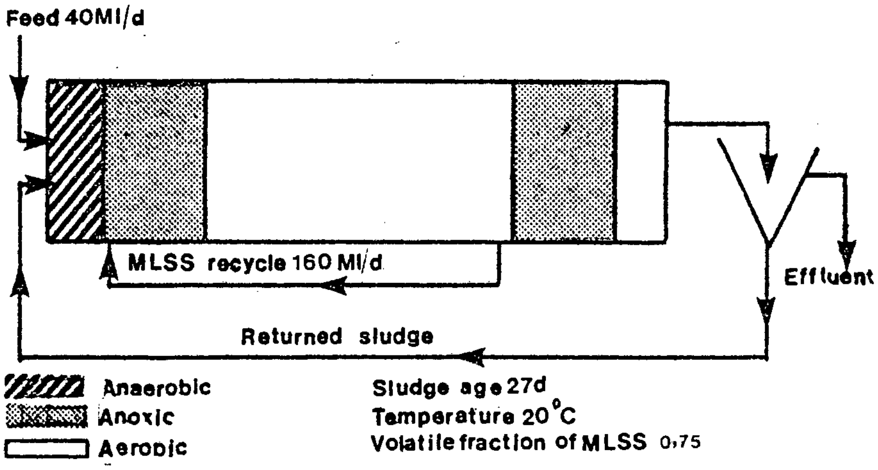
Mass balances achieved are M TKN = 99 percent recovery

M COD = 90 percent recovery

These mass balances are very good indicating that the data are acceptable.

Table 5.3.

The average performance of the Northern Works during the experimental period



| | Feed | Anaerobic | Primary Anoxic | Primary Aerobic | Secondary Anoxic | Secondary Aerobic | Effluent |
|---|---|---|---|---|---|---|---|
| Total COD | 240 | | | | | | 46 |
| Soluble COD | | 72 | 45 | 42 | 34 | 38 | 38 |
| $S_{bs}$ | 33 | | | | | | |
| TKN as N | 39 | | | | | | 2,1 |
| Ammonia as N | 24 | 16 | 6,8 | 0,7 | 0,5 | 0,0 | 0,0 |
| Nitrate as N | | 4,3 | 10 | 16 | 16 | 16 | 17 |
| Total P | 9,7 | | | | | | 7,6 |
| Soluble P | 6,5 | 6,9 | 6,6 | 6,5 | 6,6 | 6,5 | 6,5 |
| Suspended solids | | | | 1 440 | | | |
| Oxygen consumption mg/l/h | | | | 24,1 | | | |

Unless otherwise stated all results expressed as mg/l

* All reactor and effluent samples were filtered through Whatman 542 filter paper

** Reactor samples were filtered and tested by means of the orthophosphate test

*** $S_{bs}$ = readily biodegradable COD concentration mg COD/l

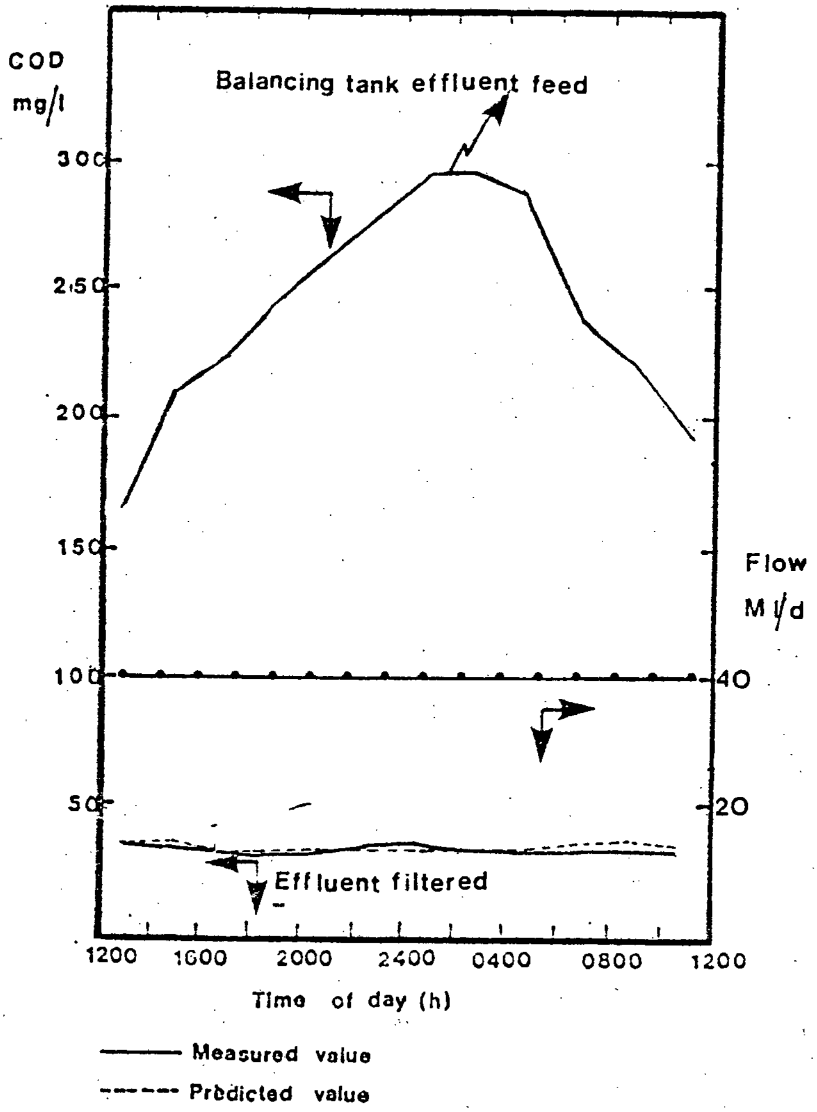


Fig. 5.3. Northern Works

Total COD concentration in the feed and filtered COD in the effluent together with predicted values. In addition the flow to the process during the test period is shown.

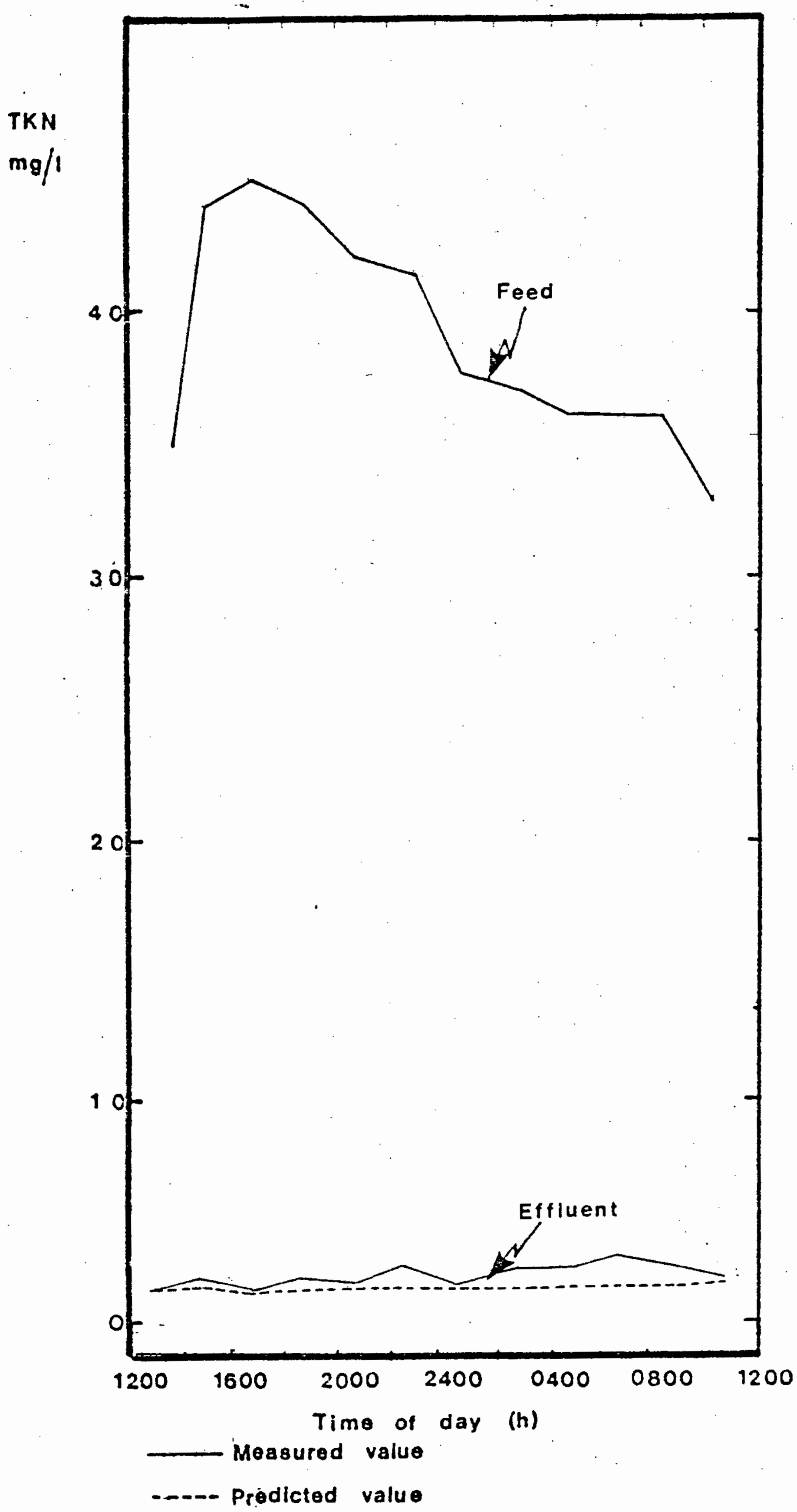


Fig. 5.4. Northern Works

TKN concentration in the feed and filtered TKN in the effluent together with predicted values for the effluent

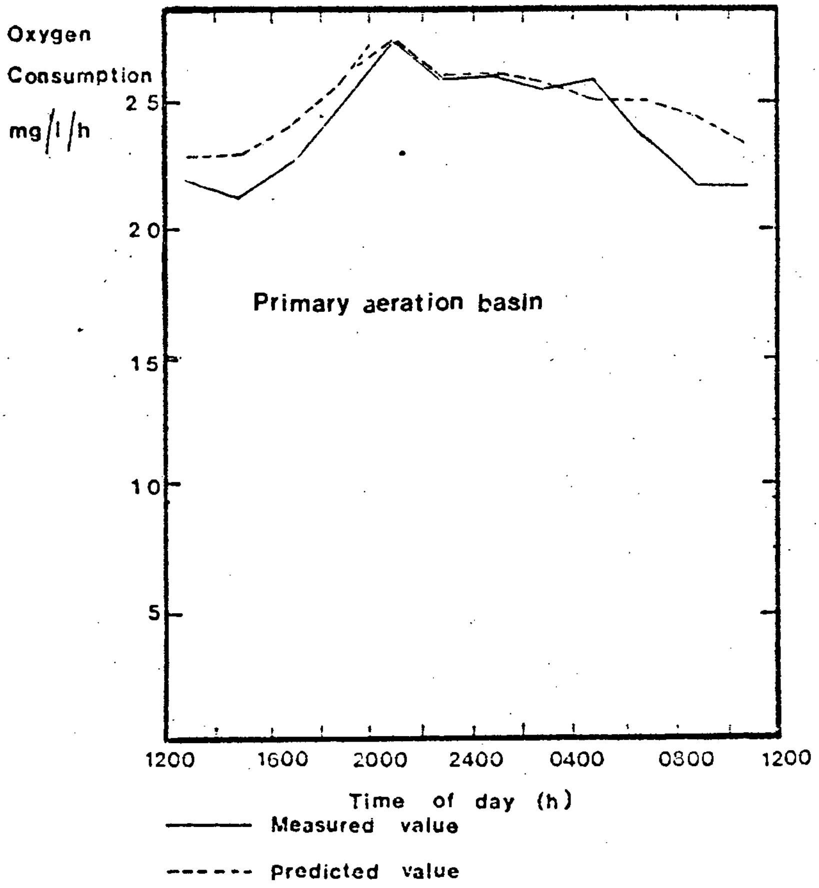


Fig. 5.5. Northern Works

Predicted and measured oxygen consumption rates in the primary aeration basin.

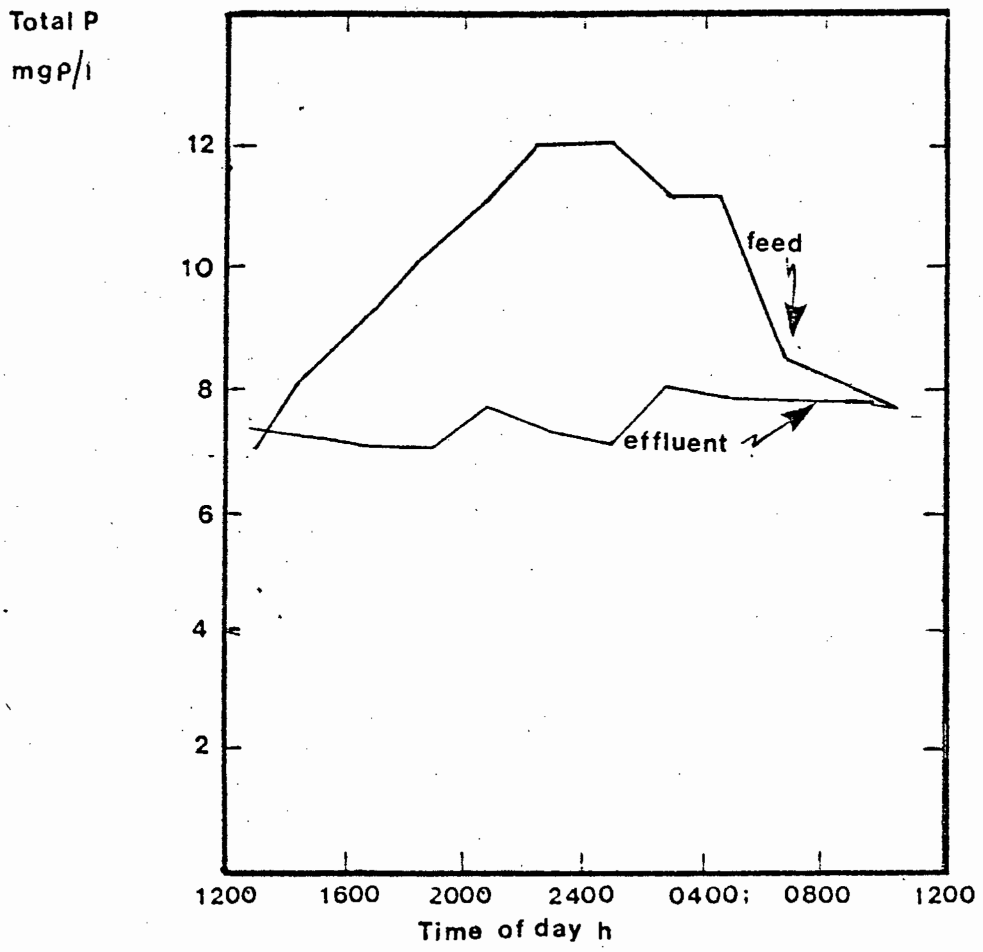


Fig. 5.6. Northern Works

Total phosphorus concentration in the feed and filtered effluent.

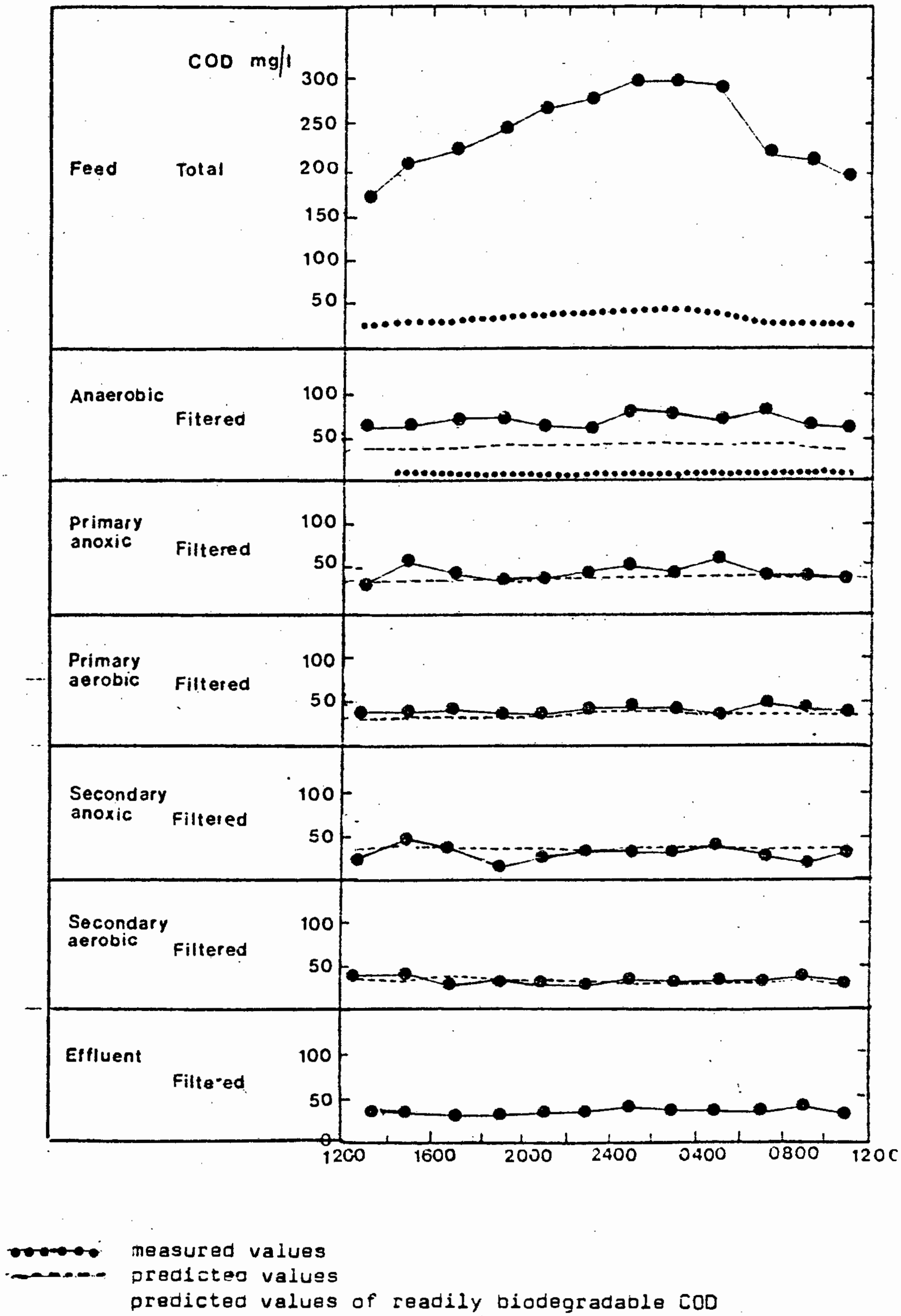
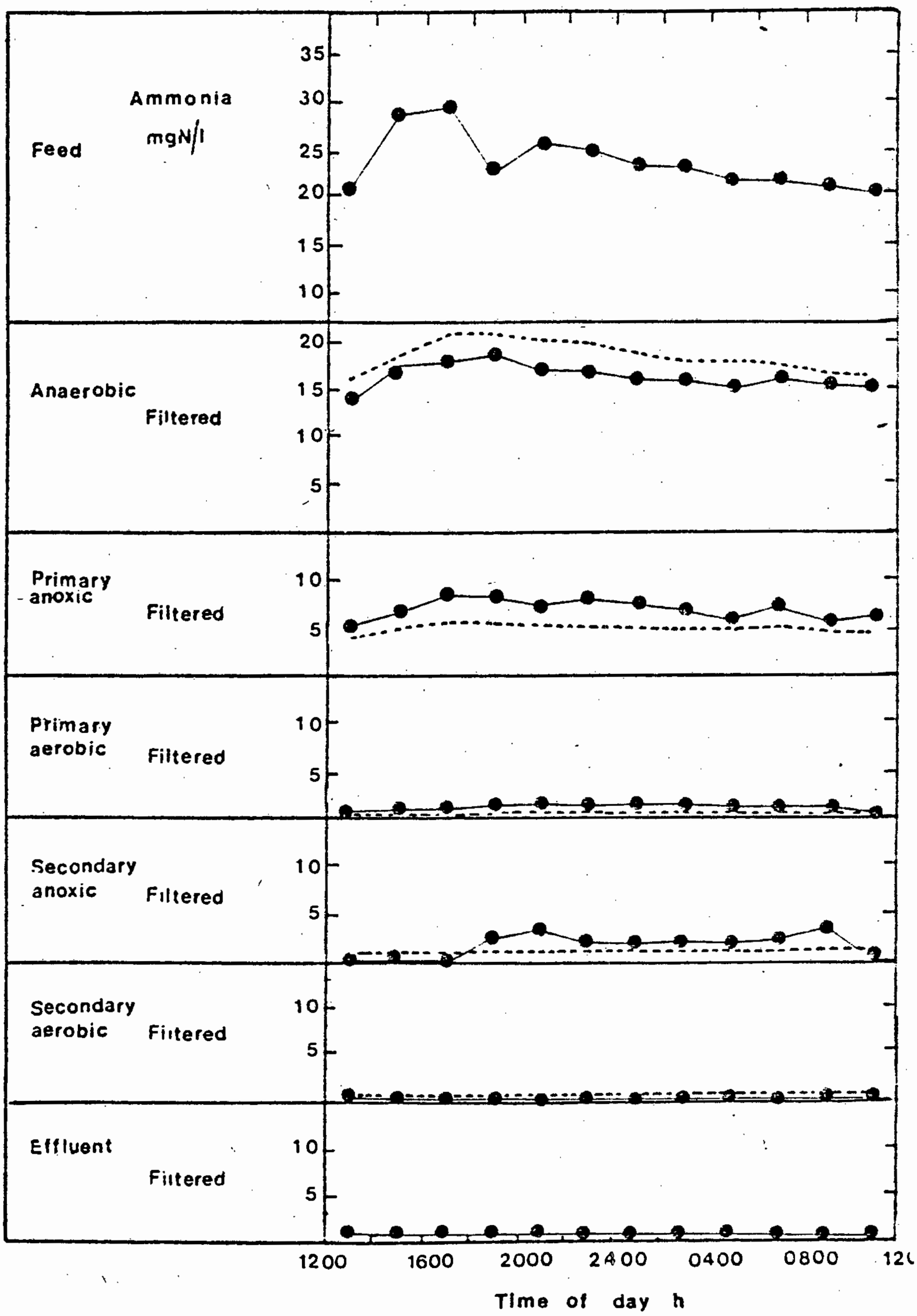


Fig. 5.7. Northern Works

Measured filtered COD and predicted soluble COD concentrations in each reactor of the system



●●●●● measured values
----- predicted values

Fig. 5.8. Northern Works

Measured filtered and predicted ammonia

concentrations in each reactor of the system

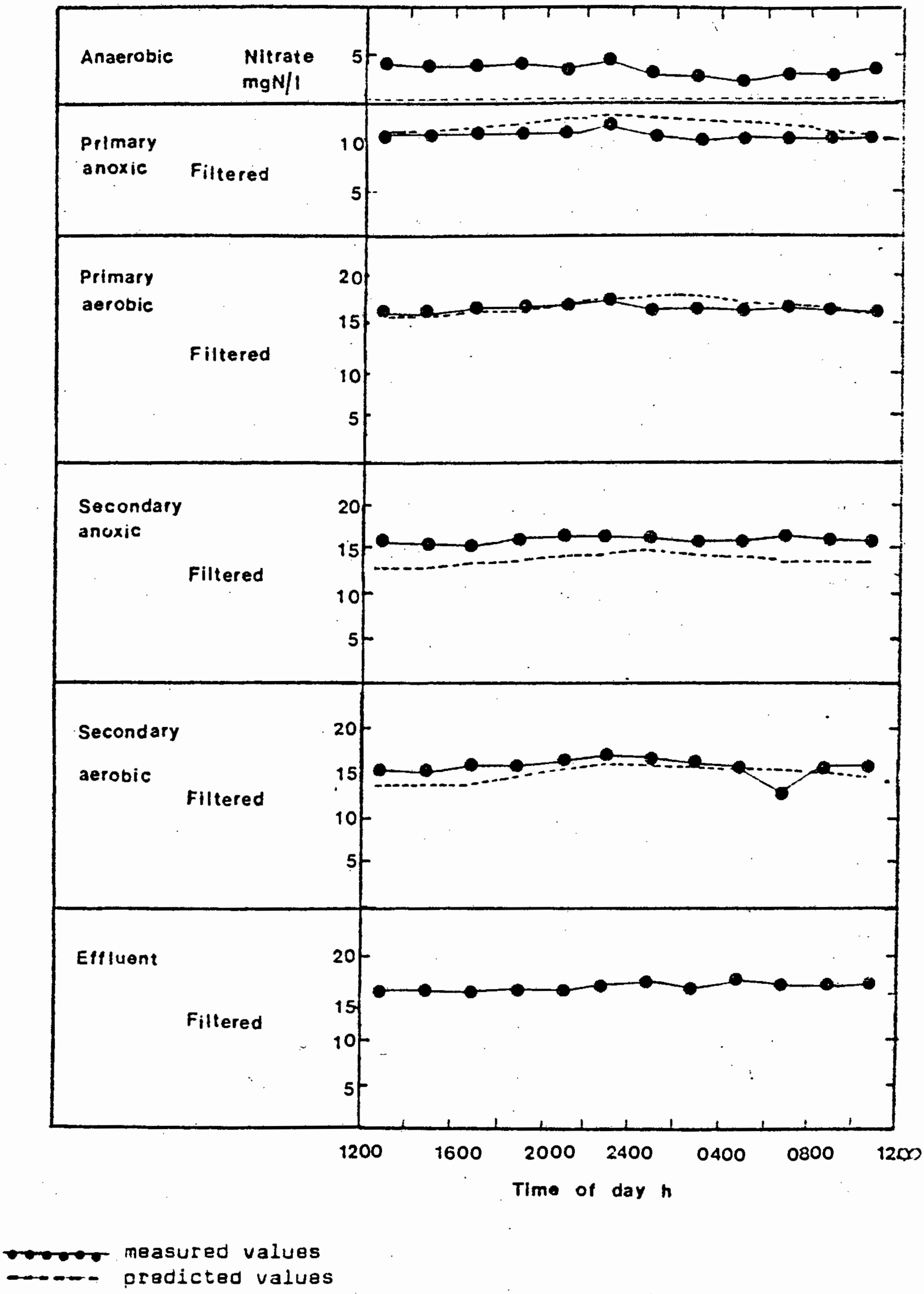


Fig. 5.9. Northern Works

Measured filtered and predicted nitrate concentrations in each reactor of the system

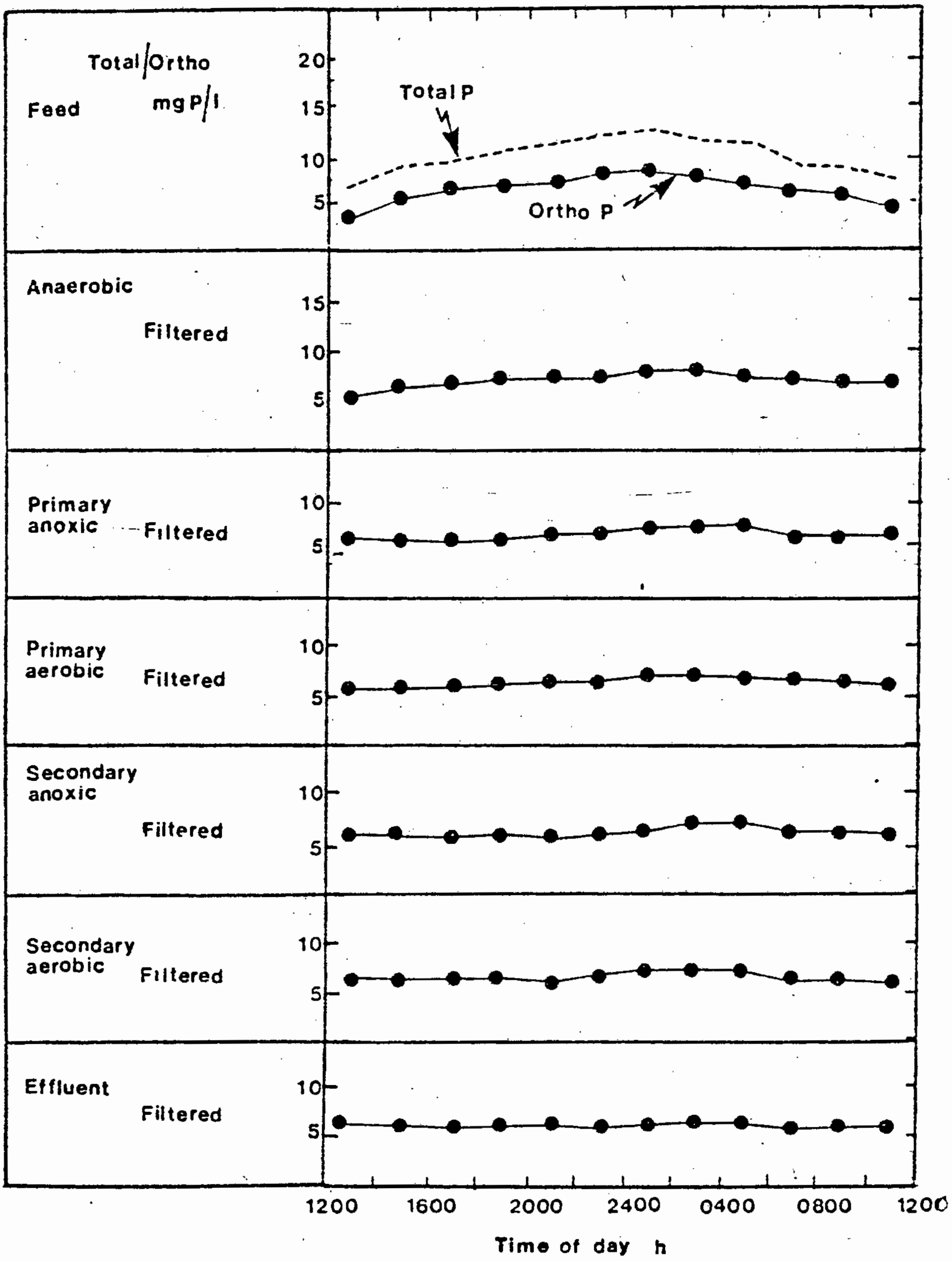


Fig. 5.10. Northern Works

Unfiltered total phosphorus concentration in the influent and filtered orthophosphorus concentration in each reactor of the system

## 4. EVALUATION OF EXPERIMENTAL PLANT RESPONSE

The reponse of particular interest is that concerned with nitrogen and phosphorus removal. Removal of nitrogen and phosphorus over the test period was relatively poor when one considers that the plant was designed specifically to accomplish the elimination of these two parameters. The total nitrogen concentration reduced from 39 mg N/l in the feed to 19,1 mg N/l in the effluent, a removal of only 19,9 mg N/l, and the total phosphorus from 9,7 mg P/l to 7,6 mg P/l i.e. 2,1 mg P/l only (see Table 5.3.)

The two most likely reasons for the poor nitrogen removal are ; the TKN/COD ratio, which was very high, equal to 0,16 (Table 5.3.) and, the fraction of easily biodegradable COD which was very low, equal to 0,16 mg COD/mg biodegradable COD (Table 5.6.) The TKN/COD ratio of the feed (equalised settled sewage) during the test period of 0,16 was considerably higher than that normally expected from a settled sewage i.e. 0,10 approximately. The nitrification capacity in consequence was high per unit COD input. In contrast, the easily biodegradable fraction was low (33 mg/l) and this fraction contributes significantly to the denitrification capacity of the system. The consequence of the combination of high nitrification and low denitrification capacities was the high nitrate in the effluent. Due to the high nitrate concentration in the underflow recycle (17,0 mg N/l) , there would have been no readily biodegradable COD ($S_{bsa}$) in the anaerobic reactor, because it would have the capacity to remove 8,6 . 17,0 . 0,4 = 58,5 mg COD/l influent readily biodegradable COD, and the concentration of readily biodegradable COD in the influent is only 33 mg/l (Table 5.3.) Consequently there would have been no $S_{bsa}$ in the anaerobic reactor and the phosphorus removal would be minimal. (Note when a primary anoxic reactor is present $\alpha$ (equation 15) has a minimal value of ± 0,06 , according to Siebritz, Ekama and Marais (1982) , as against 0,025 for a pure aerobic system.)

Evaluating the plant design, it is clear that with the influent as received, it is not possible, in terms of the excess phosphorus removal theory, for this plant to remove phosphorus by the excess phosphorus removal mechanisms under any circumstances, because the influent readily biodegradable COD concentration ($S_{bs}$) is too low ; even if complete denitrification was attainable the concentration of $S_{bsa}$ in the anaerobic reactor would be $S_{bs} / (1 + S) = 33 / (1 + 0,4) = 24$ mg $S_{bsa}$/l , which is less than the 25 mg/l necessary to initiate excess phosphorus removal. With nitrates present in the recycle the $S_{bsa}$ in the anaerobic reactor reduces to zero and no possibility exists for excess removal.

With regard to nitrogen removal, nitrate was present throughout the system (see Table 5.3.) . This implies that the anoxic reactors were loaded with nitrate above their denitrification capacities. Under these circumstances it has been shown by van Haandel <u>et al</u> (1981) that the maximum removal of nitrate will be achieved if the secondary anoxic zone is excluded from the system, and its volume combined with that of the primary anoxic reactor, because the latter is much more efficient than the former. This conclusion is verified by the experimental results : Doing a mass balance of nitrate over the primary and secondary anoxic zones respectively indicates the removal in the primary anoxic zone is 16,8 mg N/l and that in the primary anoxic zone is nil . Clearly from the above analysis the process design is not optimal for this influent .

- Although the design is not optimal for the influent received by the plant, it may be that for the assumed characteristics (Table 5.1.), the plant would have been adequate. To test this, the general model was used to simulate the plant performance taking as sewage inputs the COD and TKN assumed in the original design (Table 5.1.) (It is assumed that BOD : COD = 1 : 2 ) . The results of this simulation are summarised in Table 5.4.

Table 5.4.

The predicted performance of the Northern Works under design load conditions, treating settled sewage.

| | Feed | Anaerobic | Primary Anoxic | Primary Aerobic | Secondary Anoxic | Secondary Aerobic |
|---|---|---|---|---|---|---|
| COD | 530 | 148 | 83 | 90 | 60 | 80 |
| TKN as N | 30 | 21,3 | 8,3 | 3,6 | 6,4 | 3,6 |
| Ammonia as N | | 18,1 | 5,7 | 0,8 | 3,9 | 0,9 |
| Nitrate as N | | nil | 0,1 | 3,0 | nil | 2,0 |
| Oxygen consumption rate mg/l/h | | | | 44,2 | | |
| MLSS | | | | 4 570 | | |

Evidently the nitrate would have been near zero in the effluent and consequently the nitrate in the underflow recycle would have been minimal if the normal situation existed in that $S_{bsi} \gtrsim 0,24\ S_{ti}$ (where $S_{ti}$ = settled sewage), the $S_{bi}$ would have equaled 120, and and $S_{bsa} \approx 50$ . Under these conditions the removal potential of phosphorus would have been approximately 10 mg/l (in terms of the excess phosphorus removal theory) and an effluent phosphorus of near zero should have been achievable.

# 5. MODEL PREDICTIONS AND COMPARISON WITH PERFORMANCE DATA

## 5.1. Sewage characteristics

To test the validity of the general model to describe the behaviour of the Northern Works process, it was necessary first to estimate the characteristics of the influent waste water, in this case, the discharge from the balancing tank.

(i) Soluble unbiodegradable COD fraction , $f_{us}$

This fraction, as shown before, is estimated from the filtered effluent from a plant with a long sludge age. The average filtered effluent COD in this case was 38 mg/l ; the total influent COD concentration was 240 mg/l , hence

$f_{us}$ = 38 / 240 = 0,16 mg COD/mg COD

(ii) Unbiodegradable particulate COD fraction , $f_{up}$

For the reasons already discussed in the investigation of the Goudkoppie plant, the value of this constant was estimated by trial and error, curve fitting procedure to give

$f_{up}$ = 0,01 mg VSS/mg influent COD This value is considerably lower than that found for Goudkoppie ($f_{up}$ = 0,12) ; possible reasons for the difference are :

- The primary sedimentation tanks at Northern Works were particularly efficient, whereas those at Goudkoppie were not. The efficiency of the primary tanks can be seen from Table 5.5. , where various parameters are compared before and after the primary settling tank. (The values listed in Table 5.5. are the annual average values for the first year of operation). Principally for this reason the unbiodegradable particulate fraction entering the process would be smaller than the values found at Goudkoppie Works.

Table 5.5.

Average annual analysis of raw sewage and settled sewage

| Test | Raw Sewage | Settled Sewage |
|---|---|---|
| COD | 510 | 330 |
| TKN as N | 37 | 34 |
| Ammonia as N | 19 | 22 |
| Total phosphorus | 8,4 | 7,3 |
| Suspended solids | 190 | 66 |
| TKN/COD | 0,073 | 0,103 |

(iii) Fraction of TKN in the ammonia form, $f_{nu}$

This fraction was found by analytical measurement of the TKN and ammonia concentrations in the influent to the process and found to be approximately 24/39 = 0,62 mg N/mg N

(iv) Readily biodegradable COD fraction of the feed, $f_{bs}$

The procedure for measurement of this fraction in raw and settled sewage and balancing tank effluent is set out in Appendix A7 , and the values measured are listed in Table 5.6.

Table 5.6.

Estimation of the readily biodegradable fraction of raw sewage, settled sewage and balancing tank effluent over the test period

| | Symbol | Raw Sewage | Settled Sewage | Balancing tank effluent |
|---|---|---|---|---|
| Fraction of readily biodegradable COD COD (mg COD/mg biodegradable COD) | $f_{bs}$ | 0,15 | 0,23 | 0,15 |
| Concentration of readily biodegradable COD (mg/l) | $S_{bs}$ | 57 | 66 | 33 |

Note: In order to express as $S_{bs}$ the following constants were used ;

Raw sewage $f_{us} = 0,12$ $f_{up} = 0,09$

Settled sewage $f_{us} = 0,12$ $f_{up} = 0,01$

Balancing tank effluent $f_{us} = 0,12$ $f_{up} = 0,01$

The increase in the fraction of readily biodegradable COD in the primary sedimentation tank effluent, compared to that in raw sewage is to be expected since a considerable mass of particulate COD is removed in the primary sedimentation tanks, whereas virtually no readily biodegradable COD is removed. The decrease in readily biodegradable COD concentration across the balancing tank followed the same trend as across the tank at the Goudkoppie Works where the tank was operated not to flush the solids. At Northern Works, the balancing tanka are not emptied, so that sludge accumulates and fermentation will similarly reduce the readily biodegradable COD concentration. The following remarks are important re the fraction of readily biodegradable COD in the raw influent, the settled and balancing tank effluents :

* The readily biodegradable fraction of the raw influent was correspondingly lower than that at the Goudkoppie Works i.e. 0,15 (mg COD/mg biodegradable COD) as against 0,19 (mg COD/mg biodegradable COD) at Goudkoppie Works. One explanation for this decrease is that excess sludge generated at the Alexandra plant is returned to the sewer and forms part of the raw sewage being treated at Northern Works ; any active mass content in raw sewage will cause oxygen, entering the sewer, to be utilised immediately, by the active material, to metabolise the readily biodegradable COD at the rate 1 mg $O_2$ metabolises approximately 3 mg readily biodegradable COD .

- * The increase in the readily biodegradable fraction across the primary sedimentation tank again is to be expected because particulate COD is removed but not soluble readily biodegradable COD .

* At the Northern Works, over a day's operation, the balancing tanks did not empty sufficiently to flush the sludge accumulating on the sloping floor of the tank, so that very likely fermentation in these tanks caused the fraction of readily biodegradable COD to be reduced during the tank holdup. To check if settlement and COD reduction in fact did occur in the tank, the COD concentration at the inlet and outlet, and the flow, were monitored every two hours for one week. Using this data (see Appendix A10) , the loss in COD mass per day was calculated and is given in Table 5.7.

Table 5.7.

The mass of COD lost across the balancing tank

| | kg COD/d |
|---|---|
| Average mass of COD entering the balancing tank | 13 834 |
| Average mass of COD leaving balancing tank | 11 450 |
| Loss of COD | 2 384 |

From Table 5.7. a considerable loss (± 17 percent) occurred in the waste flow during its passage through the tank - a figure very similar to that obtained at Goudkoppie Works (± 20 percent). Doubtless, the accumulation of this COD on the floor caused the reduction in the readily biodegradable COD concentration.

A summary of the values of these and other constants necessary for simulation is set out in Tables 5.8.(a) and 5.8.(b).

Table 5.8.(a)

Kinetic parameters specific to the balancing tank effluent at the time of this investigation at Northern Works

| Name | Symbol | Units | Value |
|---|---|---|---|
| Fraction of soluble unbiodegradable COD | $f_{us}$ | mg COD/mg COD | 0,12 |
| Fraction of particulate unbiodegradable COD | $f_{up}$ | mg VSS/mg COD | 0,01 |
| Fraction of easily biodegradable COD | $f_{bs}$ | mg COD/mg biodegradable COD | 0,16 |
| Easily biodegradable COD concentration | $S_{bs}$ | mg COD/l | 32 |
| Fraction of TKN of feed in ammonia form | $f_{nu}$ | mg N/mg N | 0,62 |
| Specific growth rate for nitrifiers | $\mu_{mn}$ | $d^{-1}$ | 0,50 |

## Table 5.8.(b)

## Kinetic constants invariant for different waste flows

| Name | Symbol | Units | Value |
|---|---|---|---|
| Substrate adsorption rate coefficient | $K_{a20}$ | 1/mg VSS/d | 0,135 |
| Maximum specific growth rate coefficient for heterotrophic organisms utilising stored particulate substrate | $K_{mp20}$ | mg COD/mg VSS/d | 3,00 |
| Maximum specific growth rate coefficient for heterotrophic organisms utilising soluble substrate | $K_{ms20}$ | mg COD/mg VSS/d | 20,00 |
| Saturation coefficient for heterotrophic cell synthesis from stored particulate substrate | $K_{sp20}$ | mg COD/l | 0,04 |
| Saturation coefficient for heterotrophic cell synthesis from soluble substrate | $K_{ss20}$ | mg COD/l | 5,0 |
| Specific endogenous respiration rate for heterotrophic organisms | $b_{h20}$ | /d | 0,62 |
| Yield coefficient for heterotrophic organisms | $Y_{h20}$ | mg VSS/mg COD | 0,45 |
| Unbiodegradable fraction of the active organisms | $f$ | mg VSS/mg VSS | 0,08 |
| Nitrogen content of the sludge | $f_n$ | mg N/mg VSS | 0,10 |
| COD equivalent of volatile solids | $P$ | mg COD/mg VSS | 1,48 |
| Fraction of nitrogen released through endogenous respiration in the organic form | $f_{oe}$ | - | 1,00 |
| Fraction of nitrogen required for cell synthesis in the organic nitrogen form | $f_{os}$ | mg N/mg VSS | 0,00 |
| Maximum fraction of stored solids with respect to active mass | $f_{ma}$ | mg VSS/mg VSS | 1,00 |
| Organic nitrogen to ammonia conversion rate coefficient | $K_{r21}$ | /mg VSS/d | 0,015 |
| General parameter for pH dependency coefficients<br>adsorption on heterotrophic organisms | $h_a$ | | 1,200 |
| synthesis by heterotrophic organisms | $h_s$ | | 1,100 |
| endogenous respiration by heterotrophic organisms | $h_e$ | | 1,029 |
| Saturation coefficient for *Nitrosomonas* | $K_{n20}$ | mg N/l | 1,00 |
| Specific endogenous rate for nitrifiers | $b_{n20}$ | /d | 0,04 |
| Yield coefficient for nitrifiers | $Y_{n20}$ | mg VASS/mg N | 0,10 |
| General parameter for pH dependency coefficients<br>synthesis by *Nitrosomonas* | $_{ns}$ | | 1,123 |
| endogenous respiration by *Nitrosomonas* | $_{ne}$ | | 1,029 |

## 5.2. Simulated results

The simulated results of the Northern Works were obtained using the constants as listed in Tables 5.8.(a) and 5.8.(b) and the input data :- feed flow rate, COD and TKN concentrations as listed in Table 5.9.

Table 5.9.

Input flow and COD and TKN concentrations used in model predictions

| Time | Flow Ml/d | COD mg/l | TKN mg N/l | Time | Flow Ml/d | COD mg/l | TKN mg N/l |
|---|---|---|---|---|---|---|---|
| 0700 | 40,0 | 238 | 36 | 2000 | 40,0 | 252 | 43 |
| 0800 | 40,0 | 230 | 36 | 2100 | 40,0 | 260 | 42 |
| 0900 | 40,0 | 220 | 36 | 2200 | 40,0 | 265 | 41 |
| 1000 | 40,0 | 208 | 34 | 2300 | 40,0 | 270 | 41 |
| 1100 | 40,0 | 193 | 33 | 2400 | 40,0 | 280 | 40 |
| 1200 | 40,0 | 183 | 34 | 0100 | 40,0 | 293 | 48 |
| 1300 | 40,0 | 170 | 35 | 0200 | 40,0 | 293 | 38 |
| 1400 | 40,0 | 190 | 40 | 0300 | 40,0 | 293 | 37 |
| 1500 | 40,0 | 210 | 44 | 0400 | 40,0 | 287 | 36 |
| 1600 | 40,0 | 217 | 44 | 0500 | 40,0 | 283 | 35 |
| 1700 | 40,0 | 223 | 45 | 0600 | 40,0 | 260 | 36 |
| 1800 | 40,0 | 235 | 45 | 0700 | 40,0 | 238 | 36 |
| 1900 | 40,0 | 245 | 44 | | | | |

The simulated results are listed in tabular form in Tables 5.10. , 5.11. and 5.12. , and are shown plotted in Figs 5.3. to 5.5. and 5.7. to 5.9;

## Table 5.10.

Comparison of predicted and experimental COD concentrations in each zone of the Northern Works Plant

| Time of Day | Feed | | POSITION WITHIN PLANT | | | | | | | | | | Effluent | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Anaerobic | | Primary Anoxic | | Primary Aeration | | Secondary Anoxic | | Secondary Aeration | | | |
| h | Total | Soluble | Soluble | | Soluble | | Soluble | | Soluble | | Soluble | | Total | Soluble |
| | | | E | P | E | P | E | P | E | P | E | P | | |
| 1300 | 170 | 110 | 63 | 32 | 38 | 35 | 44 | 36 | 32 | 37 | 41 | 38 | 44 | 38 |
| 1500 | 210 | 130 | 65 | 34 | 52 | 34 | 40 | 35 | 41 | 36 | 43 | 37 | 45 | 38 |
| 1700 | 220 | 150 | 70 | 36 | 42 | 34 | 41 | 34 | 35 | 35 | 33 | 36 | 38 | 35 |
| 1900 | 240 | 160 | 77 | 38 | 39 | 35 | 38 | 34 | 29 | 35 | 36 | 35 | 41 | 34 |
| 2100 | 260 | 170 | 71 | 40 | 40 | 35 | 40 | 35 | 33 | 35 | 34 | 35 | 49 | 34 |
| 2300 | 270 | 180 | 69 | 42 | 48 | 36 | 45 | 35 | 34 | 35 | 35 | 35 | 45 | 39 |
| 0100 | 290 | 180 | 83 | 44 | 51 | 37 | 44 | 36 | 35 | 35 | 39 | 35 | 49 | 43 |
| 0300 | 290 | 200 | 81 | 46 | 47 | 36 | 43 | 37 | 36 | 36 | 38 | 36 | 48 | 35 |
| 0500 | 280 | 180 | 76 | 45 | 54 | 39 | 38 | 38 | 39 | 37 | 38 | 37 | 44 | 36 |
| 0700 | 240 | 170 | 79 | 41 | 44 | 39 | 48 | 38 | 31 | 38 | 38 | 37 | 50 | 36 |
| 0900 | 220 | 160 | 69 | 38 | 44 | 38 | 45 | 38 | 29 | 38 | 40 | 38 | 57 | 39 |
| 1100 | 190 | 150 | 63 | 35 | 41 | 37 | 43 | 38 | 31 | 38 | 39 | 38 | 45 | 36 |
| Ave. | 240 | 160 | 72 | 39 | 45 | 36 | 42 | 36 | 34 | 36 | 38 | 36 | 46 | 37 |

Note: 1. All results expressed as mg/l

2. E denotes experimental value

3. P denotes predicted value

4. Reactor and effluent samples were filtered through Whatman 542 filter paper

## Table 5.11.

Comparison of predicted and experimental ammonia concentrations in each zone of the Northern Works Plant

| Time of Day | Feed | | POSITION WITHIN PLANT | | | | | | | | | | Effluent | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Anaerobic | | Primary Anoxic | | Primary Aeration | | Secondary Anoxic | | Secondary Aeration | | | |
| h | TKN | $NH_3$ | Soluble | | Soluble | | Soluble | | Soluble | | Soluble | | TKN | $NH_3$ |
| | | | E | P | E | P | E | P | E | P | E | P | | |
| 1300 | 35 | 21 | 14 | 16 | 5,9 | 4,8 | 0,6 | 0,3 | 0,0 | 1,7 | 0,0 | 0,2 | 2,0 | 0,0 |
| 1500 | 44 | 28 | 18 | 19 | 6,6 | 5,4 | 0,7 | 0,4 | 0,0 | 1,8 | 0,0 | 0,2 | 2,2 | 0,0 |
| 1700 | 45 | 29 | 19 | 22 | 7,7 | 6,1 | 0,7 | 0,5 | 0,0 | 1,9 | 0,0 | 0,2 | 2,1 | 0,0 |
| 1900 | 44 | 23 | 19 | 21 | 7,6 | 6,3 | 0,8 | 0,5 | 0,6 | 1,9 | 0,0 | 0,2 | 2,1 | 0,0 |
| 2100 | 42 | 26 | 17 | 20 | 7,0 | 6,1 | 1,0 | 0,4 | 0,9 | 1,9 | 0,0 | 0,2 | 1,9 | 0,0 |
| 2300 | 41 | 25 | 17 | 20 | 7,6 | 5,4 | 0,9 | 0,4 | 0,6 | 1,9 | 0,0 | 0,2 | 2,2 | 0,0 |
| 0100 | 38 | 23 | 16 | 19 | 7,4 | 5,7 | 1,4 | 0,4 | 1,0 | 1,9 | 0,1 | 0,2 | 1,7 | 0,0 |
| 0300 | 37 | 23 | 16 | 18 | 6,9 | 5,3 | 1,1 | 0,4 | 0,6 | 1,8 | 0,0 | 0,2 | 2,3 | 0,1 |
| 0500 | 36 | 22 | 15 | 18 | 6,5 | 5,2 | 0,8 | 0,3 | 0,5 | 1,8 | 0,0 | 0,2 | 2,2 | 0,2 |
| 0700 | 36 | 22 | 16 | 17 | 6,6 | 5,2 | 0,4 | 0,3 | 0,6 | 1,8 | 0,1 | 0,2 | 2,6 | 0,0 |
| 0900 | 36 | 21 | 15 | 16 | 6,4 | 5,0 | 0,5 | 0,3 | 0,9 | 1,8 | 0,0 | 0,2 | 2,5 | 0,0 |
| 1100 | 33 | 20 | 15 | 16 | 6,0 | 4,8 | 0,2 | 0,3 | 0,0 | 1,8 | 0,1 | 0,2 | 2,3 | 0,0 |
| Ave. | 39 | 24 | 16 | 18 | 6,9 | 5,5 | 0,8 | 0,4 | 0,5 | 1,8 | 0,0 | 0,2 | 2,1 | 0,0 |

Note:
1. All results expressed as mg N/l
2. E denotes experimental value
3. P denotes predicted value
4. Reactor and effluent samples were filtered through Whatman 542 filter paper

Table 5.12.

Comparison of predicted and experimental nitrate concentrations in each zone of the Northern Works Plant

| Time of Day | Feed | POSITION WITHIN PLANT | | | | | | | | | | Effluent |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Anaerobic | | Primary Anoxic | | Primary Aeration | | Secondary Anoxic | | Secondary Aeration | | |
| h | | Soluble | | Soluble | | Soluble | | Soluble | | Soluble | | |
| | | E | P | E | P | E | P | E | P | E | P | |
| 1300 | 0 | 4,4 | 0,4 | 10 | 10,6 | 16 | 15,5 | 16 | 12,8 | 16 | 14,7 | 15 |
| 1500 | 0 | 4,4 | 0,3 | 10 | 10,7 | 16 | 15,7 | 16 | 12,7 | 15 | 14,5 | 16 |
| 1700 | 0 | 4,6 | 0,1 | 11 | 11,1 | 17 | 16,3 | 16 | 13,1 | 15 | 14,7 | 16 |
| 1900 | 0 | 4,7 | 0,1 | 11 | 11,6 | 17 | 17,2 | 16, | 13,7 | 16 | 15,2 | 16 |
| 2100 | 0 | 4,2 | 0,1 | 10 | 12,0 | 17 | 17,8 | 16 | 14,3 | 16 | 15,9 | 15 |
| 2300 | 0 | 5,0 | 0,1 | 11 | 12,2 | 14 | 17,9 | 16 | 14,7 | 17 | 16,4 | 17 |
| 0100 | 0 | 4,0 | 0,1 | 10 | 12,2 | 17 | 17,8 | 15 | 14,9 | 17 | 16,7 | 17 |
| 0300 | 0 | 3,9 | 0,1 | 9,9 | 11,9 | 16 | 17,5 | 15 | 14,7 | 17 | 16,6 | 17 |
| 0500 | 0 | 3,6 | 0,1 | 10 | 11,5 | 16 | 16,9 | 16 | 14,3 | 16 | 16,3 | 17 |
| 0700 | 0 | 4,4 | 0,1 | 10 | 11,2 | 17 | 16,4 | 17 | 13,8 | 18 | 15,8 | 17 |
| 0900 | 0 | 4,0 | 0,1 | 10 | 10,9 | 17 | 16,0 | 16 | 13,4 | 17 | 15,3 | 16 |
| 1100 | 0 | 4,3 | 0,2 | 11 | 10,7 | 16 | 15,7 | 16 | 13,8 | 16 | 14,9 | 16 |
| Ave. | 0 | 4,3 | 0,1 | 10 | 11,4 | 16 | 15,7 | 16 | 13,9 | 16 | 15,6 | 16 |

Note:
1. All results expressed as mg N/l
2. E denotes experimental value
3. P denotes predicted value
4. Reactor and effluent samples were filtered through Whatman 542 filter paper

# 6. DISCUSSION

## 6.1. Model predictions

The model predictions are analysed under two headings :

(i) Average daily mass response

(ii) Cyclic daily mass response

### 6.1.1. Average daily response

The average daily observed and predicted responses of the plant are shown in Table 5.13. Comparing these it can be seen that the predictive ability of the model was excellent.

Table 5.13.

Northern Works : Comparison of average predicted effluent and other results with those observed

| Test | | Average Model prediction | Average Measured value |
|---|---|---|---|
| COD | (mg O/l) | 36 | 37 |
| TKN | (mg N/l) | 3,3 | 2,1 |
| Ammonia | (mg N/l) | 0,2 | 0,0 |
| Nitrate | (mg N/l) | 15,6 | 16,4 |
| Oxygen consumption main basin | (mg/l/h) | 25,3 | 24,1 |
| MLSS | (mg/l) | 1 542 | 1 440 |

### 6.1.2. Cyclic response

Inspection of Figs 5.3. to 5.5. and 5.7. to 5.9. shows excellent agreement between the predicted and observed response of the most significant parameters thereby indicating that the model predicted the dynamic behaviour of the plant exceedingly well. The differences that are present are so slight that it is unlikely that one could ascribe a specific reason for those differences. Compared to the predictions of the Goudkoppie plant, those at Northern Works were closer to the observed data.

## 7. OPERATIONAL CHANGES TO ACHIEVE HIGHER PHOSPHORUS AND NITROGEN REMOVAL

At the Goudkoppie plant the existing process configuration was analysed for the settled flow bypassing the balancing tank, and it was shown that phosphorus removal could be achieved provided the denitrification capability was increased by creating an anoxic zone in the aerobic reactor (by switching off appropriately selected aerators). Efficient nitrification was insured by switching in extra aerators in the remaining aerobic zone. It is very likely that a similar operational modification at the Northern Works may also allow phosphorus removal. Although success is not as likely because the fraction of readily biodegradable COD in settled sewage at Northern Works is less than that at Goudkoppie Works. A more fruitful possibility for the Northern Works would be to model the process assuming that raw sewage could be added directly to the bioreactors. This is a feasible proposal for, at Northern Works, in contrast to the situation at Goudkoppie , the primary sludge is not totally committed to gas production. Both at Goudkoppie and Northern Works phosphorus removal to 1 mg P/l in the effluent is mandatory so that the proposed change in the influent feed composition to the Northern Works process may be an acceptable means of achieving this objective.

Using the model to predict effluent quality when raw sewage is used as the feed to the process, the kinetic constants used were the same as those given in Table 5.8.(b). The operational parameters used were the same as those given in Table 5.8.(a) with the following exceptions :

(i) Fraction of readily biodegradable COD , $f_{bs}$ was estimated using the method described in Appendix A7 and found to be 0,15 mg COD/mg biodegradable COD

(ii) Fraction of particulate unbiodegradable COD, $f_{up}$; the same value was used as that determined by Ekama and Marais (1978) for raw sewage i.e. 0,09 mg VSS/mg COD .

(iii) Fraction of soluble unbiodegradable COD, $f_{us}$ ; using the annual averages the COD concentration of the feed and effluent were found to be 570 mg/l and 68 mg/l respectively ; hence the fraction could be estimated by assuming that all the effluent COD was soluble and unbiodegradable i.e. 63/570 = 0,12 mg COD/mg COD .

A summary of the kinetic parameters specific to the raw sewage used in this investigation is given in Table 5.14.

The daily input data for raw sewage flow and load is given in Table 5.15.

The average daily model predictions using the above data are given in Table 5.16. and the daily cyclic variation of biodegradable COD concentration, ammonia and nitrate are given in Figs. 5.11. , 5.12. and 5.13. respectively.

## Table 5.14.

Kinetic parameters specific to raw sewage at the time of this investigation at Northern Works

| Name | Symbol | Units | Value |
|---|---|---|---|
| Fraction of soluble unbiodegradable COD | $f_{us}$ | mg COD/mg COD | 0,12 |
| Fraction of particulate unbiodegradable COD | $f_{up}$ | mg VSS/mg COD | 0,09 |
| Fraction of easily biodegradable COD | $f_{bs}$ | mg COD/mg biodegradable COD | 0,15 |
| Easily biodegradable COD concentration | $S_{bs}$ | mg COD/l | 64 |
| Fraction of TKN of feed in ammonia form | $f_{nu}$ | mg N/mg N | 0,65 |
| Specific growth rate for nitrifiers | $\mu_{mn}$ | $d^{-1}$ | 0,50 |

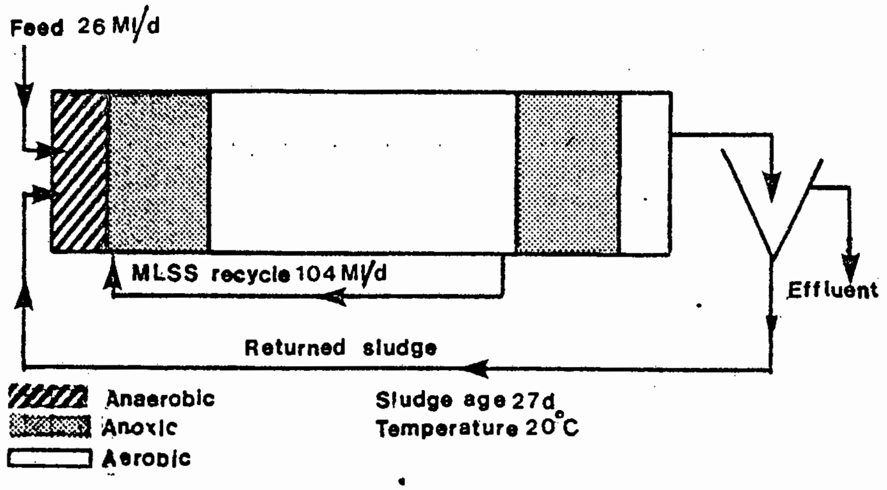
## Table 5.15.

Input flow and COD and TKN concentrations used in the model prediction when raw sewage was fed to the process

| Time | Flow Ml/d | COD mg/l | TKN mg N/l | Time | Flow Ml/d | COD mg/l | TKN mg N/l |
|---|---|---|---|---|---|---|---|
| 0700 | 25,6 | 520 | 31 | 2000 | 26,4 | 680 | 46 |
| 0800 | 24,4 | 370 | 31 | 2100 | 27,0 | 460 | 45 |
| 0900 | 24,4 | 375 | 31 | 2200 | 27,6 | 640 | 44 |
| 1000 | 24,4 | 380 | 30 | 2300 | 27,0 | 635 | 42 |
| 1100 | 25,0 | 475 | 51 | 2400 | 26,4 | 630 | 39 |
| 1200 | 25,6 | 570 | 72 | 0100 | 26,8 | 645 | 42 |
| 1300 | 25,6 | 595 | 62 | 0200 | 27,2 | 650 | 43 |
| 1400 | 25,6 | 620 | 53 | 0300 | 27,4 | 675 | 41 |
| 1500 | 25,0 | 650 | 54 | 0400 | 27,6 | 600 | 41 |
| 1600 | 26,0 | 680 | 56 | 0500 | 27,2 | 535 | 37 |
| 1700 | 26,2 | 670 | 51 | 0600 | 26,8 | 470 | 32 |
| 1800 | 26,4 | 660 | 46 | 0700 | 25,6 | 520 | 31 |
| 1900 | 26,4 | 620 | 46 | | | | |

Table 5.16.

The average predicted performance of the Northern Works when both the balancing tank and primary sedimentation tanks are bypassed



| | Feed | Anaerobic | Primary Anoxic | Primary Aerobic | Secondary Anoxic | Secondary Aerobic | Effluent |
|---|---|---|---|---|---|---|---|
| Total COD | 575 | | | | | | |
| Soluble COD | 429 | 110 | 70 | 69 | 69 | 69 | |
| $S_{bs}$ | 64 | 41,6 | 0,9 | 0 | 0 | 0 | |
| TKN as N | 44 | 24,8 | 8,5 | 3,5 | 5,4 | 3,2 | |
| Ammonia as N | 29 | 22 | 5,9 | 0,3 | 2,8 | 0,2 | |
| Nitrate as N | 0 | 0 | 0 | 5,6 | 0 | 2,5 | |
| Total P | | | | | | | |
| Soluble P | | | | | | | |
| Suspended solids | | | | 3 690 | | | |
| Oxygen consumption mg/l/h | | | | 25,1 | | | |

Unless otherwise stated all results expressed as mg/l

Note : 1. Unless otherwise stated all results expressed as mg/l

2. $S_{bs}$ - readily biodegradable COD concentration mg COD/l

3. The underflow sludge return ratio is 0,4:1

4. The MLSS recycle ratio is 4,0:1

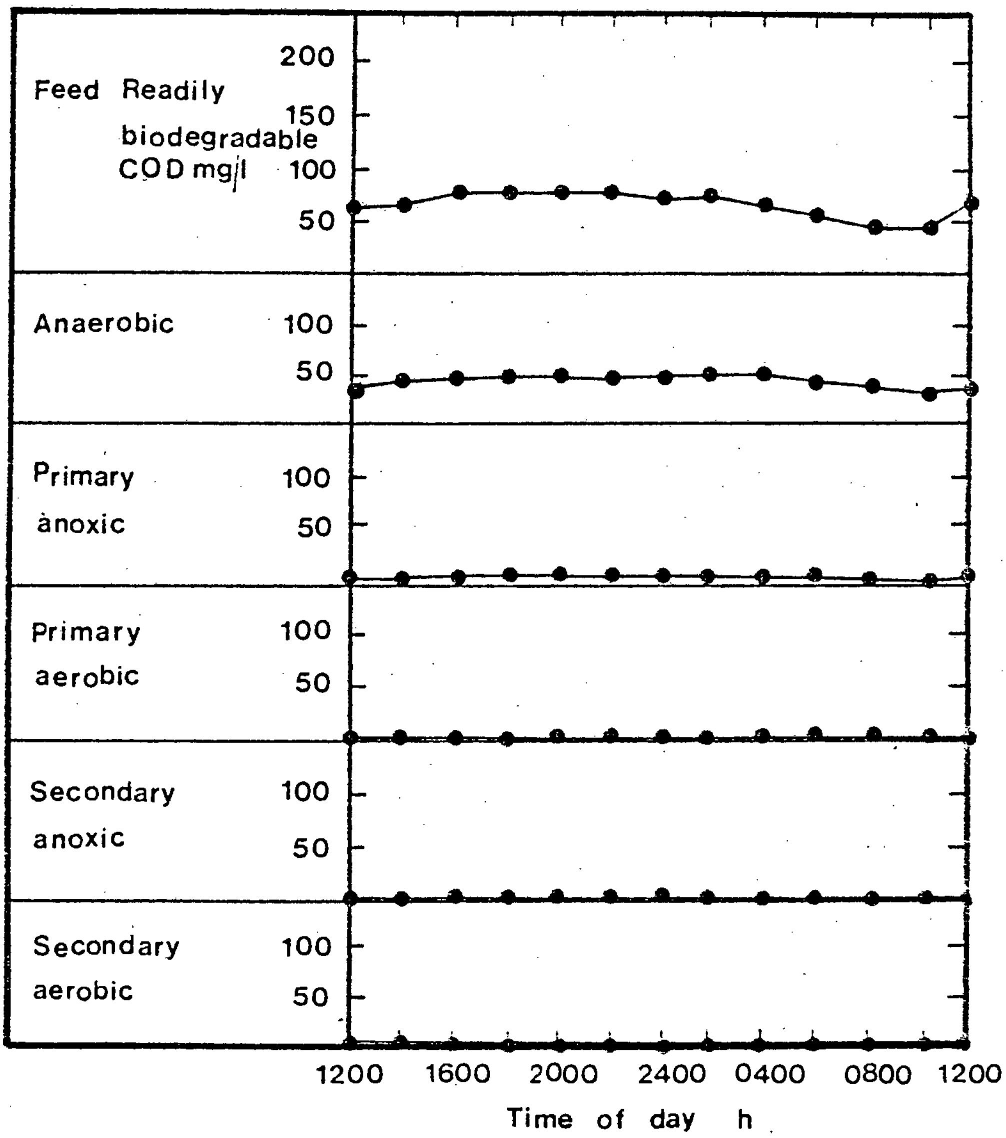


Fig. 5.11. Northern Works

Predicted readily biodegradable COD concentration when both the balancing tank and primary sedimentation tanks were bypassed

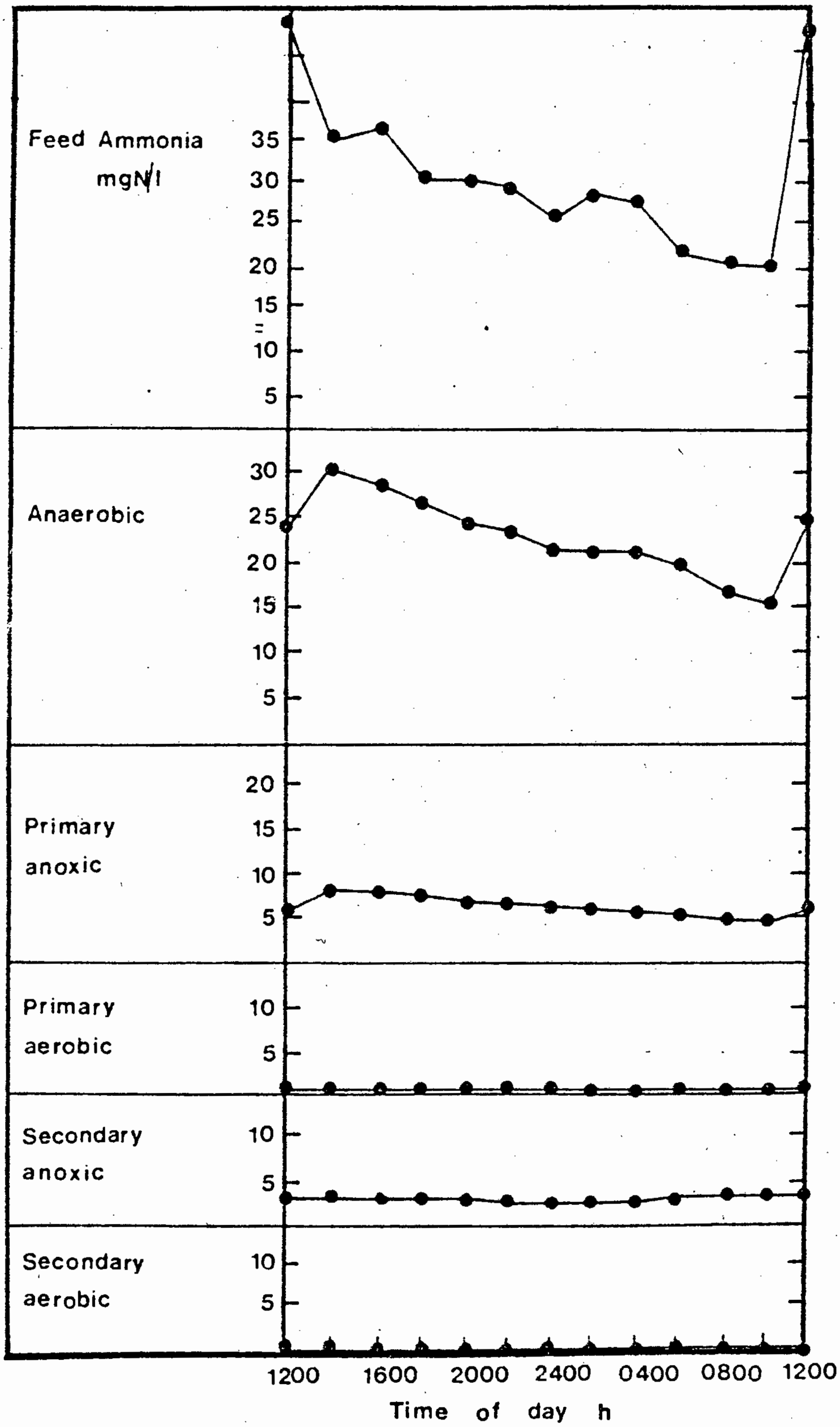


Fig. 5.12. Northern Works

Predicted ammonia concentration when both the balancing tank and primary sedimentation tanks were bypassed

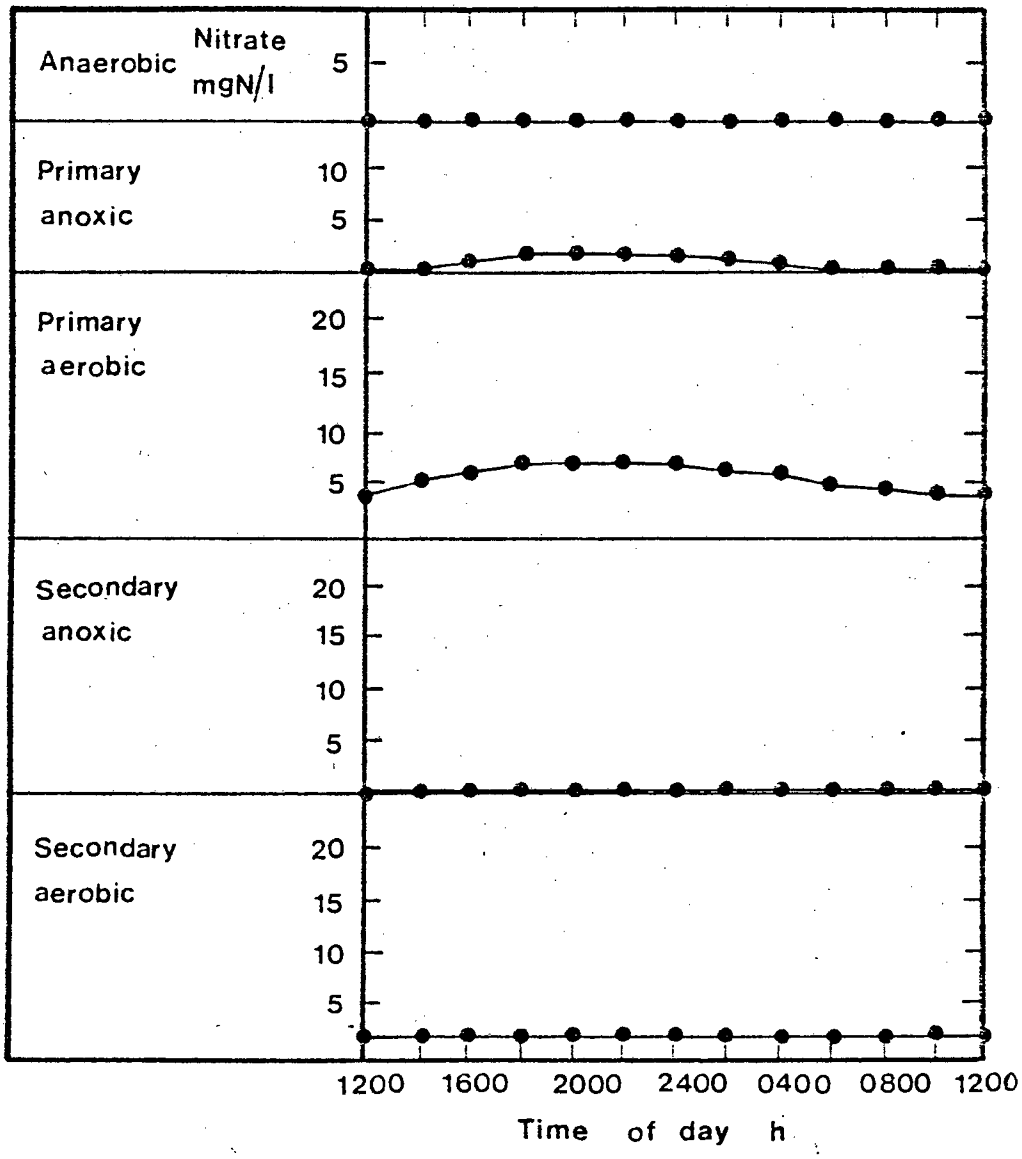


Fig. 5.13. Northern Works

Predicted nitrate concentration when both the balancing tank and primary sedimentation tanks were bypassed

From the average predicted performance (Table 5.16.) it is clear that the Northern Works process as designed would not fulfil its design objectives completely. The effluent total nitrogen would be reduced from an influent concentration of 44 mg N/l to 5,7 mg N/l, the ammonia and nitrate concentrations being 0,2 and 2,5 mg N/l respectively. Ekama, Siebritz and Marais (1982) have shown that if the TKN/COD ratio of raw sewage is not greater than 0,07 - 0,08 , the five stage Phoredox process can be designed to bring sbout virtually complete nitrification for temperatures greater than 14 °C . The simulated data for this plant verifies this conclusion so that, if raw sewage is treated, the five stage process is indicated. When one compares the performance of this plant treating raw sewage with that treating settled sewage after passing through the balancing tank, it highlights the conclusion of Ekama <u>et al</u> (1982) that the process configuration for optimal treatment of a specified influent is governed by the influent sewage characteristics.

The phosphorus removal capacity of this plant can be readily assessed. The concentration of readily biodegradable COD in the anaerobic reactor is 41,6 mg/l . Applying equations (13),(14) and (15) the concentration of phosphorus which can be removed is estimated to be 6,2 mg/l . The measured influent phosphorus concentration is 9,7 mg P/l , which is artificially high due to the recycle of digester liquors from digesters fed with primary and waste activated sludge. From the above, the process should remove 6,2 mg P/l , hence the effluent quality should be approximately 3,2 mg P/l . If the sludge age were reduced from 27 d to 15 d and equations (13) to (15) again applied, the concentration of phosphorus which could then be removed is estimated to be 8,1 mg P/l ; which means that the estimated effluent phosphorus concentration would be approximately 9,7 - 8,1 = 1,6 mg P/l .

Since the plant was designed assuming a feed COD of 600 mg/l (see Table 5.1.) and a flow of 50 Ml/d, the process should have sufficient aeration capacity available to oxidise both the COD and TKN in the raw sewage. A simulated raw sewage feed to the biological reactor can be achieved by re-blending primary clarifier sludge with the effluent from these same clarifiers. In the original design of this plant provision was made to accomplish this. Hence, should this scheme be acceptable, no additional cost need be incurred in modifications to the plant. However, the additional load entering the process would increase the power consumption sharply.

# CHAPTER SIX

## CONCLUSIONS

The objectives of this dissertation were :

(i) to investigate whether the operation of an existing large scale activated sludge plant could be modified to induce both nitrogen and excess phosphorus removal. The Johannesburg Alexandra Plant was selected for this purpose.

(ii) to evaluate the applicability of the nitrification / denitrification bi-substrate death-regeneration activated sludge model of Dold et al (1980) and van Haandel et al (1980) at full scale. For this objective the Johannesburg Goudkoppie and Northern Works were selected for evaluation.

Conclusions drawn from these investigations are summarised as follows:

### 6.1. Enhanced nutrient removed from conventional activated sludge plants

Experiments carried out at the Alexandra Works showed that it was possible to create an anoxic zone by switching off selected surface aerators at the influent end of the aeration basin. Adjacent operating aerators served to recycle some of the nitrates produced lower downstream in the first aeration basin to the anoxic area. Sludge deposition in the unaerated area was prevented by periodically operating the decommissioned aerators to resuspend the solids.

This simple modification to normal operating procedures proved to be remarkably effective. A necessary prerequisite for success in this regard was that the remaining operational aerators in in the primary aerobic basin were capable of sustaining high dissolved oxygen levels to ensure nitrification.

- Enhanced phosphorus removal proved to be possible when additional aerators were switched off at the head of the aeration basin, making certain areas of the non-aerated zone completely anaerobic. Sustained successful operation proved to be difficult to maintain and it was dependent on having a sufficient degree of anaerobiosis to induce phosphorus release in the non-aerated area.

Experience gained during these experiments showed that the introduction of non-aerated zones into conventional activated sludge systems may give rise to instability of the mixed liquor if the overall dissolved oxygen level fell below 1,5 to 2,0 mg/l . Copious growths of the floating filamentous organism Nocardia also gave warning of a possible shift in bacterial population dynamics.

## 6.2. Applicability of model predictions to full scale plant performance

The data presented in this dissertation has shown that the model generated by the University of Cape Town Group could accurately predict the performance of the Johannesburg Goudkoppie Plant. Computed and actual mass balances of selected key parameters showed a very close degree of similarity. This successful practical application of the model promoted confidence in its use, and it was subsequently used to examine the reasons for the short fall in phosphorus removal at the Johannesburg Northern Works, and the likely performance of the city's new Bushkoppie plant.

During the day to day monitoring of the Johannesburg activated sludge plants performance was continually compared with certain key criteria such as TKN/COD ratio , amount of readily biodegradable substrate in the influent etc. , and the limits proposed by the UCT group to ensure good plant performance were generally confirmed.

With this reassuring background it became possible to make predictions why many of the nutrient removing activated sludge plants in South Africa as reported by Paepka (1982) were not performing as well as expected. Failure may be attributed to one or a combination of the following :

1. Less than 25 mg/l of readily biodegradable COD in the anaerobic zone

   Experience has shown this requirement is independent of the TKN/COD ratio. Under such conditions excess biological uptake of phosphorus will not be possible, even if nitrate addition to the anaerobic zone is limited by discouraging nitrification in the aerobic zone.

   Concentrations of readily biodegradable COD in the influent to the biological reactors less than 50 mg/l (to allow for 1:1 dilution in the anaerobic zone) may arise where :

   (a) the strength of the influent sewage is weak i.e. COD is less than 150 - 200 mg/l

   (b) the readily biodegradable COD is depleted due to some biological interaction before the flow reaches the reactors e.g. fermentation in balancing tanks containing deposited solids or where the influent flow originates from septic tanks.

2. TKN/COD ratio such that complete denitrification is impossible

   In such cases, even if the required minimum amount of 50 mg/l of readily biodegradable COD is present in the influent, this will all be assimilated by denitrifiers in the anaerobic zone before the necessary free, residual of 25 mg/l can be achieved to induce phosphorus release and subsequent uptake under aerobic conditions. Such conditions exist when TKN/COD$>$0,13

3. - Readily biodegradable COD greater than 50 mg/l and TKN/COD ratio 0,08 - 0,13

In such cases it is possible to prevent nitrate from entering the anaerobic zone by adopting the UCT process with its auxillary denitrifying reactor.

4. Readily biodegradable COD greater than 50 mg/l and TKN/COD ratio less than 0,08

Under these circumstances it is likely that the 5 stage Phoredox process will achieve phosphorus removal provided the recycled liquors from the final clarifiers contain zero nitrates. However experience gained at the Johannesburg works has clearly demonstrated that if the measured TKN/COD ratio is higher or the readily biodegradable COD is lower than the values used in the design, nitrates will appear in the effluent and hence in the sludge returned from the clarifier which will in turn adversely affect phosphorus removal. A prior knowledge of the influent sewage characteristics is obviously highly desirable. Should this data not be a available and very conservative values be allocated to these parameters at the design stage, plant efficiency will suffer accordingly. If there is any doubt about sewage characteristics the adoption of the Phoredox process appears to be contra-indicated.

5. Lack of dissolved oxygen control

The operation of large scale nutrient removal activated sludge plants has clearly shown the need to match oxygen supply against oxygen requirements. If not adequately controlled excessive aeration may cause the plant not to give the expected phosphorus removal and under aeration may cause inadequate nitrification and the production of sludges with poor settling characteristics.

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# APPENDIX A1

## LIST OF VOLUTIN FORMING BACTERIA WHICH ACCUMULATE POLYPHOSPHATE

Acetobacter suboxydans

Aerobacter aerogenes

Azotobacter agilis

A. vinelandii

Bacillus subtilis

Bacterium aerogenes

B. cloacae

B. friedländeri

Caulobacter vibroides

Chlorobium thiosulphatophilum

Chromatium

Clostridium spp

Corynebacterium diptheria

C. xerosis

E. coli

Hydrogenomonas spp

Mycobacterium spp

M. chelonei

M. phlei

M. smegmatis

M. thamnapheos

M. tuberculosis

Rhodopseudomonas palustris

Rhodosprillium rubrum

Serratia marcescens

Thiobacillus thioxydans

Nitrobacter

Micrococcus denitrificans

Staphylococcus denitrificans

Chlamydomoda

Mucor racemosus

Claviceps purpurea

Acinetobacter

Zoogloea ramigera

Nitrosococcus

Beggiato

Kuhl (1960) , Harold (1966) , Fuhs and Chen (1975)

# APPENDIX A 2.1.

Raw data obtained when the Alexandra plant was operating with all the aerators closest to the feed on

| Flow Ml/d | Ammonia as N mg/l | | TKN as N mg/l | | Nitrate as N mg/l | Total COD mg/l | | Soluble COD mg/l | | Suspended solids mg/l | MLSS mg/l |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | F | E | F | E | E | F | E | F | E | E | |
| 34,3 | 20,6 | 6,2 | 38,4 | 12,0 | 23,0 | 500 | 84,6 | 315 | 49,9 | 40,4 | 2481 |
| 35,3 | 10,3 | 4,2 | 39,4 | 10,0 | 18,0 | 623 | 96,1 | 238 | 80,7 | 11,6 | - |
| 31,0 | 23,4 | 8,2 | 48,2 | 12,0 | 19,0 | 462 | 88,5 | 292 | 61,5 | 39,2 | - |
| 26,5 | 24,2 | 5,0 | 43,4 | 7,4 | 19,0 | 438 | 69,5 | 215 | 80,7 | 38,8 | 2240 |
| 37,2 | 21,0 | 3,0 | 40,1 | 9,4 | 19,0 | 534 | 39,8 | - | 11,9 | 33,6 | 2646 |
| 37,2 | 22,0 | 5,3 | 44,0 | 5,3 | 26,5 | 571 | 66,0 | 160 | 30,0 | 42,0 | 2800 |
| 37,7 | 19,9 | 8,6 | 39,1 | 11,4 | 27,0 | 498 | 72,0 | 215 | 34,0 | 26,0 | - |
| 32,4 | 21,0 | 3,0 | 34,0 | 6,8 | 26,0 | 504 | 60,0 | 216 | 20,0 | 20,8 | - |
| 28,2 | 30,0 | 3,0 | 38,0 | 3,0 | 29,2 | 510 | 88,0 | 200 | 39,0 | 12,4 | - |
| 40,3 | 18,2 | 5,0 | 32,0 | 8,0 | 21,0 | 669 | 97,0 | 300 | 66,0 | 15,0 | 2422 |
| 39,2 | 10,0 | 0,5 | 36,0 | 11,5 | 25,0 | 875 | 64,0 | 227 | 64,0 | 14,8 | 2812 |
| 41,1 | 22,8 | 7,8 | 39,0 | 10,0 | 29,0 | 1018 | 89,2 | 137 | 78,1 | 26,4 | 2624 |
| 39,5 | 23,0 | 6,7 | 46,0 | 11,0 | 31,9 | 583 | 65,0 | 210 | 60,0 | 14,0 | 2680 |
| 21,8 | 18,4 | 1,6 | 41,0 | 5,6 | 16,0 | 382 | 55,8 | 250 | 52,9 | 20,4 | - |

* F = feed

E = effluent

## APPENDIX A 2.2.

Raw data obtained when the Alexandra plant was operating with one aerator off in the first basin

| Flow Ml/d | Ammonia as N mg/l | | TKN as N mg/l | | Nitrate as N mg/l | Total COD mg/l | | Soluble COD mg/l | | Suspended solids mg/l | MLSS mg/l |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | F | E | F | E | E | F | E | F | E | E | |
| 22,8 | 18,4 | 2,2 | - | 10,3 | 21,2 | - | - | - | - | 44,0 | - |
| 20,5 | 23,6 | 2,8 | 35,2 | 6,2 | 29,0 | 1007 | 116 | 410 | 31,0 | 24,0 | - |
| 30,4 | 24,4 | 3,0 | 36,0 | 6,4 | 29,0 | 961 | 93 | 470 | 31,0 | 64,0 | 2572 |
| 30,8 | 25,2 | 5,2 | 41,0 | 6,3 | 13,0 | 255 | - | 232 | - | 32,0 | - |
| 29,8 | 20,0 | 6,0 | 32,8 | 9,2 | 19,0 | 492 | 108 | 284 | 73,0 | 34,0 | 2218 |
| 28,3 | 20,6 | 5,4 | 32,8 | 9,2 | 19,0 | 382 | 66 | 312 | 86,0 | 20,0 | 2592 |
| 27,6 | 21,2 | 4,4 | 32,8 | 8,4 | 17,0 | 388 | - | 226 | 75,0 | 21,0 | - |
| 22,2 | 30,0 | 4,1 | 37,0 | 6,5 | 14,1 | 420 | 132 | 306 | 72,0 | 32,0 | 2900 |
| 22,3 | 17,0 | 3,6 | 43,4 | 5,4 | 12,5 | 409 | 73 | 219 | 73,0 | 30,0 | 2370 |
| 30,1 | 27,6 | 5,6 | 41,2 | 9,6 | 12,0 | - | 54 | 178 | - | 57,0 | 2518 |
| 28,1 | 11,8 | 5,0 | 43,4 | 6,8 | 14,4 | 567 | 83 | 197 | 31,0 | 43,0 | 2396 |
| 30,8 | 21,6 | 6,8 | 42,8 | 6,0 | 11,6 | 494 | 69 | 320 | 53,0 | 32,0 | 2602 |
| 28,7 | 22,2 | 6,0 | 43,2 | 8,8 | 7,6 | 535 | 71 | 272 | 67,0 | 25,0 | 2792 |
| 28,4 | 23,6 | 3,0 | 35,6 | 8,8 | 10,5 | 437 | 59 | 228 | 51,0 | 10,0 | - |
| 25,6 | 19,0 | 3,6 | 39,0 | 8,0 | 14,0 | 465 | 59 | 220 | 55,5 | 17,0 | - |
| 23,4 | 36,0 | 4,3 | 36,0 | 8,6 | 17,8 | 497 | - | 110 | - | 16,0 | - |
| 32,6 | 20,0 | 4,2 | 42,0 | 10,0 | 18,0 | 504 | - | 306 | - | 27,0 | 2644 |

* F = feed

E = effluent

## APPENDIX A 2.3.

Raw data obtained when the Alexandra plant was operating with two aerators off in the first basin

| Flow Ml/d | Ammonia as N mg/l | | TKN as N mg/l | | Nitrate as N mg/l | Total COD mg/l | | Soluble COD mg/l | | Suspended solids mg/l | MLSS mg/l |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | F | E | F | E | E | F | E | F | E | E | |
| 18,0 | 23,0 | 1,2 | 38,0 | 4,0 | 10,0 | 453 | 67,6 | 147 | 55,8 | 25,6 | - |
| 16,6 | 17,4 | 2,2 | 52,0 | 15,0 | 13,6 | 318 | 47,1 | 147 | 32,3 | 74,4 | 1738 |
| 28,8 | 11,4 | 2,6 | 47,3 | 10,3 | 15,0 | 369 | 50,2 | 134 | 35,7 | 18,4 | 1498 |
| 30,0 | 17,4 | 4,0 | 31,0 | 6,6 | 12,0 | 433 | 62,5 | 216 | 42,6 | 25,9 | 2352 |
| 28,9 | 22,0 | 3,2 | 44,0 | 6,6 | 11,2 | 597 | 42,6 | 219 | 36,9 | 20,3 | 2294 |
| 29,7 | 25,2 | 2,0 | 40,2 | 7,0 | 11,6 | 506 | 53,9 | 290 | 42,6 | 19,2 | 2346 |
| 30,3 | 24,0 | 5,0 | 41,0 | 8,1 | 0,0 | 523 | 101 | 240 | 85,0 | 25,0 | 2970 |
| 23,9 | 24,2 | 4,0 | 39,2 | 8,0 | 7,8 | 356 | 100 | 222 | 103 | 29,1 | - |
| 23,0 | 17,2 | 2,0 | 41,2 | 3,6 | 7,6 | 398 | 81,4 | 225 | 40,7 | 32,7 | - |
| 32,4 | 19,2 | 1,8 | 40,0 | 3,9 | 7,0 | 640 | 98,2 | 280 | 61,8 | 43,6 | 2502 |
| 29,7 | 14,0 | 7,5 | 34,4 | - | 3,0 | 544 | 103 | 309 | 96,0 | 14,0 | - |
| 30,7 | 12,0 | 6,6 | 33,0 | 8,8 | 7,0 | 846 | 69,8 | 381 | 41,3 | 33,2 | 2252 |
| 30,5 | 20,4 | 6,0 | 34,0 | 8,2 | - | 434 | 40,4 | 214 | 40,4 | 16,0 | 2322 |
| 31,6 | 12,0 | 5,4 | 35,0 | 12,8 | 5,0 | 311 | 47,7 | 175 | 40,4 | 19,2 | - |
| 25,1 | 24,0 | 5,0 | 38,0 | 7,9 | 5,3 | 472 | 22,0 | 150 | 37,0 | 49,0 | 2350 |

* F = feed

E = effluent

# APPENDIX A 2.4.

Raw data obtained when the Alexandra plant was operating with the three aerators closest to the feed off

| Flow Ml/d | Ammonia as N mg/l | | TKN as N mg/l | | Nitrate as N mg/l | Total COD mg/l | | Soluble COD mg/l | | Suspended solids mg/l | MLSS mg/l |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | F | E | F | E | E | F | E | F | E | E | |
| 36,1 | 19,0 | 3,0 | 44,0 | 8,1 | 11,0 | 500 | 26 | - | - | 30 | 2100 |
| 34,9 | 18,4 | 2,8 | - | - | 2,6 | 624 | 68 | 304 | 56 | 12 | 2844 |
| 40,3 | 17,4 | 3,6 | 34,0 | 6,4 | 2,2 | 440 | 40 | 216 | 36 | 46 | 3002 |
| 31,7 | 18,4 | 1,0 | 33,0 | 1,8 | 17,8 | 448 | 52 | 176 | 32 | 9 | 2982 |
| 37,9 | 17,4 | 2,0 | 29,6 | 3,8 | 6,8 | 610 | 44 | 380 | 36 | 40 | 2088 |
| 35,9 | 10,2 | 1,6 | 31,0 | 5,1 | 5,6 | 432 | 72 | 104 | 60 | 7 | 3196 |
| 36,3 | 20,6 | 4,2 | 44,2 | 7,6 | 8,2 | 704 | 28 | 332 | 13 | 13 | 3092 |
| 33,8 | 20,4 | 4,0 | 37,0 | 7,0 | 4,0 | 416 | - | 220 | - | 10 | 3338 |
| 34,8 | 20,0 | 4,0 | 41,0 | 4,6 | 3,5 | 520 | 56 | 210 | 51 | 8 | 3200 |
| 34,5 | 10,3 | 2,6 | 36,8 | 3,0 | 7,2 | 400 | 48 | 280 | 44 | 45 | 3276 |
| 27,8 | 26,0 | 0,5 | 49,0 | 3,8 | 11,4 | 1152 | 55 | 223 | 39 | 8 | 3158 |
| 36,4 | 26,0 | 4,0 | - | 6,0 | 9,0 | 1198 | 34 | 503 | 34 | 5 | 3360 |
| 35,8 | 41,0 | 3,6 | - | - | 3,0 | 674 | 98 | - | - | 64 | 3354 |
| 30,8 | 17,0 | 1,5 | 24,4 | 3,0 | 7,3 | 420 | 62 | - | - | 17 | 3500 |
| 27,3 | 18,2 | 2,4 | 37,0 | 2,4 | 8,0 | 423 | 55 | - | 47 | 11 | 3328 |
| 35,7 | 16,4 | 2,0 | 32,0 | - | 7,2 | - | - | - | - | 13 | 3255 |
| 33,1 | 21,4 | 3,0 | 42,8 | 4,8 | - | 584 | 48 | 260 | 40 | - | - |
| 34,7 | 20,0 | 3,0 | 45,0 | 5,0 | 5,0 | 250 | 46 | - | - | 12 | 3178 |
| 38,3 | 21,0 | 1,6 | 37,0 | 8,0 | 9,0 | 632 | 76 | 272 | 52 | 17 | 3230 |
| 36,3 | 21,0 | 4,6 | - | - | 2,4 | 552 | 52 | 240 | 52 | 40 | 3293 |
| 37,6 | 20,3 | 4,4 | 37,6 | 8,8 | - | 512 | 56 | 280 | 29 | 29 | 3058 |
| 37,6 | 19,2 | 4,6 | 43,2 | 9,0 | 1,0 | 792 | 80 | 296 | 64 | 20 | 3216 |
| 41,3 | 23,2 | 4,6 | 43,0 | 12,8 | 7,0 | 728 | 72 | 408 | 48 | 14 | 2908 |

* F = feed

E = effluent

## APPENDIX A 3

### EXAMPLE CALCULATION OF MIXED LIQUOR SUSPENDED SOLIDS CONCENTRATION USING MARAIS EKAMA (1976) EQUATIONS

Flow = $Q$ = $34{,}4 \times 10^6$ (l/d)

Feed COD = $S_{ti}$ = 590 (mg/l)

Volume = $V$ = $33{,}5 \times 10^6$ (l)

Sludge age = $R_s$ = 15 (d)

Volatile fraction of sludge = 0,72

Process constants

$Y = 0{,}45$ (mg VSS/mg COD)

$b = 0{,}24(1{,}03)^{T-20}$ $(d^{-1})$

$SX_{ii}$ = unbiodegradable particulate influent COD

$$= \frac{f_{up}\,S_{ti}}{1{,}48}$$

$= 0{,}13\ S_{ti}$ (mg COD/l)

$S_u$ = unbiodegradable soluble influent COD

$= f_{us}\,S_{ti}$

$= 0{,}07\ S_{ti}$ (mg COD/mg VSS)

Calculation of the biodegradability of the COD

$$\begin{aligned} S_{bi} &= S_{ti} - SX_{ii} - S_u \\ &= 590 - 0{,}13\,(590) - 0{,}07\,(590) \\ &= \underline{472 \quad \text{mg/l COD}} \rightarrow \end{aligned}$$

## Calculation of the mass fractions of the MLSS

$$\text{Active mass} = MX_a$$

$$= M \frac{S_{bi} YR_s}{1 + bR_s}$$

$$= 34{,}4 \times 10^6 \; \frac{472 \cdot 0{,}45 \cdot 15}{1 + (0{,}24 \cdot 15)}$$

$$= \underrightarrow{23\ 825 \quad \text{kg/d}}$$

$$\text{Endogenous mass} = MX_e$$

$$= MX_a \; 0{,}2 \; bR_s$$

$$= 23\ 825 \cdot 0{,}2 \cdot 0{,}24 \cdot 15$$

$$= \underrightarrow{17\ 154 \quad \text{kg/d}}$$

$$\text{Inert mass} = MX_{ii}$$

$$= \frac{0{,}13 \; R_s M \; S_{ti}}{1{,}48}$$

$$= \frac{0{,}13 \cdot 15 \cdot 34{,}4 \times 10^6 \cdot 590}{1{,}48}$$

$$= \underrightarrow{26\ 741 \quad \text{kg/d}}$$

$$MX_v = MX_a + MX_e + MX_i$$

$$= \underrightarrow{67\ 720 \quad \text{kg/d}}$$

$$MX_T = \frac{MX_v}{0{,}75}$$

$$= \frac{67\ 720}{0{,}75}$$

$$= \underrightarrow{90\ 293 \quad \text{kg/d}}$$

$$X_T = \frac{90\ 293 \times 10^6}{33{,}5 \times 10^6}$$

$$= \underrightarrow{2\ 695 \quad \text{mg/l}}$$

# APPENDIX A 4

## MEASUREMENT OF OXYGEN CONSUMPTION RATE

In a preliminary exploratory investigation it was found that the oxygen consumption rate was highest at the influent and lowest at the effluent end of the aeration zone, indicating that the basin could not be regarded as completely mixed.

These results indicated that it was necessary to carry out measurements at a number of points along the basin. Three respirometers were therefore built as indicated in Fig. A 1 , and positioned at the start, middle and end of the primary aeration basin.

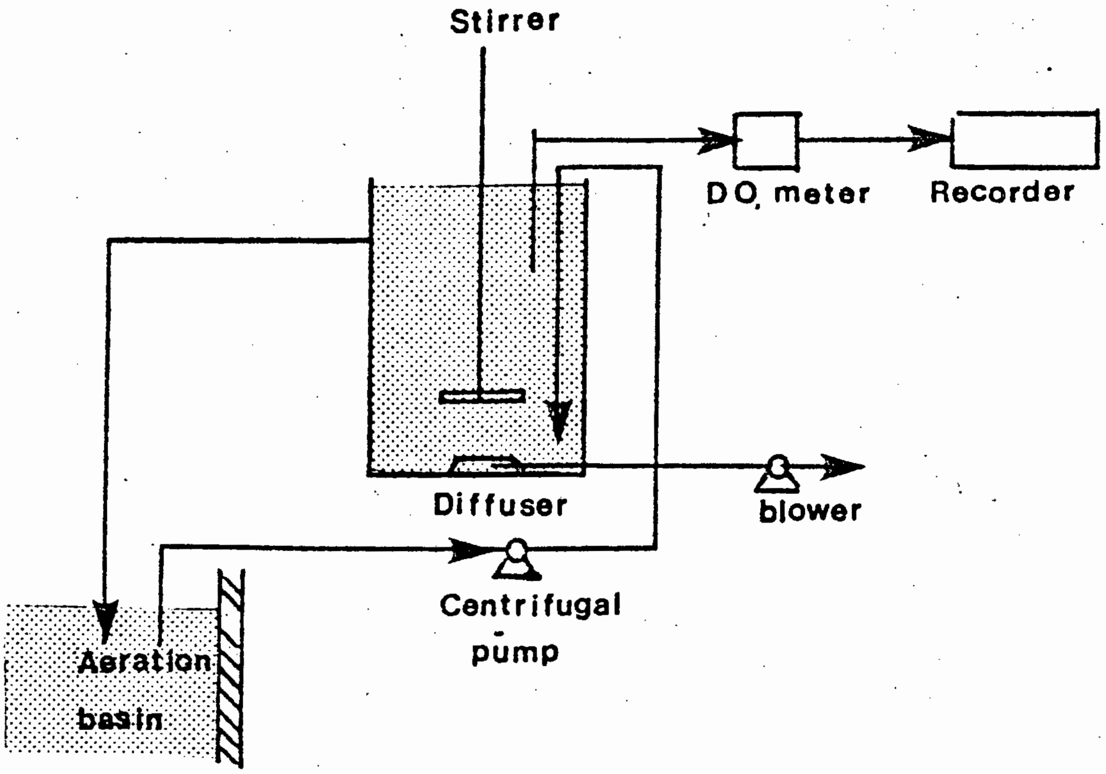


Fig. A 1 Respirometer design

When measuring oxygen consumption in a reactor, the sample must be removed from the reactor, oxygenated and the oxygen reduction with time then measured. This introduces an error as the sample does not receive the influent substrate while it is outside the reactor, possibly resulting in a reduction in the rate of oxygen utilisation. In laboratory scale units this error can be made zero by cutting off the oxygen supply, leaving the influent and effluent flows unaltered and gently stirring the reactor contents. On the plant the error can be minimised by arranging minimum time lapse between collection of the sample and measurement of the rate. To reduce the time effect as much as possible, a special respirometer, as shown in Fig. A 1 was desigend containing the following features:

- A 0,4 $m^3$ tank into which mixed liquor was pumped every half hour, thus permitting determinations to be done.
- The pumping rate was approximately 10 $m^3/h$ so that the respirometer was filled every 2,4 minutes, the liquor displaced being returned to the aeration basin.
- The pump was so controlled that the volume of the tank was replaced 4 times.
- During the pumping stage, and for 5 minutes thereafter, the sludge was aerated by compressed air discharging through a fine stone diffuser. The dissolved oxygen concentration at the end of the aeration period was usually above 4 mg/l .
- The air compressor was then switched off automatically, and the dissolved oxygen meter (coupled to a recorder) switched in.

- The subsequent decrease in the dissolved oxygen concentration with time was recorded. The gradient of the oxygen - time graph gave the utilisation rate.
- During the entire operation i e taking in a new sample, aerating it, and measuring the oxygen consumption rate, the mixed liquor in the tank was stirred. The stirring rate was designed so that no air was drawn into the mixed liquor by means of vortices.

# APPENDIX A5

## GOUDKOPPIE PLANT

The raw data obtained during the experimental period

### CODE

| | |
|---|---|
| G1 B E | Balancing tank effluent |
| G1 Z 12 | Anaerobic zone |
| G1 Z 22 | Primary anoxic zone |
| G1 Z 32 | Primary aeration zone |
| G1 Z 42 | Secondary anoxic zone |
| G1 Z 52 | Secondary aeration zone |
| G1 E 2 | Effluent |

# CHEMICAL OXYGEN DEMAND AS O

| DATE | TIME | DAY | G1BE | G1Z12 | G1Z22 | G1Z32 | G1Z42 | G1Z52 | G1E2 |
|---|---|---|---|---|---|---|---|---|---|
| 1979-10-21 | 12H00 | SUN | 150 | - | - | - | - | - | 41 |
| 1979-10-21 | 14H00 | SUN | 110 | - | - | - | - | - | 31 |
| 1979-10-21 | 16H00 | SUN | 120 | - | - | - | - | - | 26 |
| 1979-10-21 | 18H00 | SUN | 180 | - | - | - | - | - | 26 |
| 1979-10-21 | 20H00 | SUN | 210 | - | - | - | - | - | 36 |
| 1979-10-21 | 22H00 | SUN | 260 | - | - | - | - | - | 36 |
| 1979-10-21 | 24H00 | SUN | 240 | - | - | - | - | - | 41 |
| 1979-10-22 | 2H00 | MON | 290 | - | - | - | - | - | 36 |
| 1979-10-22 | 4H00 | MON | 240 | - | - | - | - | - | 31 |
| 1979-10-22 | 6H00 | MON | 260 | - | - | - | - | - | 26 |
| 1979-10-22 | 8H00 | MON | 220 | - | - | - | - | - | 36 |
| 1979-10-22 | 10H00 | MON | 130 | - | - | - | - | - | 21 |
| 1979-10-23 | 12H00 | TUE | 210 | - | - | - | - | - | 110 |
| 1979-10-23 | 14H00 | TUE | 230 | - | - | - | - | - | 97 |
| 1979-10-23 | 16H00 | TUE | 280 | - | - | - | - | - | 97 |
| 1979-10-23 | 18H00 | TUE | 330 | - | - | - | - | - | 87 |
| 1979-10-23 | 20H00 | TUE | 390 | - | - | - | - | - | 92 |
| 1979-10-23 | 22H00 | TUE | 450 | - | - | - | - | - | 97 |
| 1979-10-23 | 24H00 | TUE | 440 | - | - | - | - | - | 87 |
| 1979-10-24 | 2H00 | WED | 410 | - | - | - | - | - | 87 |
| 1979-10-24 | 4H00 | WED | 420 | - | - | - | - | - | 97 |
| 1979-10-24 | 6H00 | WED | 360 | - | - | - | - | - | 97 |
| 1979-10-24 | 8H00 | WED | 350 | - | - | - | - | - | 97 |
| 1979-10-24 | 10H00 | WED | 210 | - | - | - | - | - | 100 |
| 1979-10-25 | 12H00 | THU | 160 | - | - | - | - | - | 55 |
| 1979-10-25 | 14H00 | THU | 190 | - | - | - | - | - | 60 |
| 1979-10-25 | 16H00 | THU | 230 | - | - | - | - | - | 71 |
| 1979-10-25 | 18H00 | THU | 260 | - | - | - | - | - | 60 |
| 1979-10-25 | 20H00 | THU | 320 | - | - | - | - | - | - |
| 1979-10-25 | 22H00 | THU | 320 | - | - | - | - | - | 71 |
| 1979-10-25 | 24H00 | THU | 330 | - | - | - | - | - | 60 |
| 1979-10-26 | 2H00 | FRI | 330 | - | - | - | - | - | 44 |
| 1979-10-26 | 4H00 | FRI | 380 | - | - | - | - | - | 44 |
| 1979-10-26 | 6H00 | FRI | 260 | - | - | - | - | - | 66 |
| 1979-10-26 | 8H00 | FRI | 320 | - | - | - | - | - | 71 |
| 1979-10-26 | 10H00 | FRI | 270 | - | - | - | - | - | 60 |
| 1979-10-26 | 12H00 | FRI | 200 | - | - | - | - | - | - |
| 1979-10-26 | 14H00 | FRI | 200 | - | - | - | - | - | - |
| 1979-10-26 | 16H00 | FRI | 260 | - | - | - | - | - | - |
| 1979-10-26 | 18H00 | FRI | 320 | - | - | - | - | - | - |
| 1979-10-26 | 20H00 | FRI | 320 | - | - | - | - | - | - |
| 1979-10-26 | 22H00 | FRI | 340 | - | - | - | - | - | - |
| 1979-10-26 | 24H00 | FRI | 270 | - | - | - | - | - | - |
| 1979-10-27 | 2H00 | SAT | 270 | - | - | - | - | - | - |
| 1979-10-27 | 4H00 | SAT | 240 | - | - | - | - | - | - |
| 1979-10-27 | 6H00 | SAT | 230 | - | - | - | - | - | - |
| 1979-10-27 | 8H00 | SAT | 290 | - | - | - | - | - | - |
| 1979-10-27 | 10H00 | SAT | 220 | - | - | - | - | - | - |
| NO. RESULTS | | | 48 | 0 | 0 | 0 | 0 | 0 | 35 |
| MEAN | | | 270 | - | - | - | - | - | 63 |
| STD. DEVIATION | | | 83 | - | - | - | - | - | 28 |

## CHEMICAL OXYGEN DEMAND (SOLUBLE) AS O

| DATE | TIME | DAY | G1BE | G1Z12 | G1Z22 | G1Z32 | G1Z42 | G1Z52 | G1E2 |
|---|---|---|---|---|---|---|---|---|---|
| 1979-10-21 | 12H00 | SUN | 83 | 73 | 93 | 170 | 87 | 190 | 41 |
| 1979-10-21 | 14H00 | SUN | 67 | 120 | 78 | 130 | 51 | 150 | 30 |
| 1979-10-21 | 16H00 | SUN | 73 | 160 | 130 | 87 | 56 | 120 | 20 |
| 1979-10-21 | 18H00 | SUN | 93 | 78 | 120 | 56 | 41 | 56 | 20 |
| 1979-10-21 | 20H00 | SUN | 110 | 150 | 46 | 87 | 46 | 56 | 36 |
| 1979-10-21 | 22H00 | SUN | 110 | 120 | 46 | 71 | 36 | 97 | 21 |
| 1979-10-21 | 24H00 | SUN | 160 | 93 | 46 | 66 | 41 | 46 | 31 |
| 1979-10-22 | 2H00 | MON | 140 | - | 160 | 200 | 140 | 150 | 26 |
| 1979-10-22 | 4H00 | MON | 150 | 62 | 46 | 36 | - | - | 25 |
| 1979-10-22 | 6H00 | MON | 130 | 57 | 46 | 41 | - | - | 25 |
| 1979-10-22 | 8H00 | MON | 150 | 57 | 41 | 41 | 56 | 51 | 30 |
| 1979-10-22 | 10H00 | MON | 150 | 52 | 46 | 46 | 46 | 77 | 20 |
| 1979-10-23 | 12H00 | TUE | 97 | 87 | 36 | 100 | 56 | 77 | 66 |
| 1979-10-23 | 14H00 | TUE | 140 | 51 | 41 | 82 | 87 | 87 | 56 |
| 1979-10-23 | 16H00 | TUE | 150 | 67 | 97 | 92 | 56 | 87 | 66 |
| 1979-10-23 | 18H00 | TUE | 150 | 87 | - | 120 | 77 | 71 | 71 |
| 1979-10-23 | 20H00 | TUE | 210 | 140 | - | 120 | 77 | 56 | 77 |
| 1979-10-23 | 22H00 | TUE | 250 | 97 | 56 | 110 | 56 | 66 | 71 |
| 1979-10-23 | 24H00 | TUE | 290 | 110 | 51 | 97 | 110 | 100 | 77 |
| 1979-10-24 | 2H00 | WED | 300 | 140 | - | 71 | 87 | 87 | 71 |
| 1979-10-24 | 4H00 | WED | 310 | 110 | 77 | 71 | 77 | 77 | 71 |
| 1979-10-24 | 6H00 | WED | 290 | 130 | 82 | 46 | 51 | 87 | 66 |
| 1979-10-24 | 8H00 | WED | 260 | 82 | 260 | 77 | 61 | 66 | 71 |
| 1979-10-24 | 10H00 | WED | 200 | 110 | 87 | 77 | 87 | 92 | 77 |
| 1979-10-25 | 12H00 | THU | 110 | 76 | 76 | 76 | 33 | 82 | 27 |
| 1979-10-25 | 14H00 | THU | 100 | 54 | 65 | 54 | 38 | 98 | 33 |
| 1979-10-25 | 16H00 | THU | 120 | 49 | 54 | 49 | 38 | 60 | 55 |
| 1979-10-25 | 18H00 | THU | 120 | 60 | 38 | 60 | 33 | 44 | 49 |
| 1979-10-25 | 20H00 | THU | 140 | 38 | 44 | 76 | 38 | 22 | 60 |
| 1979-10-25 | 22H00 | THU | 160 | 44 | 54 | 82 | 33 | 38 | 38 |
| 1979-10-25 | 24H00 | THU | 170 | 54 | 60 | 49 | 33 | 38 | 44 |
| 1979-10-26 | 2H00 | FRI | 240 | 27 | 76 | 33 | 54 | 49 | 27 |
| 1979-10-26 | 4H00 | FRI | 230 | 38 | 82 | 27 | 16 | 44 | 27 |
| 1979-10-26 | 6H00 | FRI | 210 | 44 | 76 | 33 | 16 | 38 | 49 |
| 1979-10-26 | 8H00 | FRI | 120 | 49 | 98 | 44 | 33 | 22 | 49 |
| 1979-10-26 | 10H00 | FRI | 210 | 82 | 82 | 180 | 60 | 38 | 27 |
| 1979-10-26 | 12H00 | FRI | 140 | 54 | 33 | 38 | 76 | 76 | 49 |
| 1979-10-26 | 14H00 | FRI | 130 | 60 | 38 | 33 | 76 | 76 | 44 |
| 1979-10-26 | 16H00 | FRI | 190 | 60 | 49 | 60 | 71 | 91 | 38 |
| 1979-10-26 | 18H00 | FRI | 220 | 71 | 49 | 65 | 65 | 91 | 33 |
| 1979-10-26 | 20H00 | FRI | 220 | 76 | 44 | 65 | 60 | 92 | 27 |
| 1979-10-26 | 22H00 | FRI | 230 | 110 | 38 | 49 | 54 | 92 | 27 |
| 1979-10-26 | 24H00 | FRI | 230 | 98 | 49 | 54 | 44 | 91 | 38 |
| 1979-10-27 | 2H00 | SAT | 170 | 60 | 33 | 44 | 33 | 54 | 33 |
| 1979-10-27 | 4H00 | SAT | 150 | 54 | 38 | 38 | 33 | 49 | 38 |
| 1979-10-27 | 6H00 | SAT | 160 | 38 | 44 | 27 | 44 | 28 | 33 |
| 1979-10-27 | 8H00 | SAT | 160 | 44 | 38 | 60 | 38 | 33 | 27 |
| 1979-10-27 | 10H00 | SAT | 160 | 49 | 44 | 76 | 38 | 38 | 38 |
| NO. RESULTS | | | 48 | 47 | 45 | 48 | 46 | 46 | 48 |
| MEAN | | | 170 | 77 | 67 | 73 | 55 | 72 | 43 |
| STD. DEVIATION | | | 61 | 34 | 41 | 39 | 24 | 35 | 18 |

## AMMONIA AS N

| DATE | TIME | DAY | G1BE | G1Z12 | G1Z22 | G1Z32 | G1Z42 | G1Z52 | G1E2 |
|---|---|---|---|---|---|---|---|---|---|
| 1979-10-21 | 12H00 | SUN | 18 | 9,7 | 4,7 | 3,4 | 2,8 | 2,2 | 2,2 |
| 1979-10-21 | 14H00 | SUN | 17 | 12 | 4,8 | 2,9 | 1,6 | 1,7 | 1,7 |
| 1979-10-21 | 16H00 | SUN | 17 | 18 | 5,8 | 3,0 | 2,0 | 1,1 | 1,1 |
| 1979-10-21 | 18H00 | SUN | 23 | 19 | 5,7 | 0,0 | 0,8 | 0,0 | 0,0 |
| 1979-10-21 | 20H00 | SUN | 27 | 17 | 5,7 | 0,0 | 0,9 | 1,0 | 1,0 |
| 1979-10-21 | 22H00 | SUN | 28 | 16 | 5,4 | 0,0 | 0,8 | 1,1 | 1,1 |
| 1979-10-21 | 24H00 | SUN | 23 | 15 | 5,5 | 4,7 | 0,0 | 0,9 | 0,9 |
| 1979-10-22 | 2H00 | MON | 25 | 19 | - | - | - | - | - |
| 1979-10-22 | 4H00 | MON | 22 | 12 | 4,4 | 3,4 | - | - | - |
| 1979-10-22 | 6H00 | MON | 23 | 12 | 4,3 | 3,1 | - | - | - |
| 1979-10-22 | 8H00 | MON | 20 | 10 | 2,0 | 2,6 | 0,0 | 1,6 | 1,6 |
| 1979-10-22 | 10H00 | MON | 15 | 8,2 | 3,3 | 2,5 | 1,3 | 1,1 | 1,1 |
| 1979-10-23 | 12H00 | TUE | 16 | 14 | 4,1 | 1,9 | 1,9 | 1,5 | 1,5 |
| 1979-10-23 | 14H00 | TUE | 20 | 14 | 4,0 | 1,9 | 1,6 | 1,4 | 1,4 |
| 1979-10-23 | 16H00 | TUE | 22 | 16 | 4,7 | 1,5 | 1,5 | 1,5 | 1,5 |
| 1979-10-23 | 18H00 | TUE | 25 | 19 | - | 1,5 | 2,1 | 1,2 | 1,2 |
| 1979-10-23 | 20H00 | TUE | 29 | 21 | - | 1,5 | 1,8 | 1,5 | 1,5 |
| 1979-10-23 | 22H00 | TUE | 29 | 21 | 5,3 | 2,1 | 1,5 | 1,6 | 1,6 |
| 1979-10-23 | 24H00 | TUE | 29 | 21 | 5,8 | 1,5 | 1,6 | 1,5 | 1,5 |
| 1979-10-24 | 2H00 | WED | 28 | 19 | 5,5 | 1,9 | 2,1 | 2,0 | 2,0 |
| 1979-10-24 | 4H00 | WED | 27 | 19 | 4,9 | 1,9 | 1,7 | 2,0 | 2,0 |
| 1979-10-24 | 6H00 | WED | 25 | 17 | 4,3 | 1,5 | 1,5 | 1,5 | 1,5 |
| 1979-10-24 | 8H00 | WED | 22 | 15 | 3,6 | 1,7 | 1,5 | 1,5 | 1,5 |
| 1979-10-24 | 10H00 | WED | 19 | 13 | 4,4 | 1,6 | 1,3 | 1,6 | 1,6 |
| 1979-10-25 | 12H00 | THU | 16 | 15 | 3,7 | 1,4 | 1,5 | 1,5 | 1,5 |
| 1979-10-25 | 14H00 | THU | 22 | 15 | 3,8 | 1,7 | 1,7 | 1,4 | 1,4 |
| 1979-10-25 | 16H00 | THU | 22 | 18 | 4,6 | 1,5 | 1,4 | 1,4 | 1,4 |
| 1979-10-25 | 18H00 | THU | 32 | 22 | 5,9 | 1,9 | 1,7 | 1,5 | 1,5 |
| 1979-10-25 | 20H00 | THU | 36 | 23 | 6,3 | 2,1 | 0,0 | 1,6 | 1,6 |
| 1979-10-25 | 22H00 | THU | 37 | 23 | 7,0 | 2,1 | 1,8 | 1,4 | 1,4 |
| 1979-10-25 | 24H00 | THU | 35 | 23 | 7,0 | 2,1 | 2,0 | 1,5 | 1,5 |
| 1979-10-26 | 2H00 | FRI | 33 | 19 | 5,5 | 1,7 | 1,9 | 0,0 | 0,0 |
| 1979-10-26 | 4H00 | FRI | 29 | 19 | 5,9 | 1,9 | 2,1 | 1,5 | 1,5 |
| 1979-10-26 | 6H00 | FRI | 20 | 18 | 5,8 | 1,9 | 1,7 | 1,7 | 1,7 |
| 1979-10-26 | 8H00 | FRI | 26 | 15 | 4,8 | 1,5 | 1,7 | 1,6 | 1,6 |
| 1979-10-26 | 10H00 | FRI | 23 | 13 | 4,1 | 1,4 | 1,6 | 1,6 | 1,6 |
| 1979-10-26 | 12H00 | FRI | 21 | 7,0 | 4,5 | 1,5 | 1,6 | 1,6 | 1,6 |
| 1979-10-26 | 14H00 | FRI | 26 | 7,3 | 4,3 | 1,5 | 2,0 | 1,6 | 1,6 |
| 1979-10-26 | 16H00 | FRI | 27 | 9,0 | 5,2 | 1,5 | 1,8 | 1,7 | 1,7 |
| 1979-10-26 | 18H00 | FRI | 35 | 11 | 6,3 | 2,0 | 1,5 | 2,0 | 2,0 |
| 1979-10-26 | 20H00 | FRI | 43 | 12 | 7,2 | 2,2 | 1,7 | 1,5 | 1,5 |
| 1979-10-26 | 22H00 | FRI | 43 | 13 | 7,5 | 2,0 | 1,5 | 1,6 | 1,6 |
| 1979-10-26 | 24H00 | FRI | 38 | 12 | 7,2 | 2,7 | 2,2 | 1,8 | 1,8 |
| 1979-10-27 | 2H00 | SAT | 37 | 11 | - | 2,8 | 2,8 | 2,8 | 2,8 |
| 1979-10-27 | 4H00 | SAT | 32 | 11 | - | - | - | - | - |
| 1979-10-27 | 6H00 | SAT | 28 | 9,8 | 5,3 | 1,5 | 1,3 | 1,5 | 1,5 |
| 1979-10-27 | 8H00 | SAT | 36 | 8,2 | 4,5 | 1,5 | 2,0 | 1,9 | 1,9 |
| 1979-10-27 | 10H00 | SAT | 23 | 7,0 | 4,1 | 1,8 | 1,2 | 2,2 | 2,2 |
| NO. RESULTS | | | 48 | 48 | 43 | 46 | 44 | 44 | 44 |
| MEAN | | | 26 | 15 | 5,1 | 1,9 | 1,6 | 1,5 | 1,5 |
| STD. DEVIATION | | | 7,1 | 4,6 | 1,2 | 0,8 | 0,6 | 0,5 | 0,5 |

# NITRATE AS N

| DATE | TIME | DAY | G1BE | G1Z12 | G1Z22 | G1Z32 | G1Z42 | G1Z52 | G1E2 |
|---|---|---|---|---|---|---|---|---|---|
| 1979-10-21 | 12H00 | SUN | - | 2,6 | 11 | 13 | 15 | 16 | 15 |
| 1979-10-21 | 14H00 | SUN | - | 3,3 | 11 | 12 | 12 | 14 | 16 |
| 1979-10-21 | 16H00 | SUN | - | 1,6 | 11 | 13 | 9,6 | 14 | 16 |
| 1979-10-21 | 18H00 | SUN | - | 1,3 | 12 | 15 | 12 | 14 | 16 |
| 1979-10-21 | 20H00 | SUN | - | 1,1 | 13 | 15 | 14 | 14 | 16 |
| 1979-10-21 | 22H00 | SUN | - | 1,4 | 11 | 15 | 14 | 14 | 16 |
| 1979-10-21 | 24H00 | SUN | - | 1,9 | 13 | 15 | 14 | 14 | 16 |
| 1979-10-22 | 2H00 | MON | - | 0,0 | - | 14 | 15 | 16 | 16 |
| 1979-10-22 | 4H00 | MON | - | 3,7 | 14 | - | - | - | 16 |
| 1979-10-22 | 6H00 | MON | - | 3,9 | 14 | 16 | - | - | - |
| 1979-10-22 | 8H00 | MON | - | 4,7 | 14 | 16 | - | - | 15 |
| 1979-10-22 | 10H00 | MON | - | 5,1 | 13 | 16 | 16 | 17 | 17 |
| 1979-10-23 | 12H00 | TUE | - | 1,3 | 11 | 14 | 15 | 15 | 15 |
| 1979-10-23 | 14H00 | TUE | - | 0,7 | 10 | 14 | 13 | 14 | 14 |
| 1979-10-23 | 16H00 | TUE | - | 0,4 | 10 | 14 | 13 | 14 | 14 |
| 1979-10-23 | 18H00 | TUE | - | 0,0 | - | 14 | 14 | 14 | 14 |
| 1979-10-23 | 20H00 | TUE | - | 0,3 | - | 14 | 14 | 14 | 14 |
| 1979-10-23 | 22H00 | TUE | - | 0,3 | 9,5 | 15 | 14 | 14 | 14 |
| 1979-10-23 | 24H00 | TUE | - | 0,0 | 10 | 15 | 14 | 15 | 14 |
| 1979-10-24 | 2H00 | WED | - | 1,9 | 9,8 | 14 | 14 | 15 | 13 |
| 1979-10-24 | 4H00 | WED | - | 0,0 | 9,5 | 14 | 14 | 14 | 13 |
| 1979-10-24 | 6H00 | WED | - | 0,4 | 9,3 | 14 | 13 | 14 | 13 |
| 1979-10-24 | 8H00 | WED | - | 0,5 | 9,6 | 13 | 12 | 14 | 13 |
| 1979-10-24 | 10H00 | WED | - | 0,4 | 9,6 | 13 | 13 | 14 | 13 |
| 1979-10-25 | 12H00 | THU | - | 0,8 | 9,2 | 12 | 12 | 13 | 12 |
| 1979-10-25 | 14H00 | THU | - | 0,6 | 9,3 | 10 | 12 | 12 | 12 |
| 1979-10-25 | 16H00 | THU | - | 0,0 | 8,6 | 13 | 12 | 12 | 12 |
| 1979-10-25 | 18H00 | THU | - | 0,6 | 8,3 | 13 | 12 | 12 | 11 |
| 1979-10-25 | 20H00 | THU | - | 0,0 | 7,8 | 14 | 11 | 13 | 12 |
| 1979-10-25 | 22H00 | THU | - | 0,6 | 8,6 | 14 | 12 | 13 | 12 |
| 1979-10-25 | 24H00 | THU | - | 0,0 | 8,5 | 13 | 12 | 13 | 12 |
| 1979-10-26 | 2H00 | FRI | - | 1,1 | 8,7 | 14 | 12 | 14 | 9,7 |
| 1979-10-26 | 4H00 | FRI | - | 1,4 | 8,8 | 14 | 12 | 13 | 12 |
| 1979-10-26 | 6H00 | FRI | - | 0,3 | 9,1 | 13 | 12 | 13 | 12 |
| 1979-10-26 | 8H00 | FRI | - | 0,8 | 9,5 | 13 | 11 | 13 | 11 |
| 1979-10-26 | 10H00 | FRI | - | 0,8 | 8,9 | 12 | 11 | 12 | 12 |
| 1979-10-26 | 12H00 | FRI | - | 0,5 | 8,9 | 11 | 10 | 11 | - |
| 1979-10-26 | 14H00 | FRI | - | - | 8,7 | 12 | 11 | 11 | - |
| 1979-10-26 | 16H00 | FRI | - | 1,0 | 8,6 | 12 | 11 | 11 | - |
| 1979-10-26 | 18H00 | FRI | - | - | 8,1 | 11 | 11 | 12 | - |
| 1979-10-26 | 20H00 | FRI | - | 0,7 | 8,3 | 13 | 12 | 12 | - |
| 1979-10-26 | 22H00 | FRI | - | - | 8,3 | 13 | 11 | 12 | - |
| 1979-10-26 | 24H00 | FRI | - | 0,2 | 8,0 | 12 | 11 | 12 | - |
| 1979-10-27 | 2H00 | SAT | - | 0,0 | - | - | - | - | - |
| 1979-10-27 | 4H00 | SAT | - | 0,0 | 8,8 | 7,0 | 8,6 | 7,3 | - |
| 1979-10-27 | 6H00 | SAT | - | 0,6 | 9,7 | 14 | 11 | 13 | - |
| 1979-10-27 | 8H00 | SAT | - | 0,7 | 9,4 | 13 | 12 | 13 | - |
| 1979-10-27 | 10H00 | SAT | - | 0,6 | 8,7 | 13 | 12 | 12 | - |
| NO. RESULTS | | | 0 | 45 | 44 | 46 | 44 | 44 | 35 |
| MEAN | | | - | 1,1 | 9,8 | 13 | 12 | 13 | 14 |
| STD. DEVIATION | | | - | 1,3 | 1,9 | 1,6 | 1,5 | 1,6 | 1,9 |

## TOTAL PHOSPHORUS AS P

| DATE | TIME | DAY | G1BE | G1Z12 | G1Z22 | G1Z32 | G1Z42 | G1Z52 | G1E2 |
|---|---|---|---|---|---|---|---|---|---|
| 1979-10-21 | 12H00 | SUN | 3,7 | - | - | - | - | - | 4,3 |
| 1979-10-21 | 14H00 | SUN | 2,9 | - | - | - | - | - | 4,4 |
| 1979-10-21 | 16H00 | SUN | 3.6 | - | - | - | - | - | 4,4 |
| 1979-10-21 | 18H00 | SUN | 4,6 | - | - | - | - | - | 4,4 |
| 1979-10-21 | 20H00 | SUN | 5,4 | - | - | - | - | - | 4,4 |
| 1979-10-21 | 22H00 | SUN | 6,1 | - | - | - | - | - | 4,5 |
| 1979-10-21 | 24H00 | SUN | 4,9 | - | - | - | - | - | 4,4 |
| 1979-10-22 | 2H00 | MON | 6,1 | - | - | - | - | - | 4,4 |
| 1979-10-22 | 4H00 | MON | 6,0 | - | - | - | - | - | 4,4 |
| 1979-10-22 | 6H00 | MON | 5,4 | - | - | - | - | - | 4,4 |
| 1979-10-22 | 8H00 | MON | 4.6 | - | - | - | - | - | 4,4 |
| 1979-10-22 | 10H00 | MON | 3,2 | - | - | - | - | - | 4,5 |
| 1979-10-23 | 12H00 | TUE | 5,0 | - | - | - | - | - | 5,7 |
| 1979-10-23 | 14H00 | TUE | 5,5 | - | - | - | - | - | 5,4 |
| 1979-10-23 | 16H00 | TUE | 6,0 | - | - | - | - | - | 5,6 |
| 1979-10-23 | 18H00 | TUE | 6,7 | - | - | - | - | - | 5,1 |
| 1979-10-23 | 20H00 | TUE | 6,0 | - | - | - | - | - | 5,0 |
| 1979-10-23 | 22H00 | TUE | 6,9 | - | - | - | - | - | 5,2 |
| 1979-10-23 | 24H00 | TUE | 7,5 | - | - | - | - | - | 5,0 |
| 1979-10-24 | 2H00 | WED | 7,0 | - | - | - | - | - | 5,0 |
| 1979-10-24 | 4H00 | WED | 6,6 | - | - | - | - | - | 5,1 |
| 1979-10-24 | 6H00 | WED | 6,0 | - | - | - | - | - | 5,2 |
| 1979-10-24 | 8H00 | WED | 4,9 | - | - | - | - | - | 5,2 |
| 1979-10-24 | 10H00 | WED | 4.1 | - | - | - | - | - | 5,0 |
| 1979-10-25 | 12H00 | THU | 4,0 | - | - | - | - | - | 3,1 |
| 1979-10-25 | 14H00 | THU | 4,7 | - | - | - | - | - | 2,7 |
| 1979-10-25 | 16H00 | THU | 5,1 | - | - | - | - | - | 2,3 |
| 1979-10-25 | 18H00 | THU | 6,2 | - | - | - | - | - | 2,7 |
| 1979-10-25 | 20H00 | THU | 7,0 | - | - | - | - | - | 2,7 |
| 1979-10-25 | 22H00 | THU | 7,4 | - | - | - | - | - | 2,8 |
| 1979-10-25 | 24H00 | THU | 7,1 | - | - | - | - | - | 2,9 |
| 1979-10-26 | 2H00 | FRI | 6,9 | - | - | - | - | - | 2,8 |
| 1979-10-26 | 4H00 | FRI | 6,5 | - | - | - | - | - | 2,9 |
| 1979-10-26 | 6H00 | FRI | 4,7 | - | - | - | - | - | 2,9 |
| 1979-10-26 | 8H00 | FRI | 5,9 | - | - | - | - | - | 2,9 |
| 1979-10-26 | 10H00 | FRI | 5,2 | - | - | - | - | - | 3,1 |
| 1979-10-26 | 12H00 | FRI | 4,7 | - | - | - | - | - | 2,7 |
| 1979-10-26 | 14H00 | FRI | 5,9 | - | - | - | - | - | 2,5 |
| 1979-10-26 | 16H00 | FRI | 6,4 | - | - | - | - | - | 1,8 |
| 1979-10-26 | 18H00 | FRI | 7,4 | - | - | - | - | - | 1,7 |
| 1979-10-26 | 20H00 | FRI | 7,9 | - | - | - | - | - | 1,8 |
| 1979-10-26 | 22H00 | FRI | 8,1 | - | - | - | - | - | 2,0 |
| 1979-10-26 | 24H00 | FRI | 7,8 | - | - | - | - | - | 2,4 |
| 1979-10-27 | 2H00 | SAT | 7,4 | - | - | - | - | - | 3,8 |
| 1979-10-27 | 4H00 | SAT | 6,8 | - | - | - | - | - | 2,6 |
| 1979-10-27 | 6H00 | SAT | 6,2 | - | - | - | - | - | 2,4 |
| 1979-10-27 | 8H00 | SAT | 5,7 | - | - | - | - | - | 2,2 |
| 1979-10-27 | 10H00 | SAT | 5,4 | - | - | - | - | - | 2,0 |
| NO. RESULTS | | | 48 | 0 | 0 | 0 | 0 | 0 | 48 |
| MEAN | | | 5,8 | - | - | - | - | - | 3,7 |
| STD. DEVIATION | | | 1,3 | - | - | - | - | - | 1,2 |

# ORTHO - PHOSPHATE AS P

| DATE | TIME | DAY | G1BE | G1Z12 | G1Z22 | G1Z32 | G1Z42 | G1Z52 | G1E2 |
|---|---|---|---|---|---|---|---|---|---|
| 1979-10-21 | 12H00 | SUN | 2,2 | 4,2 | 3,8 | 3,4 | 3,3 | 2,8 | 3,7 |
| 1979-10-21 | 14H00 | SUN | 2,1 | 3,1 | 3,2 | 3,2 | 3,3 | 2,8 | 3,8 |
| 1979-10-21 | 16H00 | SUN | 1,9 | 4,8 | 3,7 | 3,3 | 3,1 | 2,9 | 3,8 |
| 1979-10-21 | 18H00 | SUN | 2,3 | 5,6 | 3,4 | 3,8 | 3,2 | 3,0 | 3,8 |
| 1979-10-21 | 20H00 | SUN | 2,9 | 5,3 | 3,9 | 3,7 | 3,7 | 3,1 | 3,7 |
| 1979-10-21 | 22H00 | SUN | 3,5 | 4,8 | 3,6 | 4,0 | 3,6 | 3,0 | 3,8 |
| 1979-10-21 | 24H00 | SUN | 3,0 | 5,0 | 3,1 | 4,0 | 3,2 | 3,7 | 3,8 |
| 1979-10-22 | 2H00 | MON | 3,3 | 2,6 | 2,4 | 3,1 | 2,2 | 2,1 | 3,8 |
| 1979-10-22 | 4H00 | MON | 2,9 | 4,2 | 4,6 | 4,3 | - | - | 3,8 |
| 1979-10-22 | 6H00 | MON | 3,2 | 4,3 | 4,2 | 4,4 | - | - | 0,4 |
| 1979-10-22 | 8H00 | MON | 2,6 | 3,8 | 4,2 | 4,2 | 3,8 | 3,9 | 3,6 |
| 1979-10-22 | 10H00 | MON | 1,9 | 3,6 | 4,2 | 4,3 | 3,9 | 3,9 | 3,8 |
| 1979-10-23 | 12H00 | TUE | 3,0 | 8,2 | 5,5 | 5,0 | 5,1 | 5,4 | 5,2 |
| 1979-10-23 | 14H00 | TUE | 3,1 | 8,4 | 5,2 | 4,5 | 4,8 | 4,9 | 5,1 |
| 1979-10-23 | 16H00 | TUE | 3,8 | 10 | 5,3 | 4,5 | 4,6 | 4,4 | 4,9 |
| 1979-10-23 | 18H00 | TUE | 4,2 | 13 | - | 4,5 | 4,3 | 4,2 | 4,6 |
| 1979-10-23 | 20H00 | TUE | 4,8 | 17 | - | 4,8 | 4,1 | 4,2 | 4,5 |
| 1979-10-23 | 22H00 | TUE | 5,1 | 18 | 6,9 | 5,3 | 4,6 | 4,3 | 4,6 |
| 1979-10-23 | 24H00 | TUE | 4,9 | 19 | 7,1 | 5,4 | 4,9 | 4,5 | 4,5 |
| 1979-10-24 | 2H00 | WED | 4,3 | 17 | 7,7 | 6,0 | 5,3 | 4,7 | 4,4 |
| 1979-10-24 | 4H00 | WED | 4,2 | 18 | 7,6 | 5,4 | 5,3 | 4,8 | 4,5 |
| 1979-10-24 | 6H00 | WED | 3,8 | 15 | 6,9 | 5,4 | 5,2 | 4,8 | 4,6 |
| 1979-10-24 | 8H00 | WED | 3,6 | 11 | 5,7 | 4,8 | 4,8 | 4,4 | 4,6 |
| 1979-10-24 | 10H00 | WED | 2,8 | 7,3 | 4,9 | 4,2 | 4,4 | 4,3 | 4,4 |
| 1979-10-25 | 12H00 | THU | 2,8 | 7,3 | 3,4 | 2,6 | 3,0 | 2,6 | 3,1 |
| 1979-10-25 | 14H00 | THU | 3,1 | 10 | 3,1 | 2,9 | 2,5 | 2,6 | 2,7 |
| 1979-10-25 | 16H00 | THU | 3,4 | 16 | 3,9 | 2,5 | 2,4 | 2,2 | 2,3 |
| 1979-10-25 | 18H00 | THU | 4,6 | 18 | 4,9 | 3,0 | 2,5 | 2,2 | 2,4 |
| 1979-10-25 | 20H00 | THU | 4,6 | 19 | 5,7 | 3,5 | 2,8 | 2,4 | 2,5 |
| 1979-10-25 | 22H00 | THU | 4,7 | 19 | 6,2 | 3,9 | 3,1 | 2,6 | 2,6 |
| 1979-10-25 | 24H00 | THU | 4,6 | 20 | 6,5 | 4,1 | 3,4 | 3,2 | 2,7 |
| 1979-10-26 | 2H00 | FRI | 4,6 | 18 | 7,0 | 4,5 | 3,9 | 3,2 | 2,8 |
| 1979-10-26 | 4H00 | FRI | 4,4 | 17 | 7,2 | 4,6 | 3,9 | 3,1 | 2,9 |
| 1979-10-26 | 6H00 | FRI | 3,1 | 19 | 7,4 | 4,7 | 4,0 | 3,3 | 2,9 |
| 1979-10-26 | 8H00 | FRI | 4,1 | 15 | 6,4 | 4,4 | 3,9 | 3,4 | 2,9 |
| 1979-10-26 | 10H00 | FRI | 3,5 | 11 | 5,1 | 3,8 | 3,8 | 3,1 | 3,1 |
| 1979-10-26 | 12H00 | FRI | 2,8 | 5,4 | 4,2 | 3,2 | 3,3 | 2,7 | - |
| 1979-10-26 | 14H00 | FRI | 3,6 | 6,2 | 3,7 | 2,9 | 2,8 | 2,5 | - |
| 1979-10-26 | 16H00 | FRI | 3,9 | 8,6 | 4,3 | 2,6 | 2,3 | 1,8 | - |
| 1979-10-26 | 18H00 | FRI | 4,5 | 9,3 | 5,0 | 3,8 | 2,5 | 1,7 | - |
| 1979-10-26 | 20H00 | FRI | 4,6 | 9,5 | 5,6 | 3,1 | 2,4 | 1,8 | - |
| 1979-10-26 | 22H00 | FRI | 5,0 | 10 | 5,9 | 3,2 | 2,5 | 1,9 | - |
| 1979-10-26 | 24H00 | FRI | 4,7 | 9,6 | 6,1 | 3,7 | 2,9 | 2,2 | - |
| 1979-10-27 | 2H00 | SAT | 4,5 | 6,2 | 3,5 | 3,4 | 3,3 | 3,7 | - |
| 1979-10-27 | 4H00 | SAT | 3,9 | 6,3 | 3,4 | 3,2 | 3,1 | 2,5 | - |
| 1979-10-27 | 6H00 | SAT | 3,1 | 8,2 | 5,5 | 3,4 | 3,0 | 2,3 | - |
| 1979-10-27 | 8H00 | SAT | 3,2 | 8,8 | 4,9 | 2,7 | 3,0 | 2,2 | - |
| 1979-10-27 | 10H00 | SAT | 2,8 | 5,3 | 4,5 | 2,4 | 2,4 | 1,5 | - |
| NO. RESULTS | | | 48 | 48 | 46 | 48 | 46 | 46 | 36 |
| MEAN | | | 3,6 | 10 | 5,0 | 3,9 | 3,6 | 3,2 | 3,6 |
| STD. DEVIATION | | | 0,9 | 5,5 | 1,4 | 0,9 | 0,9 | 1,0 | 1,0 |

# APPENDIX A5

## OXYGEN CONSUMPTION RATE

| Date | Time of Day h | Oxygen Consumption Rate mg/l/h | | | Date | Time of Day h | Oxygen Consumption Rate mg/l/h | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Position in Aeration basin | | | | | Position in Aeration basin | | |
| | | Start | Middle | End | | | Start | Middle | End |
| 21/22 | 1200 | 10,3 | 9,8 | 8,4 | 23/24 | 1200 | 11,9 | 10,2 | 7,0 |
| October | 1400 | 9,8 | 8,8 | 8,0 | October | 1400 | 13,9 | 9,2 | 7,7 |
| 1979 | 1600 | 18,9 | 9,7 | 7,2 | 1979 | 1600 | 16,4 | 12,1 | 7,7 |
| | 1800 | 29,5 | 14,1 | 7,7 | | 1800 | 21,3 | 13,5 | 7,7 |
| | 2000 | 20,5 | 14,1 | 7,2 | | 2000 | 23,0 | 18.1 | 8,8 |
| | 2200 | 19,7 | 11,3 | 6,8 | | 2200 | 20,5 | 22,3 | 8,9 |
| | 2400 | 13,9 | 10,6 | 8,3 | | 2400 | 19,7 | 19,5 | 8,3 |
| | 0200 | 10,3 | 9,2 | 8,4 | | 0200 | 20,5 | 20,3 | 8,8 |
| | 0400 | 9,8 | 8,5 | 8,8 | | 0400 | 20,5 | 14,8 | 8,8 |
| | 0600 | 8,9 | 8,5 | 7,7 | | 0600 | 16,4 | 10,6 | 9,3 |
| | 0800 | 8,4 | 7,8 | 7,2 | | 0800 | 8,2 | 19,7 | 8,8 |
| | 1000 | 7,8 | 7,1 | 7,9 | | 1000 | 10,0 | 22,6 | 8,3 |
| 25/26 | 1200 | 24,6 | 19,7 | 5,9 | 26/27 | 1200 | 18,0 | 10,6 | 9,3 |
| October | 1400 | 25,5 | 21,2 | 6,2 | October | 1400 | 21,1 | 11,3 | 9,3 |
| 1979 | 1600 | 29,8 | 18,3 | 9,3 | 1979 | 1600 | 29,9 | 16,9 | 9,8 |
| | 1800 | 32,3 | 21,2 | 9,8 | | 1800 | 29,5 | 24,0 | 9,3 |
| | 2000 | 30,6 | 28,2 | 10,3 | | 2000 | 32,8 | 31,0 | 11,6 |
| | 2200 | 42,5 | 28,2 | 16,5 | | 2200 | 31,2 | 21,2 | 21,7 |
| | 2400 | 32,3 | 25,4 | 11,1 | | 2400 | 35,9 | 28,2 | 21,2 |
| | 0200 | 34,0 | 28,2 | 10,3 | | 0200 | 35,7 | 29,6 | 14,0 |
| | 0400 | 34,0 | 15,6 | 9,8 | | 0400 | 35,4 | 28,3 | 9,3 |
| | 0600 | 30,6 | 18,3 | 9,6 | | 0600 | 30,6 | 18,3 | 9,3 |
| | 0800 | 27,2 | 12,0 | 9,0 | | 0800 | 22,1 | 12,7 | 10,3 |
| | 1000 | 20,6 | 10,2 | 9,3 | | 1000 | 17,2 | 11,3 | 9,8 |

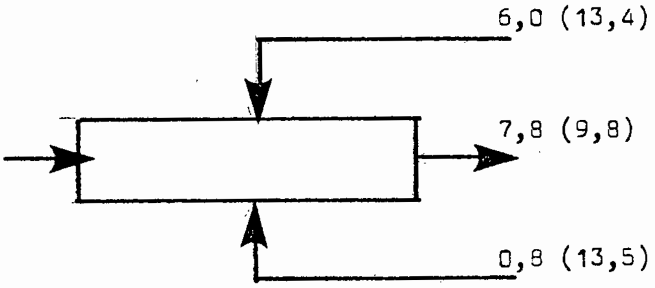
## APPENDIX A 6.1.

## GOUDKOPPIE PLANT

## CALCULATION OF NITROGEN BALANCE

### a) Nitrogen loss due to denitrification

#### Primary anaerobic/anoxic zones



Figures in brackets depict the nitrate concentration and the other figures depict the flow relative to the incoming flow

Nitrogen loss in first anaerobic/anoxic basins $= NO_3/N_{in} - NO_3/N_{out}$

$= 6{,}0\ (13{,}4) + 0{,}88\ (13{,}5) - 7{,}88\ (9{,}8)$

$= 80{,}4 + 11{,}9 - 77{,}2$

$= 92{,}3 - 77{,}2$

$= 15{,}1$ mg N/l

#### Secondary anoxic zone

Nitrate loss in the secondary anoxic zone due to denitrification is depicted below.

In this case the flows entering and leaving the second anoxic zone are the same. The figures depict the nitrate concentration in and out of this zone.

Hence the nitrate nitrogen loss $= NO_3/N_{in} - NO_3/N_{out}$

$= 13{,}4 - 12{,}5$

$= 0{,}9$ mg N/l

b) Total loss of nitrogen

The total loss of nitrogen due to denitrification $= 15{,}1 + 0{,}9$

$= 16{,}0$ mg N/l

Nitrogen balance

TKN influent = 35 mg N/l

TKN effluent = 2,0 mg N/l

$NO_3$ in effluent = 13,5 mg N/l

Nitrogen in waste sludge $= \dfrac{f_n X_v V}{R_s Q}$

$f_n$ = nitrogen fraction of the sludge = 0,1

$X_v$ = VSS volatile fraction of MLSS = 0,72 MLSS

V = volume of process (l)

Q = flow to plant (l/d)

$R_s$ = Sludge age (d)

Hence nitrogen loss in waste sludge $= \dfrac{0{,}1 \,.\, 0{,}72 \,.\, 1940 \,.\, 29{,}080 \times 10^6}{22 \,.\, 30400 \times 10^6}$

$= 6{,}1$ mg/l

Nitrogen loss due to denitrification = 16,0 mg N/l

Total concentration of nitrogen removed = 2,0 + 13,5 + 6,1 + 16,0

= 37,6 mg N/l

Hence nitrogen recovery $= \frac{37{,}6}{35} \times 100$

$= 107\ \%$

## APPENDIX A 6.2.

## GOUDKOPPIE PLANT

## CALCULATION OF COD BALANCE

One mg/l of nitrate nitrogen is equivalent to 2,85 mg/l of oxygen. The equivalent oxygen demand for denitrification for the process is denoted by $O_{dp}$

$$\text{Hence } O_{dp} = \frac{2{,}85 \text{ (nitrogen loss due to denitrification) } Q}{24 \times V}$$

$$= \frac{2{,}85 \; (15{,}1 + 0{,}9) \; . \; 30{,}4 \times 10^6}{24 \; . \; 29{,}080 \times 10^6}$$

$$= 1{,}99 \text{ mg/l/h}$$

→

For every 1 mg N/l of ammonia converted to nitrate 4,57 mg O/l of oxygen are consumed. The nitrification oxygen demand for the process is denoted $O_{np}$.

$$\text{Hence } O_{np} = \frac{4{,}57 \text{ (}NO_3\text{ loss during denitrification + }NO_3\text{ in effluent) } Q}{24 \times V}$$

$$= \frac{4{,}57 \; (16{,}0 + 13{,}5) \; . \; 30{,}4 \times 10^6}{24 \; . \; 29{,}08 \times 10^6}$$

$$= 5{,}88 \text{ mg/l/h}$$

→

The oxygen consumption rate for the two aeration zones is as follows:

Primary aeration zone = $O_{t1}$ = 16,2 mg/l/h

Secondary aeration zone = $O_{t2}$ = 9,5 mg/l/h

The total oxygen demand for the process is denoted by $O_{tp}$

$$O_{tp} = \frac{O_{t1}(\text{Vol. primary aeration basin}) + 9{,}5(\text{Vol. secondary aeration basin})}{\text{Total volume}}$$

$$= \frac{16{,}2\ (14{,}7 \times 10^6)\ +\ 9{,}5\ (2{,}7 \times 10^6)}{29{,}08 \times 10^6}$$

$$= \frac{238 + 26}{29{,}08}$$

$$\doteq 9{,}1 \quad \text{mg/l/h}$$

$\longrightarrow$

Equivqlent carbon oxygen demand for the process is denoted by $O_{cp}$

$$O_{cp} = O_{tp} + O_{dp} - O_{np}$$

$$= 9{,}1 + 1{,}99 - 5{,}88$$

$$= 5{,}21 \quad \text{mg/l/h}$$

$\longrightarrow$

<u>Carbonaceous material balance</u>

Influent COD = 270 mg/l Effluent COD = 63 mg/l

$$\text{Oxygen demand} = \frac{O_{cp} \cdot 24\ V}{Q}$$

$$= \frac{5{,}21 \cdot 24 \cdot 29{,}08 \times 10^6}{30{,}4 \times 10^6}$$

$$= 119{,}6 \quad \text{mg/l}$$

$$\text{COD loss in waste sludge} = \frac{P\ X_v\ V}{R_s\ Q}$$

$P = 1{,}48$

$X_v = 0{,}72$ MLSS mg/l

Hence

$$\text{Loss} = \frac{1{,}48 \cdot 0{,}72 \cdot 1940 \cdot 29{,}08 \times 10^6}{22 \cdot 30{,}4 \times 10^6}$$

$$= 89{,}9 \quad \text{mg/l}$$

$\longrightarrow$

Total COD recovered $= 63 + 119{,}6 + 89{,}8$

$= 273$ mg/l COD

% recovery $= \frac{273}{272} \times 100$

$= 99{,}8$

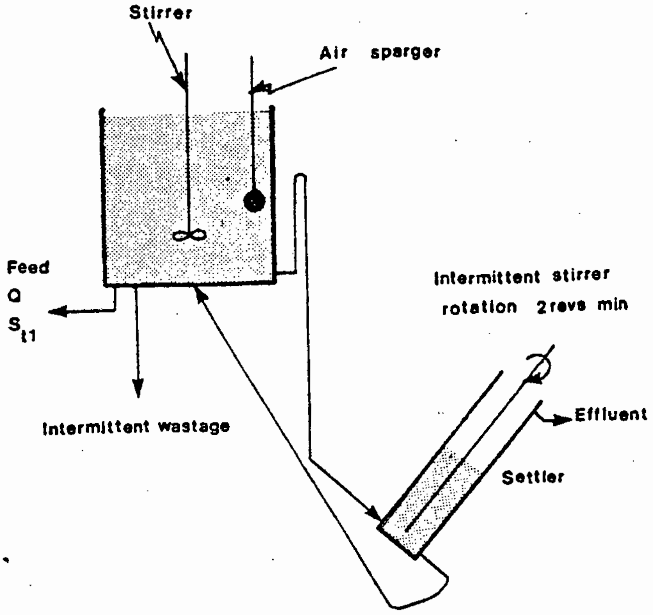
→

## APPENDIX A7

## CALCULATION OF READILY BIODEGRADABLE INFLUENT COD FRACTION

### 1. Reactor configuration

Single reactor (aerobic) with return of settled sludge.



### 2. Operation

1) Each day collect the volume of waste to be fed over 24 hours (Q litres) at the same time each day - place in a feed container which is stirred enough to keep solids in suspension, but not too much or else oxygen is taken up.

2) The feed pump must be set to feed the volume Q litres over 34 hours (± 1/2 hour) It is convenient to start the feed at, say, 9 a.m. Take a sample for COD analysis ($S_{ti}$).

3) Several hours after feed has started (say 2 p.m.) measure the Oxygen Utilisation Rate (OUR) as follows:
With additional air supply, raise D.O. in reactor to about 7 - 8 mg O/l With feed still on, switch off air supply and monitor drop in D.O. with time. Call this $OUR_Q$ mg O/l/h

4) After first OUR test raise D.O. again to about 7 - 8 mg O/l Switch off feed pump. After about 3 minutes switch off air supply and measure OUR again Call this

$OUR_{no\ Q}$ mg O/l/h

5) Restart feed. After about 1/2 hour steps 3 and 4 could be repeated to obtain more data if required.

## 3. Calculation

Q = feed rate (l/d)
V = reactor volume (l)

1) $\Delta O = (OUR_Q - OUR_{no\ Q})$ mg O/l/h

2) Easily biodegradable COD concentration

$$S_{bsi} = \frac{\Delta O \cdot V \cdot 3{,}33 \cdot 24}{Q}$$

3) Fraction of total COD which is easily biodegradable

$= S_{bsi} / S_{ti}$

4) or Fraction of total biodegradable COD which is easily biodegradable

$f_{bs} = f_{ca} = S_{bsi} / S_{ti}(1 - f_{us} - PF_{up})$

## 4. Example calculation for Goudkoppie data

BTE data:

$Q = 50$ l/d

$V = 7{,}5$ l

$S_{ti} = 370$ mg COD/l

$OUR_Q = 24{,}1$ mg O/l/h

$OUR_{no\ Q} = 20{,}1$ mg O/l/h

$$\Delta O = 24{,}1 - 20{,}1 = 4{,}0 \text{ mg O/l/h}$$

$$S_{bsi} = \frac{4{,}0 \cdot 7{,}5 \cdot 3{,}33 \cdot 24}{50{,}0}$$

$$= 48 \text{ mg COD/l}$$

Therefore fraction of total COD which is easily biodegradable

$$= 48 / 370 = 0{,}13 \text{ mg COD/mg COD}$$

## 3. Advice about loading rate

In order to obtain accurate results it is desirable that OUR is not too small i.e. 4 mg O/l/h. The load on the plant should be such that the $OUR_Q$ is about 35 - 40 mg O/l/h. This can be obtained if the loading rate is about

$$\frac{QS_{ti}}{V} = \frac{36 \cdot 500}{7} \approx 2\ 500 \text{ mg COD/l reactor/d}$$

However, if $S_{ti}$ is well below 500 mg COD/l, then Q may have to be very large to obtain this load. Q must not be so large that the retention time is less than about 0,15 day. i e V/Q not less than 0,15 day

# APPENDIX A8

## NORTHERN WORKS

The raw data obtained during the experimental period

### CODE

| | |
|---|---|
| N3 BE 3 | Balancing tank effluent |
| N3 Z 13 | Anaerobic zone |
| N3 Z 23 | Primary anoxic zone |
| N3 Z 33 | Primary aeration zone |
| N3 Z 43 | Secondary anoxic zone |
| N3 E 3 | Effluent |

## CHEMICAL OXYGEN DEMAND AS O

| DATE | TIME | DAY | N3BE3 | N3Z13 | N3Z23 | N3Z33 | N3Z43 | N3Z53 | N3E3 |
|---|---|---|---|---|---|---|---|---|---|
| 1980- 8-10 | 7H00 | SUN | 250 | - | - | - | - | - | 60 |
| 1980- 8-10 | 9H00 | SUN | 230 | - | - | - | - | - | 60 |
| 1980- 8-10 | 11H00 | SUN | 200 | - | - | - | - | - | 50 |
| 1980- 8-10 | 13H00 | SUN | 160 | - | - | - | - | - | 50 |
| 1980- 8-10 | 15H00 | SUN | 190 | - | - | - | - | - | 55 |
| 1980- 8-10 | 17H00 | SUN | 190 | - | - | - | - | - | 35 |
| 1980- 8-10 | 19H00 | SUN | 220 | - | - | - | - | - | 40 |
| 1980- 8-10 | 21H00 | SUN | 230 | - | - | - | - | - | 40 |
| 1980- 8-10 | 23H00 | SUN | 250 | - | - | - | - | - | 50 |
| 1980- 8-11 | 1H00 | MON | 300 | - | - | - | - | - | 45 |
| 1980- 8-11 | 3H00 | MON | 310 | - | - | - | - | - | 50 |
| 1980- 8-11 | 5H00 | MON | 290 | - | - | - | - | - | 45 |
| 1980- 8-11 | 7H00 | MON | 220 | - | - | - | - | - | 45 |
| 1980- 8-11 | 9H00 | MON | 210 | - | - | - | - | - | 60 |
| 1980- 8-11 | 11H00 | MON | 180 | - | - | - | - | - | 45 |
| 1980- 8-11 | 13H00 | MON | 170 | - | - | - | - | - | 40 |
| 1980- 8-11 | 15H00 | MON | 230 | - | - | - | - | - | 40 |
| 1980- 8-11 | 17H00 | MON | 230 | - | - | - | - | - | 35 |
| 1980- 8-11 | 19H00 | MON | 260 | - | - | - | - | - | 40 |
| 1980- 8-11 | 21H00 | MON | 290 | - | - | - | - | - | 40 |
| 1980- 8-11 | 23H00 | MON | 300 | - | - | - | - | - | 40 |
| 1980- 8-12 | 1H00 | TUE | 290 | - | - | - | - | - | 51 |
| 1980- 8-12 | 3H00 | TUE | 290 | - | - | - | - | - | 35 |
| 1980- 8-12 | 5H00 | TUE | 280 | - | - | - | - | - | 35 |
| 1980- 8-14 | 7H00 | THU | 260 | - | - | - |  | - | 40 |
| 1980- 8-14 | 9H00 | THU | 230 | - | - | - |  | - | 45 |
| 1980- 8-14 | 11H00 | THU | 210 | - | - | - |  | - | 45 |
| 1980- 8-14 | 13H00 | THU | 130 | - | - | - |  | - | 35 |
| 1980- 8-14 | 15H00 | THU | 200 | - | - | - |  | - | 40 |
| 1980- 8-14 | 17H00 | THU | 210 | - | - | - |  | - | 35 |
| 1980- 8-14 | 19H00 | THU | 230 | - | - | - |  | - | 45 |
| 1980- 8-14 | 21H00 | THU | 240 | - | - | - |  | - | 66 |
| 1980- 8-14 | 23H00 | THU | 250 | - | - | - |  | - | 45 |
| 1980- 8-15 | 1H00 | FRI | 300 | - | - | - | - | - | 56 |
| 1980- 8-15 | 3H00 | FRI | 280 | - | - | - | - | - | 56 |
| 1980- 8-15 | 5H00 | FRI | 280 | - | - | - | - | - | 45 |
| 1980- 8-15 | 7H00 | FRI | 220 | - | - | - | - | - | 56 |
| 1980- 8-15 | 9H00 | FRI | 210 | - | - | - | - | - | 61 |
| 1980- 8-15 | 11H00 | FRI | 180 | - | - | - | - | - | 40 |
| 1980- 8-15 | 13H00 | FRI | 150 | - | - | - | - | - | 51 |
| 1980- 8-15 | 15H00 | FRI | 220 | - | - | - | - | - | 45 |
| 1980- 8-15 | 17H00 | FRI | 260 | - | - | - | - | - | 45 |
| 1980- 8-15 | 19H00 | FRI | 270 | - | - | - | - | - | 40 |
| 1980- 8-15 | 21H00 | FRI | 280 | - | - | - | - | - | 51 |
| 1980- 8-15 | 23H00 | FRI | 280 | - | - | - | - | - | 45 |
| 1980- 8-16 | 1H00 | SAT | 280 | - | - | - | - | - | 45 |
| 1980- 8-16 | 3H00 | SAT | 290 | - | - | - | - | - | 51 |
| 1980- 8-16 | 5H00 | SAT | 280 | - | - | - | - | - | 51 |
| NO. RESULTS |  |  | 48 | 0 | 0 | 0 |  | 0 | 48 |
| MEAN |  |  | 240 | - | - | - |  | - | 46 |
| STD. DEVIATION |  |  | 43 | - | - | - |  | - | 8 |

## CHEMICAL OXYGEN DEMAND (SOLUBLE) AS O

| DATE | TIME | DAY | N3BE3 | N3E3 | N3Z13 | N3Z23 | N3Z33 | N3Z43 | N3Z53 |
|---|---|---|---|---|---|---|---|---|---|
| 1980- 8-10 | 7H00 | SUN | 210 | 35 | 80 | 45 | 50 | 35 | 30 |
| 1980- 8-10 | 9H00 | SUN | 210 | 35 | 70 | 50 | 55 | 35 | 45 |
| 1980- 8-10 | 11H00 | SUN | 200 | 30 | 70 | 45 | 35 | 30 | 35 |
| 1980- 8-10 | 13H00 | SUN | 140 | 35 | 65 | 40 | 50 | 35 | 50 |
| 1980- 8-10 | 15H00 | SUN | 130 | 45 | 70 | 50 | 40 | 70 | 50 |
| 1980- 8-10 | 17H00 | SUN | 130 | 30 | 80 | 40 | 45 | 40 | 30 |
| 1980- 8-10 | 19H00 | SUN | 150 | 35 | 75 | 40 | 45 | 35 | 35 |
| 1980- 8-10 | 21H00 | SUN | 160 | 35 | 85 | 40 | 35 | 35 | 30 |
| 1980- 8-10 | 23H00 | SUN | 180 | 35 | 65 | 45 | 35 | 40 | 25 |
| 1980- 8-11 | 1H00 | MON | 190 | 45 | 76 | 45 | 40 | 25 | 40 |
| 1980- 8-11 | 3H00 | MON | 230 | 35 | 71 | 51 | 35 | 25 | 40 |
| 1980- 8-11 | 5H00 | MON | 210 | 35 | 66 | 51 | 30 | 30 | 45 |
| 1980- 8-11 | 7H00 | MON | 180 | 40 | 66 | 40 | 30 | 40 | 40 |
| 1980- 8-11 | 9H00 | MON | 170 | 35 | 66 | 40 | 35 | 35 | 40 |
| 1980- 8-11 | 11H00 | MON | 150 | 45 | 56 | 35 | 45 | 35 | 35 |
| 1980- 8-11 | 13H00 | MON | 110 | 40 | 61 | 35 | 30 | 40 | 35 |
| 1980- 8-11 | 15H00 | MON | 140 | 35 | 66 | 76 | 30 | 35 | 40 |
| 1980- 8-11 | 17H00 | MON | 170 | 35 | 66 | 51 | 35 | 35 | 30 |
| 1980- 8-11 | 19H00 | MON | 190 | 30 | 71 | 51 | 30 | 35 | 35 |
| 1980- 8-11 | 21H00 | MON | 220 | 30 | 71 | 40 | 35 | 40 | 40 |
| 1980- 8-11 | 23H00 | MON | 230 | 40 | 66 | 45 | 30 | 45 | 35 |
| 1980- 8-12 | 1H00 | TUE | 200 | 45 | 85 | 45 | 35 | 30 | 25 |
| 1980- 8-12 | 3H00 | TUE | 210 | 35 | 85 | 45 | 35 | 30 | 25 |
| 1980- 8-12 | 5H00 | TUE | 220 | 30 | 75 | 50 | 30 | 35 | 30 |
| 1980- 8-14 | 7H00 | THU | 160 | 40 | 80 | 51 | 60 | 15 | 45 |
| 1980- 8-14 | 9H00 | THU | 160 | 35 | 75 | 45 | 50 | 15 | 40 |
| 1980- 8-14 | 11H00 | THU | 130 | 35 | 70 | 45 | 45 | 14 | 40 |
| 1980- 8-14 | 13H00 | THU | 100 | 35 | 70 | 35 | 45 | 14 | 35 |
| 1980- 8-14 | 15H00 | THU | 130 | 35 | 70 | 35 | 45 | 14 | 35 |
| 1980- 8-14 | 17H00 | THU | 130 | 35 | 60 | 35 | 45 | 14 | 35 |
| 1980- 8-14 | 19H00 | THU | 150 | 35 | 65 | 30 | 35 | 15 | 35 |
| 1980- 8-14 | 21H00 | THU | 150 | 35 | 55 | 45 | 50 | 15 | 35 |
| 1980- 8-14 | 23H00 | THU | 160 | 45 | 80 | 61 | 55 | 16 | 50 |
| 1980- 8-15 | 1H00 | FRI | 160 | 45 | 80 | 56 | 50 | 45 | 45 |
| 1980- 8-15 | 3H00 | FRI | 160 | 35 | 85 | 40 | 50 | 55 | 35 |
| 1980- 8-15 | 5H00 | FRI | 160 | 40 | 80 | 45 | 40 | 50 | 35 |
| 1980- 8-15 | 7H00 | FRI | 140 | 30 | 90 | 40 | 50 | 35 | 35 |
| 1980- 8-15 | 9H00 | FRI | 130 | 50 | 65 | 40 | 40 | 30 | 35 |
| 1980- 8-15 | 11H00 | FRI | 110 | 35 | 55 | 40 | 45 | 45 | 45 |
| 1980- 8-15 | 13H00 | FRI | 91 | 40 | 55 | 40 | 50 | 40 | 45 |
| 1980- 8-15 | 15H00 | FRI | 130 | 35 | 55 | 45 | 45 | 45 | 45 |
| 1980- 8-15 | 17H00 | FRI | 160 | 40 | 75 | 40 | 40 | 50 | 35 |
| 1980- 8-15 | 19H00 | FRI | 170 | 35 | 96 | 35 | 40 | 30 | 40 |
| 1980- 8-15 | 21H00 | FRI | 170 | 35 | 71 | 35 | 40 | 40 | 30 |
| 1980- 8-15 | 23H00 | FRI | 170 | 35 | 66 | 40 | 60 | 35 | 30 |
| 1980- 8-16 | 1H00 | SAT | 190 | 35 | 91 | 56 | 50 | 40 | 45 |
| 1980- 8-16 | 3H00 | SAT | 190 | 35 | 81 | 51 | 50 | 35 | 50 |
| 1980- 8-16 | 5H00 | SAT | 160 | 40 | 81 | 71 | 50 | 40 | 40 |
| NO. RESULTS | | | 48 | 48 | 48 | 48 | 48 | 48 | 48 |
| MEAN | | | 160 | 37 | 72 | 45 | 42 | 34 | 38 |
| STD. DEVIATION | | | 34 | 5 | 10 | 9 | 8 | 12 | 7 |

# AMMONIA AS N

| DATE | TIME | DAY | N3BE3 | N3Z13 | N3Z23 | N3Z33 | N3Z43 | N3Z53 | N3E3 |
|---|---|---|---|---|---|---|---|---|---|
| 1980- 8-10 | 7H00 | SUN | 24 | 14 | 5,4 | 0,0 | 0,0 | 0,0 | 0,0 |
| 1980- 8-10 | 9H00 | SUN | 24 | 14 | 5,4 | 0,0 | 0,0 | 0,0 | 0,0 |
| 1980- 8-10 | 11H00 | SUN | 24 | 14 | 5,2 | 0,0 | 0,0 | 0,0 | 0,0 |
| 1980- 8-10 | 13H00 | SUN | 24 | 14 | 5,2 | 0,0 | 0,0 | 0,0 | 0,0 |
| 1980- 8-10 | 15H00 | SUN | 26 | 14 | 5,2 | 0,0 | 0,0 | 0,0 | 0,0 |
| 1980- 8-10 | 17H00 | SUN | 29 | 15 | 7,2 | 0,0 | 0,0 | 0,0 | 0,0 |
| 1980- 8-10 | 19H00 | SUN | 29 | 16 | 6,4 | 0,0 | 0,0 | 0,0 | 0,0 |
| 1980- 8-10 | 21H00 | SUN | 30 | 15 | 5,2 | 0,0 | 0,0 | 0,0 | 0,0 |
| 1980- 8-10 | 23H00 | SUN | 29 | 14 | 6,4 | 0,0 | 0,0 | 0,0 | 0,0 |
| 1980- 8-11 | 1H00 | MON | 23 | 22 | 12 | 2,5 | 3,0 | 0,0 | 0,0 |
| 1980- 8-11 | 3H00 | MON | 24 | 21 | 11 | 2,0 | 2,5 | 0,0 | 0,0 |
| 1980- 8-11 | 5H00 | MON | 23 | 21 | 11 | 1,5 | 2,0 | 0,0 | 0,0 |
| 1980- 8-11 | 7H00 | MON | 23 | 23 | 12 | 1,5 | 2,5 | 0,0 | 0,0 |
| 1980- 8-11 | 9H00 | MON | 21 | 23 | 12 | 1,5 | 3,5 | 0,0 | 0,0 |
| 1980- 8-11 | 11H00 | MON | 21 | 21 | 11 | 0,0 | 0,0 | 0,0 | 0,0 |
| 1980- 8-11 | 13H00 | MON | 22 | 21 | 11 | 1,5 | 0,0 | 0,0 | 0,0 |
| 1980- 8-11 | 15H00 | MON | 29 | 26 | 12 | 2,0 | 0,0 | 0,0 | 0,0 |
| 1980- 8-11 | 17H00 | MON | 29 | 25 | 14 | 2,0 | 0,0 | 0,0 | 0,0 |
| 1980- 8-11 | 19H00 | MON | 28 | 26 | 14 | 2,5 | 2,5 | 0,0 | 0,0 |
| 1980- 8-11 | 21H00 | MON | 27 | 25 | 13 | 3,0 | 3,5 | 0,0 | 0,0 |
| 1980- 8-11 | 23H00 | MON | 23 | 23 | 13 | 2,5 | 2,5 | 0,0 | 0,0 |
| 1980- 8-12 | 1H00 | TUE | 24 | 16 | 7,0 | 1,8 | 1,0 | 0,0 | 0,0 |
| 1980- 8-12 | 3H00 | TUE | 25 | 15 | 7,0 | 1,1 | 0,0 | 0,0 | 0,0 |
| 1980- 8-12 | 5H00 | TUE | 23 | 14 | 6,3 | 1,1 | 0,0 | 0,0 | 0,0 |
| 1980- 8-14 | 7H00 | THU | 19 | 12 | 4,5 | 0,0 | 0,0 | 0,0 | 0,0 |
| 1980- 8-14 | 9H00 | THU | 19 | 11 | 4,2 | 0,0 | 0,0 | 0,0 | 0,0 |
| 1980- 8-14 | 11H00 | THU | 17 | 12 | 3,9 | 0,0 | 0,0 | 0,0 | 0,0 |
| 1980- 8-14 | 13H00 | THU | 19 | 11 | 3,4 | 0,0 | 0,0 | 0,0 | 0,0 |
| 1980- 8-14 | 15H00 | THU | 28 | 15 | 4,4 | 0,0 | 0,0 | 0,0 | 0,0 |
| 1980- 8-14 | 17H00 | THU | 23 | 15 | 4,6 | 0,0 | 0,0 | 0,0 | 0,0 |
| 1980- 8-14 | 19H00 | THU | 11 | 16 | 4,7 | 0,0 | 0,0 | 0,0 | 0,0 |
| 1980- 8-14 | 21H00 | THU | 21 | 16 | 5,0 | 0,0 | 0,0 | 0,0 | 0,0 |
| 1980- 8-14 | 23H00 | THU | 24 | 16 | 5,3 | 0,0 | 0,0 | 0,0 | 0,0 |
| 1980- 8-15 | 1H00 | FRI | 22 | 13 | 4,9 | 1,1 | 0,0 | 0,3 | 0,0 |
| 1980- 8-15 | 3H00 | FRI | 20 | 13 | 4,4 | 0,5 | 0,0 | 0,0 | 0,6 |
| 1980- 8-15 | 5H00 | FRI | 20 | 12 | 4,1 | 0,0 | 0,0 | 0,0 | 0,7 |
| 1980- 8-15 | 7H00 | FRI | 20 | 14 | 4,6 | 0,0 | 0,0 | 0,2 | 0,0 |
| 1980- 8-15 | 9H00 | FRI | 20 | 12 | 4,1 | 0,6 | 0,0 | 0,0 | 0,0 |
| 1980- 8-15 | 11H00 | FRI | 18 | 12 | 3,9 | 0,7 | 0,0 | 0,2 | 0,0 |
| 1980- 8-15 | 13H00 | FRI | 20 | 11 | 3,8 | 0,8 | 0,0 | 0,0 | 0,0 |
| 1980- 8-15 | 15H00 | FRI | 28 | 15 | 4,8 | 0,6 | 0,0 | 0,0 | 0,0 |
| 1980- 8-15 | 17H00 | FRI | 28 | 16 | 5,0 | 0,6 | 0,0 | 0,0 | 0,0 |
| 1980- 8-15 | 19H00 | FRI | 24 | 16 | 5,3 | 0,6 | 0,0 | 0,0 | 0,0 |
| 1980- 8-15 | 21H00 | FRI | 26 | 13 | 4,8 | 0,9 | 0,0 | 0,0 | 0,0 |
| 1980- 8-15 | 23H00 | FRI | 22 | 14 | 5,5 | 1,1 | 0,0 | 0,0 | 0,0 |
| 1980- 8-16 | 1H00 | SAT | 24 | 13 | 5,6 | 0,0 | 0,0 | 0,0 | 0,0 |
| 1980- 8-16 | 3H00 | SAT | 24 | 14 | 5,1 | 0,8 | 0,0 | 0,0 | 0,0 |
| 1980- 8-16 | 5H00 | SAT | 22 | 12 | 4,5 | 0,7 | 0,0 | 0,0 | 0,0 |
| NO. RESULTS | | | 48 | 48 | 48 | 48 | 48 | 48 | 48 |
| MEAN | | | 24 | 16 | 6,8 | 0,7 | 0,5 | 0,0 | 0,0 |
| STD. DEVIATION | | | 3,9 | 4,4 | 3,3 | 0,9 | 1,1 | 0,1 | 0,1 |

# NITRATE AS N

| DATE | TIME | DAY | N3BE3 | N3Z13 | N3Z23 | N3Z33 | N3Z43 | N3Z53 | N3E3 |
|---|---|---|---|---|---|---|---|---|---|
| 1980- 8-10 | 7H00 | SUN | - | 5,0 | 9,7 | 16 | 17 | 18 | 15 |
| 1980- 8-10 | 9H00 | SUN | - | 3,7 | 9,7 | 16 | 15 | 15 | 15 |
| 1980- 8-10 | 11H00 | SUN | - | 3,7 | 9,7 | 15 | 15 | 15 | 15 |
| 1980- 8-10 | 13H00 | SUN | - | 3,8 | 9,8 | 15 | 15 | 15 | 15 |
| 1980- 8-10 | 15H00 | SUN | - | 4,0 | 9,8 | 15 | 15 | 15 | 15 |
| 1980- 8-10 | 17H00 | SUN | - | 4,4 | 11 | 15 | 15 | 15 | 15 |
| 1980- 8-10 | 19H00 | SUN | - | 4,3 | 9,6 | 16 | 16 | 15 | 15 |
| 1980- 8-10 | 21H00 | SUN | - | 4,0 | 9,8 | 16 | 16 | 15 | 15 |
| 1980- 8-10 | 23H00 | SUN | - | 5,0 | 12 | - | 14 | 15 | 17 |
| 1980- 8-11 | 1H00 | MON | - | 4,7 | 11 | 17 | 17 | 18 | 19 |
| 1980- 8-11 | 3H00 | MON | - | 4,7 | 10 | 17 | 16 | 17 | 19 |
| 1980- 8-11 | 5H00 | MON | - | 4,0 | 10 | 16 | 16 | 16 | 19 |
| 1980- 8-11 | 7H00 | MON | - | 5,1 | 12 | 18 | 18 | 18 | 18 |
| 1980- 8-11 | 9H00 | MON | - | 4,6 | 12 | 19 | 18 | 18 | 18 |
| 1980- 8-11 | 11H00 | MON | - | 5,5 | 12 | 18 | 17 | 18 | 18 |
| 1980- 8-11 | 13H00 | MON | - | 5,1 | 12 | 18 | 17 | 17 | 18 |
| 1980- 8-11 | 15H00 | MON | - | 4,8 | 12 | 18 | 17 | 17 | 18 |
| 1980- 8-11 | 17H00 | MON | - | 5,5 | 12 | 19 | 17 | 18 | 18 |
| 1980- 8-11 | 19H00 | MON | - | 4,9 | 13 | 19 | 17 | 18 | 18 |
| 1980- 8-11 | 21H00 | MON | - | 4,8 | 13 | 19 | 18 | 19 | 18 |
| 1980- 8-11 | 23H00 | MON | - | 5,5 | 12 | 18 | 18 | 19 | 18 |
| 1980- 8-12 | 1H00 | TUE | - | 2,0 | 8,6 | 15 | 14 | 15 | 15 |
| 1980- 8-12 | 3H00 | TUE | - | 2,2 | 8,3 | 15 | 14 | 15 | 14 |
| 1980- 8-12 | 5H00 | TUE | - | 2,2 | 8,4 | 15 | 14 | 15 | 14 |
| 1980- 8-14 | 7H00 | THU | - | 3,2 | 9,4 | 16 | 15 | 18 | 16 |
| 1980- 8-14 | 9H00 | THU | - | 2,9 | 8,6 | 15 | 15 | 16 | 15 |
| 1980- 8-14 | 11H00 | THU | - | 3,2 | 9,1 | 15 | 14 | 15 | 15 |
| 1980- 8-14 | 13H00 | THU | - | 3,4 | 8,8 | 15 | 14 | 15 | 15 |
| 1980- 8-14 | 15H00 | THU | - | 3,6 | 9,5 | 15 | 14 | 13 | 15 |
| 1980- 8-14 | 17H00 | THU | - | 3,5 | 9,7 | 16 | 14 | 14 | 15 |
| 1980- 8-14 | 19H00 | THU | - | 3,3 | 9,2 | 16 | 15 | 15 | 15 |
| 1980- 8-14 | 21H00 | THU | - | 3,2 | 8,6 | 16 | 15 | 14 | 15 |
| 1980- 8-14 | 23H00 | THU | - | 4,1 | 11 | 18 | 16 | 17 | 16 |
| 1980- 8-15 | 1H00 | FRI | - | 4.5 | 11 | 18 | 17 | 18 | 18 |
| 1980- 8-15 | 3H00 | FRI | - | 4,3 | 11 | 17 | 16 | 17 | 17 |
| 1980- 8-15 | 5H00 | FRI | - | 4.2 | 11 | 17 | 16 | 17 | 18 |
| 1980- 8-15 | 7H00 | FRI | - | 4,1 | 11 | 17 | 17 | 17 | 17 |
| 1980- 8-15 | 9H00 | FRI | - | 4,6 | 11 | 17 | 16 | 17 | 17 |
| 1980- 8-15 | 11H00 | FRI | - | 4,9 | 12 | 17 | 17 | 17 | 17 |
| 1980- 8-15 | 13H00 | FRI | - | 5,4 | 11 | 16 | 16 | 17 | 17 |
| 1980- 8-15 | 15H00 | FRI | - | 5,0 | 11 | 16 | 16 | 17 | 17 |
| 1980- 8-15 | 17H00 | FRI | - | 5,0 | 11 | 17 | 16 | 17 | 17 |
| 1980- 8-15 | 19H00 | FRI | - | 6,2 | 12 | 18 | 16 | 17 | 17 |
| 1980- 8-15 | 21H00 | FRI | - | 4,9 | 11 | 18 | 16 | 17 | 17 |
| 1980- 8-15 | 23H00 | FRI | - | 5,3 | 12 | 18 | 17 | 18 | 18 |
| 1980- 8-16 | 1H00 | SAT | - | 4,6 | 10 | 17 | 16 | 17 | 16 |
| 1980- 8-16 | 3H00 | SAT | - | 4,3 | 10 | 17 | 16 | 17 | 17 |
| 1980- 8-16 | 5H00 | SAT | - | 4,1 | 11 | 17 | 17 | 17 | 17 |
| NO. RESULTS | | | 0 | 48 | 48 | 47 | 48 | 48 | 48 |
| MEAN | | | - | 4,3 | 10 | 17 | 16 | 16 | 17 |
| STD. DEVIATION | | | - | 0,9 | 1,1 | 1,3 | 1,2 | 1,5 | 1,4 |

## TOTAL PHOSPHORUS AS P

| DATE | TIME | DAY | N3BE3 | N3Z13 | N3Z23 | N3Z33 | N3Z43 | N3Z53 | N3E3 |
|---|---|---|---|---|---|---|---|---|---|
| 1980- 8-10 | 7H00 | SUN | 9,0 | - | - | - | - | - | 7,4 |
| 1980- 8-10 | 9H00 | SUN | 9,2 | - | - | - | - | - | 7,3 |
| 1980- 8-10 | 11H00 | SUN | 10 | - | - | - | - | - | 7,3 |
| 1980- 8-10 | 13H00 | SUN | 8,0 | - | - | - | - | - | 7,2 |
| 1980- 8-10 | 15H00 | SUN | 8,4 | - | - | - | - | - | 7,1 |
| 1980- 8-10 | 17H00 | SUN | 8,0 | - | - | - | - | - | 7,4 |
| 1980- 8-10 | 19H00 | SUN | 8,8 | - | - | - | - | - | 7,8 |
| 1980- 8-10 | 21H00 | SUN | 9,6 | - | - | - | - | - | 9,0 |
| 1980- 8-10 | 23H00 | SUN | 9,8 | - | - | - | - | - | 8,0 |
| 1980- 8-11 | 1H00 | MON | 15 | - | - | - | - | - | 7,1 |
| 1980- 8-11 | 3H00 | MON | 15 | - | - | - | - | - | 7,2 |
| 1980- 8-11 | 5H00 | MON | 15 | - | - | - | - | - | 7,3 |
| 1980- 8-11 | 7H00 | MON | 9,0 | - | - | - | - | - | 7,2 |
| 1980- 8-11 | 9H00 | MON | 8,4 | - | - | - | - | - | 7,3 |
| 1980- 8-11 | 11H00 | MON | 7,6 | - | - | - | - | - | 7,4 |
| 1980- 8-11 | 13H00 | MON | 7,4 | - | - | - | - | - | 7,3 |
| 1980- 8-11 | 15H00 | MON | 9,6 | - | - | - | - | - | 7,3 |
| 1980- 8-11 | 17H00 | MON | 11 | - | - | - | - | - | 7,0 |
| 1980- 8-11 | 19H00 | MON | 13 | - | - | - | - | - | 6,8 |
| 1980- 8-11 | 21H00 | MON | 14 | - | - | - | - | - | 6,9 |
| 1980- 8-11 | 23H00 | MON | 15 | - | - | - | - | - | 7,2 |
| 1980- 8-12 | 1H00 | TUE | 11 | - | - | - | - | - | 7,7 |
| 1980- 8-12 | 3H00 | TUE | 9,6 | - | - | - | - | - | 8,0 |
| 1980- 8-12 | 5H00 | TUE | 9,2 | - | - | - | - | - | 7,6 |
| 1980- 8-14 | 7H00 | THU | 8,0 | - | - | - | - | - | 8,4 |
| 1980- 8-14 | 9H00 | THU | 7,6 | - | - | - | - | - | 8,2 |
| 1980- 8-14 | 11H00 | THU | 6,6 | - | - | - | - | - | 8,2 |
| 1980- 8-14 | 13H00 | THU | 6,2 | - | - | - | - | - | 8,4 |
| 1980- 8-14 | 15H00 | THU | 7,2 | - | - | - | - | - | 8,0 |
| 1980- 8-14 | 17H00 | THU | 8,0 | - | - | - | - | - | 7,8 |
| 1980- 8-14 | 19H00 | THU | 8,8 | - | - | - | - | - | 7,6 |
| 1980- 8-14 | 21H00 | THU | 9,6 | - | - | - | - | - | 7,7 |
| 1980- 8-14 | 23H00 | THU | 10 | - | - | - | - | - | 7,4 |
| 1980- 8-15 | 1H00 | FRI | 12 | - | - | - | - | - | 7,6 |
| 1980- 8-15 | 3H00 | FRI | 10 | - | - | - | - | - | 8,6 |
| 1980- 8-15 | 5H00 | FRI | 10 | - | - | - | - | - | 8,7 |
| 1980- 8-15 | 7H00 | FRI | 7,8 | - | - | - | - | - | 8,5 |
| 1980- 8-15 | 9H00 | FRI | 7,0 | - | - | - | - | - | 8,7 |
| 1980- 8-15 | 11H00 | FRI | 6,2 | - | - | - | - | - | 7,5 |
| 1980- 8-15 | 13H00 | FRI | 6,4 | - | - | - | - | - | 7,2 |
| 1980- 8-15 | 15H00 | FRI | 8,0 | - | - | - | - | - | 7,3 |
| 1980- 8-15 | 17H00 | FRI | 10 | - | - | - | - | - | 7,1 |
| 1980- 8-15 | 19H00 | FRI | 11 | - | - | - | - | - | 7,0 |
| 1980- 8-15 | 21H00 | FRI | 12 | - | - | - | - | - | 7,0 |
| 1980- 8-15 | 23H00 | FRI | 12 | - | - | - | - | - | 7,3 |
| 1980- 8-16 | 1H00 | SAT | 11 | - | - | - | - | - | 7,1 |
| 1980- 8-16 | 3H00 | SAT | 11 | - | - | - | - | - | 8,1 |
| 1980- 8-16 | 5H00 | SAT | 9,4 | - | - | - | - | - | 7,8 |
| NO. RESULTS | | | 48 | 0 | 0 | 0 | 0 | 0 | 48 |
| MEAN | | | 9,7 | - | - | - | - | - | 7,6 |
| STD. DEVIATION | | | 2,4 | - | - | - | - | - | 0,5 |

## ORTHO – PHOSPHATE AS P

| DATE | TIME | DAY | N3BE3 | N3Z13 | N3Z23 | N3Z33 | N3Z43 | N3Z53 | N3E3 |
|---|---|---|---|---|---|---|---|---|---|
| 1980- 8-10 | 7H00 | SUN | 6,4 | 7,0 | 6,8 | 6,6 | 6,4 | 6,0 | 6,2 |
| 1980- 8-10 | 9H00 | SUN | 6,0 | 6,6 | 6,6 | 6,4 | 7,0 | 6,2 | 6,2 |
| 1980- 8-10 | 11H00 | SUN | 5,2 | 6,6 | 4,6 | 6,4 | 6,8 | 6,2 | 6,3 |
| 1980- 8-10 | 13H00 | SUN | 4,6 | 3,0 | 6,4 | 6,4 | 6,4 | 6,0 | 6,3 |
| 1980- 8-10 | 15H00 | SUN | 4,8 | 5,8 | 6,0 | 6,2 | 6,0 | 5,8 | 6,3 |
| 1980- 8-10 | 17H00 | SUN | 5,2 | 5,8 | 6,0 | 5,8 | 6,0 | 5,8 | 6,4 |
| 1980- 8-10 | 19H00 | SUN | 5,6 | 6,4 | 5,6 | 6,0 | 6,2 | 5,6 | 6,3 |
| 1980- 8-10 | 21H00 | SUN | 6,2 | 6,8 | 5,8 | 5,8 | 6,2 | 5,6 | 6,4 |
| 1980- 8-10 | 23H00 | SUN | 6,6 | 6,6 | 6,4 | 5,8 | 6,2 | 5,6 | 5,9 |
| 1980- 8-11 | 1H00 | MON | 9,0 | 8,3 | 7,5 | 7,1 | 7,1 | 7,0 | 6,3 |
| 1980- 8-11 | 3H00 | MON | 9,4 | 8,6 | 8,0 | 7,6 | 7,7 | 7,5 | 6,3 |
| 1980- 8-11 | 5H00 | MON | 9,4 | 8,5 | 8,0 | 7,9 | 7,9 | 7,7 | 6,2 |
| 1980- 8-11 | 7H00 | MON | 6,2 | 6,5 | 6,4 | 6,4 | 6,5 | 6,4 | 6,1 |
| 1980- 8-11 | 9H00 | MON | 5,8 | 6,3 | 6,2 | 6,3 | 6,3 | 6,4 | 6,1 |
| 1980- 8-11 | 11H00 | MON | 5,2 | 5,7 | 6,0 | 6,1 | 6,4 | 6,2 | 6,3 |
| 1980- 8-11 | 13H00 | MON | 4,6 | 5,4 | 5,7 | 5,9 | 6,3 | 7,8 | 6,2 |
| 1980- 8-11 | 15H00 | MON | 6,0 | 5,9 | 5,7 | 5,8 | 6,0 | 6,1 | 6,2 |
| 1980- 8-11 | 17H00 | MON | 7,6 | 6,3 | 6,1 | 5,8 | 6,0 | 6,0 | 6,2 |
| 1980- 8-11 | 19H00 | MON | 8,4 | 7,0 | 6,4 | 6,2 | 6,1 | 6,0 | 6,1 |
| 1980- 8-11 | 21H00 | MON | 8,8 | 7,3 | 6,8 | 6,6 | 6,4 | 6,4 | 6,2 |
| 1980- 8-11 | 23H00 | MON | 9,4 | 7,9 | 7,3 | 6,8 | 6,7 | 6,7 | 6,2 |
| 1980- 8-12 | 1H00 | TUE | 8,2 | 8,1 | 7,6 | 7,3 | 7,4 | 7,4 | 7,2 |
| 1980- 8-12 | 3H00 | TUE | 7,4 | 7,9 | 7,6 | 7,3 | 7,6 | 7,5 | 7,3 |
| 1980- 8-12 | 5H00 | TUE | 6,8 | 7,7 | 7,6 | 7,5 | 7,7 | 7,6 | 7,4 |
| 1980- 8-14 | 7H00 | THU | 6,0 | 7,5 | 7,1 | 7,1 | 7,0 | 7,1 | 7,0 |
| 1980- 8-14 | 9H00 | THU | 5,4 | 7,3 | 7,0 | 7,1 | 7,0 | 7,1 | 7,0 |
| 1980- 8-14 | 11H00 | THU | 4,6 | 6,6 | 6,7 | 6,9 | 6,9 | 7,0 | 7,1 |
| 1980- 8-14 | 13H00 | THU | 3,8 | 5,8 | 6,4 | 6,6 | 6,7 | 6,8 | 6,9 |
| 1980- 8-14 | 15H00 | THU | 4,8 | 6,2 | 6,2 | 6,3 | 6,5 | 6,8 | 6,9 |
| 1980- 8-14 | 17H00 | THU | 5,8 | 6,8 | 6,4 | 6,2 | 6,3 | 6,5 | 6,7 |
| 1980- 8-14 | 19H00 | THU | 4,8 | 7,3 | 6,5 | 6,2 | 6,3 | 6,3 | 6,6 |
| 1980- 8-14 | 21H00 | THU | 5,0 | 7,6 | 6,7 | 6,3 | 6,4 | 6,4 | 6,6 |
| 1980- 8-14 | 23H00 | THU | 7,6 | 7,3 | 6,6 | 6,4 | 6,3 | 6,2 | 6,3 |
| 1980- 8-15 | 1H00 | FRI | 8,0 | 7,8 | 6,9 | 6,8 | 6,5 | 6,4 | 6,3 |
| 1980- 8-15 | 3H00 | FRI | 7,2 | 7,9 | 7,3 | 7,0 | 6,7 | 6,8 | 6,8 |
| 1980- 8-15 | 5H00 | FRI | 7,4 | 7,6 | 7,1 | 6,9 | 6,9 | 7,0 | 6,9 |
| 1980- 8-15 | 7H00 | FRI | 6,0 | 7,0 | 6,7 | 6,6 | 6,6 | 6,6 | 6,5 |
| 1980- 8-15 | 9H00 | FRI | 5,0 | 6,4 | 6,6 | 6,5 | 6,5 | 6,5 | 6,5 |
| 1980- 8-15 | 11H00 | FRI | 4,0 | 6,5 | 6,4 | 6,6 | 6,4 | 6,4 | 6,6 |
| 1980- 8-15 | 13H00 | FRI | 4,0 | 5,9 | 6,3 | 6,5 | 6,5 | 6,5 | 6,5 |
| 1980- 8-15 | 15H00 | FRI | 5,6 | 5,9 | 6,1 | 6,2 | 6,1 | 6,2 | 6,5 |
| 1980- 8-15 | 17H00 | FRI | 6,8 | 6,8 | 6,1 | 6,2 | 6,1 | 6,0 | 6,4 |
| 1980- 8-15 | 19H00 | FRI | 7,8 | 6,9 | 6,4 | 6,2 | 6,1 | 6,0 | 6,4 |
| 1980- 8-15 | 21H00 | FRI | 8,2 | 7,8 | 6,8 | 6,6 | 6,4 | 6,3 | 6,4 |
| 1980- 8-15 | 23H00 | FRI | 8,8 | 7,5 | 6,8 | 6,6 | 6,4 | 6,3 | 6,4 |
| 1980- 8-16 | 1H00 | SAT | 8,0 | 7,5 | 7,0 | 6,6 | 6,7 | 6,7 | 6,4 |
| 1980- 8-16 | 3H00 | SAT | 7,8 | 7,7 | 6,9 | 6,5 | 6,6 | 6,6 | 6,9 |
| 1980- 8-16 | 5H00 | SAT | 7,2 | 7,1 | 7,0 | 6,9 | 6,7 | 6,8 | 6,7 |
| NO. RESULTS | | | 48 | 48 | 48 | 48 | 48 | 48 | 48 |
| MEAN | | | 6,5 | 6,9 | 6,6 | 6,5 | 6,6 | 6,5 | 6,5 |
| STD. DEVIATION | | | 1,6 | 1,0 | 0,7 | 0,5 | 0,5 | 0,6 | 0,3 |

# KJELDAHL NITROGEN AS N

| DATE | TIME | DAY | N3BE3 | N3Z13 | N3Z23 | N3Z33 | N3Z43 | N3Z53 | N3E3 |
|---|---|---|---|---|---|---|---|---|---|
| 1980- 8-10 | 7H00 | SUN | 36 | - | - | - | - | - | 2,6 |
| 1980- 8-10 | 9H00 | SUN | 34 | - | - | - | - | - | 2,8 |
| 1980- 8-10 | 11H00 | SUN | 34 | - | - | - | - | - | 2,3 |
| 1980- 8-10 | 13H00 | SUN | 33 | - | - | - | - | - | 2,6 |
| 1980- 8-10 | 15H00 | SUN | 38 | - | - | - | - | - | 1,9 |
| 1980- 8-10 | 17H00 | SUN | 43 | - | - | - | - | - | 1,6 |
| 1980- 8-10 | 19H00 | SUN | 42 | - | - | - | - | - | 1,3 |
| 1980- 8-10 | 21H00 | SUN | 45 | - | - | - | - | - | 1,6 |
| 1980- 8-10 | 23H00 | SUN | 42 | - | - | - | - | - | 2,3 |
| 1980- 8-11 | 1H00 | MON | 33 | - | - | - | - | - | 1,3 |
| 1980- 8-11 | 3H00 | MON | 38 | - | - | - | - | - | 1,4 |
| 1980- 8-11 | 5H00 | MON | 38 | - | - | - | - | - | 1,3 |
| 1980- 8-11 | 7H00 | MON | 36 | - | - | - | - | - | 1,4 |
| 1980- 8-11 | 9H00 | MON | 34 | - | - | - | - | - | 1,4 |
| 1980- 8-11 | 11H00 | MON | 32 | - | - | - | - | - | 1,4 |
| 1980- 8-11 | 13H00 | MON | 32 | - | - | - | - | - | 1,3 |
| 1980- 8-11 | 15H00 | MON | 44 | - | - | - | - | - | 1,5 |
| 1980- 8-11 | 17H00 | MON | 42 | - | - | - | - | - | 1,1 |
| 1980- 8-11 | 19H00 | MON | 42 | - | - | - | - | - | 1,6 |
| 1980- 8-11 | 21H00 | MON | 40 | - | - | - | - | - | 1,3 |
| 1980- 8-11 | 23H00 | MON | 38 | - | - | - | - | - | 1,3 |
| 1980- 8-12 | 1H00 | TUE | 37 | - | - | - | - | - | 2,2 |
| 1980- 8-12 | 3H00 | TUE | 33 | - | - | - | - | - | 1,9 |
| 1980- 8-12 | 5H00 | TUE | 32 | - | - | - | - | - | 1,5 |
| 1980- 8-14 | 7H00 | THU | 34 | - | - | - | - | - | 3,5 |
| 1980- 8-14 | 9H00 | THU | 36 | - | - | - | - | - | 3,2 |
| 1980- 8-14 | 11H00 | THU | 34 | - | - | - | - | - | 2,5 |
| 1980- 8-14 | 13H00 | THU | 38 | - | - | - | - | - | 2,2 |
| 1980- 8-14 | 15H00 | THU | 48 | - | - | - | - | - | 2,8 |
| 1980- 8-14 | 17H00 | THU | 44 | - | - | - | - | - | 2,4 |
| 1980- 8-14 | 19H00 | THU | 46 | - | - | - | - | - | 2,4 |
| 1980- 8-14 | 21H00 | THU | 44 | - | - | - | - | - | 2,6 |
| 1980- 8-14 | 23H00 | THU | 44 | - | - | - | - | - | 2,5 |
| 1980- 8-15 | 1H00 | FRI | 40 | - | - | - | - | - | 1,6 |
| 1980- 8-15 | 3H00 | FRI | 34 | - | - | - | - | - | 3,0 |
| 1980- 8-15 | 5H00 | FRI | 38 | - | - | - | - | - | 2,8 |
| 1980- 8-15 | 7H00 | FRI | 38 | - | - | - | - | - | 3,0 |
| 1980- 8-15 | 9H00 | FRI | 33 | - | - | - | - | - | 2,6 |
| 1980- 8-15 | 11H00 | FRI | 32 | - | - | - | - | - | 2,9 |
| 1980- 8-15 | 13H00 | FRI | 36 | - | - | - | - | - | 1,7 |
| 1980- 8-15 | 15H00 | FRI | 46 | - | - | - | - | - | 2,6 |
| 1980- 8-15 | 17H00 | FRI | 50 | - | - | - | - | - | 2,1 |
| 1980- 8-15 | 19H00 | FRI | 44 | - | - | - | - | - | 3,0 |
| 1980- 8-15 | 21H00 | FRI | 40 | - | - | - | - | - | 2,2 |
| 1980- 8-15 | 23H00 | FRI | 38 | - | - | - | - | - | 2,8 |
| 1980- 8-16 | 1H00 | SAT | 38 | - | - | - | - | - | 1,7 |
| 1980- 8-16 | 3H00 | SAT | 42 | - | - | - | - | - | 2,8 |
| 1980- 8-16 | 5H00 | SAT | 34 | - | - | - | - | - | 3,3 |
| NO. RESULTS | | | 48 | 0 | 0 | 0 | 0 | 0 | 48 |
| MEAN | | | 39 | - | - | - | - | - | 2,1 |
| STD. DEVIATION | | | 4,6 | - | - | - | - | - | 0,7 |

# APPENDIX A8

## OXYGEN CONSUMPTION RATE

## NORTHERN WORKS

| Date | Time of Day h | Oxygen Consumption Rate mg/l/h<br>Position in Aeration Basin | | | Date | Time of Day h | Oxygen Consumption Rate mg/l/h<br>Position in Aeration Basin | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Start | Middle | End | | | Start | Middle | End |
| 10/8/80 | 0700 | 34,2 | 22,4 | 9,6 | 14/8/80 | 0700 | 32,4 | 29,8 | 8,7 |
| | 0900 | 34,2 | 22,4 | 8,7 | | 0900 | 34,2 | 29,8 | 6,3 |
| | 1100 | 34,2 | 34,0 | 7,8 | | 1100 | 32,4 | 27,2 | 4,8 |
| | 1300 | 33,4 | 28,1 | 7,8 | | 1300 | 32,4 | 23,8 | 6,3 |
| | 1500 | 32,4 | 22,1 | 6,9 | | 1500 | 36,0 | 26,4 | 5,4 |
| | 1700 | 34,2 | 26,4 | 7,5 | | 1700 | 36,0 | 29,8 | 6,0 |
| | 1900 | 34,2 | 28,1 | 7,5 | | 1900 | 36,0 | 28,9 | 10,2 |
| | 2100 | 36,0 | 30,6 | 10,5 | | 2100 | 32,4 | 30,6 | 14,7 |
| | 2300 | 36,0 | 26,4 | 13,2 | | 2300 | 32,4 | 29,8 | 13,8 |
| 11/8/80 | 0100 | 36,0 | 29,8 | - | 15/8/80 | 0100 | 34,2 | 29,8 | 12,6 |
| | 0300 | 36,0 | 31,5 | 7,5 | | 0300 | 32,4 | 28,9 | 11,7 |
| | 0500 | 36,0 | 32,3 | 10,5 | | 0500 | 34,2 | 27,2 | 12,3 |
| | 0700 | 36,7 | 31,5 | 9,0 | | 0700 | 34,2 | 28,1 | 7,2 |
| | 0900 | 34,0 | 28,9 | 8,7 | | 0900 | 34,2 | 26,4 | 6,0 |
| | 1100 | 33,4 | 27,2 | 7,8 | | 1100 | 37,5 | 23,0 | 5,1 |
| | 1300 | 34,0 | 23,8 | 7,2 | | 1300 | 37,5 | 27,2 | 5,1 |
| | 1500 | 31,6 | 23,0 | 6,3 | | 1500 | 40,5 | 26,4 | 4,8 |
| | 1700 | 28,2 | 21,3 | 7,5 | | 1700 | 39,0 | 28,9 | 7,5 |
| | 1900 | 34,0 | 31,5 | 13,5 | | 1900 | 39,0 | - | 10,8 |
| | 2100 | 35,2 | 32,3 | 18,6 | | 2100 | 39,0 | 30,6 | 12,9 |
| | 2300 | 36,0 | 26,4 | 13,2 | | 2300 | 39,0 | 30,6 | 11,7 |
| 12/8/80 | 0100 | 36,0 | 29,8 | - | 16/8/80 | 0100 | 36,0 | 28,9 | 13,2 |
| | 0300 | 36,0 | 31,5 | 7,5 | | 0300 | 36,0 | 28,1 | 15,6 |
| | 0500 | 36,0 | 32,3 | 10,5 | | 0500 | 36,0 | 28,9 | 9,6 |

# APPENDIX A 9

## NORTHERN WORKS

## NITROGEN BALANCE

| | | |
|---|---|---|
| TKN influent | (mg N/l) | 39 |
| TKN effluent | (mg N/l) | 2,1 |
| Nitrate nitrogen effluent | (mg N/l) | 17 |
| Total nitrogen in waste sludge | (mg N/l) | 2,9 |
| Nitrogen loss due to denitrification | (mg N/l) | 16,8 |
| Total nitrogen recovered | (mg N/l) | 38,8 |
| % recovery | | 99 |

## COD BALANCE

| | | |
|---|---|---|
| Influent COD | (mg/l) | 240 |
| Effluent COD | (mg/l) | 46 |
| Oxygen demand | (mg/l) | 128 |
| COD in waste sludge | (mg/l) | 43 |
| Total COD recovered | (mg/l) | 217 |
| % Recovery | | 90 |

# COD concentrations; raw sewage N3I, settled sewage N3TE, balancing tank effluent N3BE2

| | | | | N3I | N3TE | N3BE2 |
|---|---|---|---|---|---|---|
| 1980- | 7- 6 | 2H00 | SUN | 600 | 370 | 420 |
| 1980- | 7- 6 | 4H00 | SUN | 520 | 360 | 430 |
| 1980- | 7- 6 | 6H00 | SUN | 430 | 420 | 410 |
| 1980- | 7- 6 | 8H00 | SUN | 550 | 370 | 390 |
| 1980- | 7- 6 | 10H00 | SUN | 450 | 340 | 380 |
| 1980- | 7- 6 | 12H00 | SUN | 410 | 330 | 270 |
| 1980- | 7- 6 | 14H00 | SUN | 740 | 270 | 350 |
| 1980- | 7- 6 | 16H00 | SUN | 790 | 290 | 330 |
| 1980- | 7- 6 | 18H00 | SUN | 740 | 310 | 410 |
| 1980- | 7- 6 | 20H00 | SUN | 920 | 330 | 420 |
| 1980- | 7- 6 | 22H00 | SUN | 760 | 370 | 360 |
| 1980- | 7- 6 | 24H00 | SUN | 630 | 430 | 350 |
| 1980- | 7- 7 | 2H00 | MON | 510 | 360 | 390 |
| 1980- | 7- 7 | 4H00 | MON | 510 | 340 | 320 |
| 1980- | 7- 7 | 6H00 | MON | 430 | 310 | 330 |
| 1980- | 7- 7 | 8H00 | MON | 270 | 300 | 310 |
| 1980- | 7- 7 | 10H00 | MON | 310 | 280 | 240 |
| 1980- | 7- 7 | 12H00 | MON | 300 | 250 | 280 |
| 1980- | 7- 7 | 14H00 | MON | 440 | 320 | 290 |
| 1980- | 7- 7 | 16H00 | MON | 770 | 360 | 350 |
| 1980- | 7- 7 | 18H00 | MON | 610 | 410 | 390 |
| 1980- | 7- 7 | 20H00 | MON | 450 | 480 | 360 |
| 1980- | 7- 7 | 22H00 | MON | 640 | 360 | 350 |
| 1980- | 7- 7 | 24H00 | MON | 680 | 430 | 360 |
| 1980- | 7- 8 | 2H00 | TUE | 600 | 410 | 340 |
| 1980- | 7- 8 | 4H00 | TUE | 510 | 370 | 350 |
| 1980- | 7- 8 | 6H00 | TUE | 430 | 320 | 360 |
| 1980- | 7- 8 | 8H00 | TUE | 340 | 360 | 350 |
| 1980- | 7- 8 | 10H00 | TUE | 320 | 300 | 410 |
| 1980- | 7- 8 | 12H00 | TUE | 670 | 310 | 400 |
| 1980- | 7- 8 | 14H00 | TUE | 730 | 390 | 310 |
| 1980- | 7- 8 | 16H00 | TUE | 750 | 420 | 340 |
| 1980- | 7- 8 | 18H00 | TUE | 710 | 430 | 340 |
| 1980- | 7- 8 | 20H00 | TUE | 820 | 470 | 170 |
| 1980- | 7- 8 | 22H00 | TUE | 690 | 470 | 390 |
| 1980- | 7- 8 | 24H00 | TUE | 670 | 480 | 330 |
| 1980- | 7- 9 | 2H00 | WED | 680 | 450 | 240 |
| 1980- | 7- 9 | 4H00 | WED | 650 | 420 | 420 |
| 1980- | 7- 9 | 6H00 | WED | 420 | 440 | 420 |
| 1980- | 7- 9 | 8H00 | WED | 290 | 430 | 400 |
| 1980- | 7- 9 | 10H00 | WED | 290 | 360 | 360 |
| 1980- | 7- 9 | 12H00 | WED | 790 | 330 | 390 |
| 1980- | 7- 9 | 14H00 | WED | 590 | 310 | 340 |
| 1980- | 7- 9 | 16H00 | WED | 590 | 380 | 400 |
| 1980- | 7- 9 | 18H00 | WED | 730 | 410 | 390 |
| 1980- | 7- 9 | 20H00 | WED | 710 | 420 | 420 |
| 1980- | 7- 9 | 22H00 | WED | 750 | 470 | 410 |
| 1980- | 7- 9 | 24H00 | WED | 760 | 460 | - |
| 1980- | 7-10 | 2H00 | THU | 790 | 450 | 410 |
| 1980- | 7-10 | 4H00 | THU | 630 | 470 | 410 |
| 1980- | 7-10 | 6H00 | THU | 660 | 450 | 390 |
| 1980- | 7-10 | 8H00 | THU | 200 | 290 | 380 |
| 1980- | 7-10 | 10H00 | THU | 250 | 230 | 370 |
| 1980- | 7-10 | 12H00 | THU | 650 | 280 | 330 |
| 1980- | 7-10 | 14H00 | THU | 700 | 340 | 300 |
| 1980- | 7-10 | 16H00 | THU | 760 | 370 | 310 |
| 1980- | 7-10 | 18H00 | THU | 730 | 370 | 320 |
| 1980- | 7-10 | 20H00 | THU | 700 | 390 | 340 |
| 1980- | 7-10 | 22H00 | THU | 660 | 440 | 350 |
| 1980- | 7-10 | 24H00 | THU | 660 | 370 | 370 |
| 1980- | 7-11 | 2H00 | FRI | 670 | 360 | 390 |
| 1980- | 7-11 | 4H00 | FRI | 670 | 390 | 370 |
| 1980- | 7-11 | 6H00 | FRI | 430 | 360 | 360 |
| 1980- | 7-11 | 8H00 | FRI | 750 | 330 | 330 |
| 1980- | 7-11 | 10H00 | FRI | 830 | 360 | 310 |
| 1980- | 7-11 | 12H00 | FRI | 840 | 280 | 310 |
| 1980- | 7-11 | 14H00 | FRI | 790 | 350 | 330 |
| 1980- | 7-11 | 16H00 | FRI | 760 | 370 | 370 |
| 1980- | 7-11 | 18H00 | FRI | 760 | 410 | 370 |
| 1980- | 7-11 | 20H00 | FRI | 760 | 400 | 360 |
| 1980- | 7-11 | 22H00 | FRI | 680 | 440 | 380 |
| 1980- | 7-11 | 24H00 | FRI | 680 | 450 | 380 |
| 1980- | 7-12 | 2H00 | SAT | 700 | 440 | 340 |
| 1980- | 7-12 | 4H00 | SAT | 720 | 420 | 350 |
| 1980- | 7-12 | 6H00 | SAT | 440 | 360 | 340 |
| 1980- | 7-12 | 8H00 | SAT | 370 | 400 | 290 |
| 1980- | 7-12 | 10H00 | SAT | 350 | 350 | 300 |
| 1980- | 7-12 | 12H00 | SAT | 330 | 800 | 280 |
| 1980- | 7-12 | 14H00 | SAT | 330 | 790 | 310 |
| 1980- | 7-12 | 16H00 | SAT | 350 | 780 | 350 |
| 1980- | 7-12 | 18H00 | SAT | 350 | 760 | 370 |
| 1980- | 7-12 | 20H00 | SAT | 370 | 790 | 360 |
| 1980- | 7-12 | 22H00 | SAT | 370 | 630 | 400 |
| 1980- | 7-12 | 24H00 | SAT | 370 | 700 | 410 |
| NO RESULTS | | | | 84 | 84 | 83 |
| MEAN | | | | 580 | 400 | 350 |
| STD. DEVIATION | | | | 180 | 120 | 50 |

19 JUL 1983