Biological phosphorus removal at the Johannesburg Northern and Goudkoppies wastewater purification plants*

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Abstract

Criteria for phosphate removal are described and the performance of two 150 Mℓ/d plants evaluated against these requirements. Improved performance was achieved by the addition of products generated by the fermentation of raw sludge either in acid digesters or in primary settling tanks, where improved sludge thickening was also recorded. Uptake of phosphorus in the primary anoxic zone is noted as requiring optimisation. Unexplained phosphorus release and uptake in the secondary anoxic and aerobic zones is documented and the need for further research indicated.

Introduction

Over the past decade numerous full-scale experiments to improve biological phosphorus removal have been conducted on two 5-stage Phoredox wastewater treatment plants in Johannesburg (Osborn, Pitman, and Venter, 1979; Nicholls, and Osborn 1979). In this paper these experiments are re-examined in terms of the current understanding of biological phosphorus removal. (Ekama, Siebritz and Marais, 1983; Marais, Loewenthal and Siebritz, 1983).

Criteria associated with good biological phosphorus removal

- An anaerobic reactor is required, the feed to which must preferably contain no oxygen and no nitrate (Barnard, 1974).
- Once the conditions, as stated above, have been met and provided there is sufficient readily biodegradable COD or volatile acids in the anaerobic reactor, release of phosphorus occurs. It would appear that this release is a prerequisite for excess phosphorus removal (Ekama, Siebritz and Marais, 1983).
- Significant quantities of phosphorus may be taken up in the primary anoxic reactor but the precise controlling factors are not known. Koch and Oldham (1984) have drawn attention to the usefulness of oxidation-reduction potentials (ORP) to define the conditions under which uptake or release of phosphorus takes place.
- The aerobic uptake of phosphorus is dependent *inter alia* upon the dissolved oxygen (DO) concentration; if too low, uptake is impaired and if too high, release occurs (Carberry and Tenney, 1973).
- When good uptake of phosphorus occurs, the phosphate concentration in the effluent from the primary aerobic reactor is almost always less than 1 mg o-P/ℓ (Figure 1a). Under these conditions the uptake rate is very rapid. By contrast, when limited uptake occurs, a slower rate is found (Fig. 1b), (Nicholls, 1978).
- Release of phosphorus in the second anoxic reactor is possible and it would appear that this is not governed by the same conditions as those causing release in the anaerobic reactor (Barnard, 1984).
- Adsorbed particulate COD will improve nitrogen removal in the second anoxic reactor by providing a source of energy for denitrifiers.

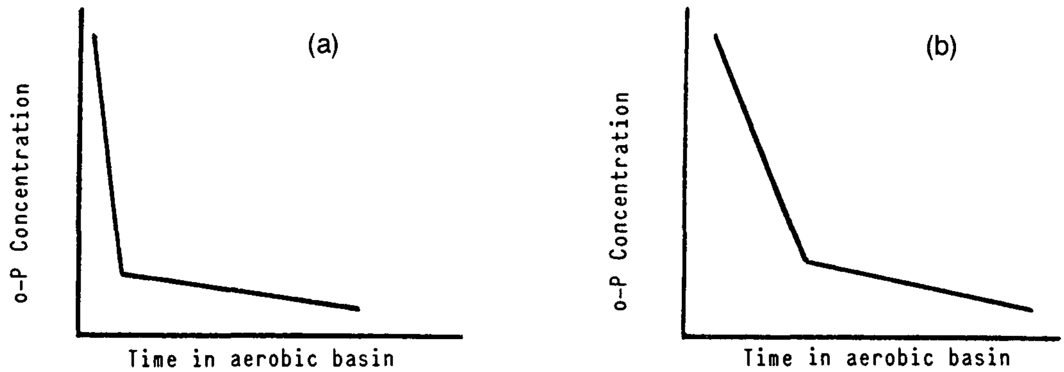

Figure 1
Typical uptake rates in aerobic basin
(a) during period of good P removal
(b) during period of average P removal

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These criteria will now be used to examine the performance of the Goudkoppies and Northern Works under different operating conditions.

Plant performance

The influence of nitrates on phosphorus removal

The data presented in Table 1 for the two Johannesburg Works represent a period when denitrification was inadequate and nitrates were returned to the anaerobic zone. Under such conditions, effective phosphorus removal is not achievable. By contrast, the Kelowna plant, receiving roughly the same strength of sewage, appears to achieve good denitrification. This difference is attributable to more effective nitrogen removal at Kelowna in the primary anoxic zone, which is sub-divided into three compartments and which promotes a more plug-flow regime. In the Johannesburg Works, the anoxic reactors are completely mixed.

Recent research at the University of Cape Town (UCT) suggests that this difference may be the key to improved nitrogen removal (Ekama and Marais, 1985). They found that when high loadings were applied to small aerobic fill and draw activated sludge units, the readily biodegradable COD utilisation rate increased by a factor of 3 when compared to a continuous feed system. Similarly, the rate of uptake of particulate COD increased by a factor of 1,5.

The data provide further support for the concept of "selectors" as proposed by Eikelboom (1982). He placed a small *aerated* plug-flow reactor with a retention time of only a few minutes ahead of the main activated sludge reactor, with the basic objective of providing a more concentrated food source for non-filamentous bacteria, thus to ensure their more selective rapid growth over filamentous organisms.

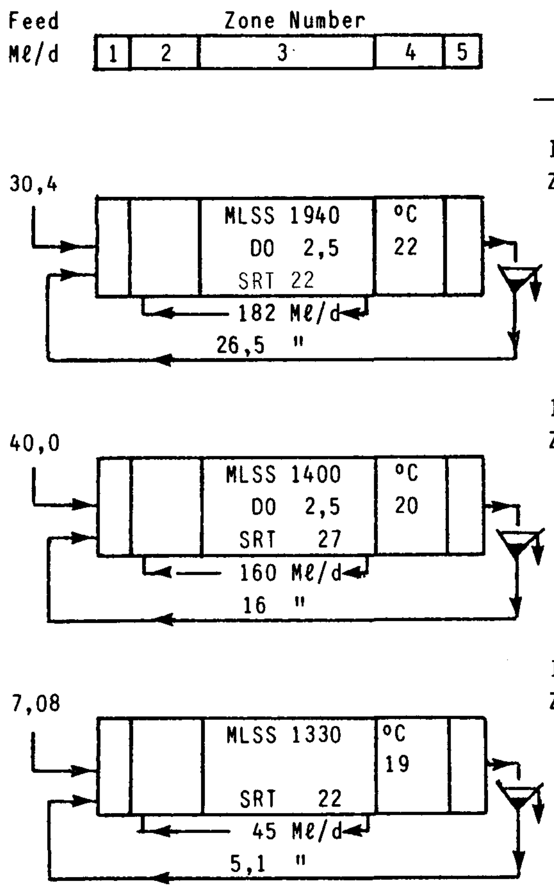
There is an urgent need to determine whether *non-aerated* selectors can be utilised to prevent the growth of unwanted filamentous bacteria. With this in mind, one 50 Mℓ/d module of the Northern Works has been modified to have compartmentalised anaerobic and anoxic zones, also incorporating a selector into the former.

Restriction of nitrification by limiting air supply

When the dissolved oxygen concentration at the Goudkoppies Works was reduced to such an extent that complete nitrification was impossible, the results shown in Table 2 were obtained and the following comments are offered:

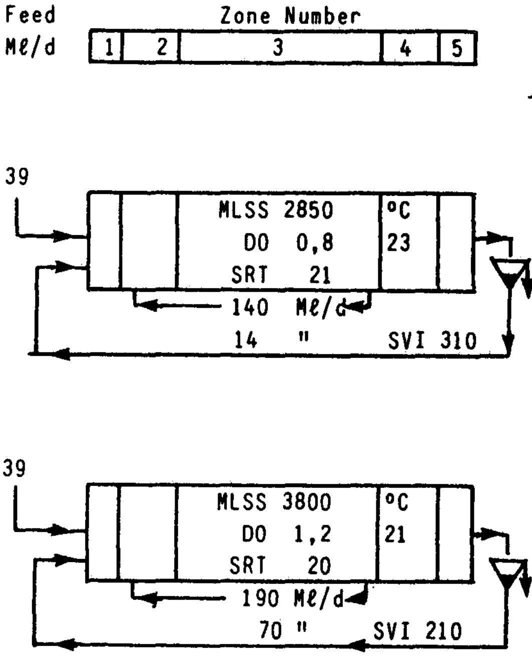
- Applying the UCT steady state model to this data (Marais and Ekama, 1976), effluent nitrate concentration was estimated to be 7,5 mg N/ℓ. The measured value was 4,6 mg N/ℓ which would suggest that 3 mg N/ℓ as nitrate was removed in the anoxic pockets artificially created in the aerobic zone.

TABLE 1
PERFORMANCE OF THE GOUDKOPPIES AND NORTHERN WORKS
Compared with the Kelowna Works, British Columbia, Canada (Meiring and Partners, 1983)



Sample Point	COD	Nitrogen TKN	NH₄	NO₃	Phosphorus Total	ortho
GOUDKOPPIES						
Influent	270	35	25		5,8	3,6
Zone :						
Anaerobic			15	1,1		1,0
Anoxic 1			5,1	9,8		5,0
Aerobic 1			1,9	12,4		3,9
Anoxic 2			1,6	12,5		3,6
Final Eff			1,5	13,2		3,1
NORTHERN WORKS						
Influent	240	39	24		9,8	6,5
Zone :						
Anaerobic			16	4,3		6,9
Anoxic 1			6,8	10		6,6
Aerobic 1			0,7	16		6,5
Anoxic 2			0,5	16		6,6
Final Effl			nil	17		6,5
KELOWNA : NORTH UNIT						
Influent	190	19	15		3,8	3,1
Zone :						
Anaerobic			1,6	0,2		8,1
Anoxic 1			0,2	1,2		1,7
Aerobic 1			0,1	2,5		0,7
Anoxic 2			0,1	2,7		0,3
Final Effl			0,1	1,8		0,1

TABLE 2
GOUDKOPPIES OPERATION DATA



Sample Point	COD	Nitrogen TKN	NH_4	NO_3	Phosphorus Total	ortho
D O Reduced						
Influent	340	39	28	-	5,9	3,7
Zone :						
Anaerobic			21	0,1		17
Anoxic 1			10	2,6		6,7
Aerobic 1			4,4	5,0		2,0
Anoxic 2			4,1	4,3		1,6
Final Effl			4,0	4,6		1,5
Return Sludge				0,4		
Load Increased						
Influent	700	42	32	-	8,3	6,3
Zone :						
Anaerobic			17	0,3		19
Anoxic 1			6,5	1,6		7,0
Aerobic 1			2,0	2,8		1,3
Anoxic 2			-	-		-
Final Effl			2,3	2,4		0,6

- The denitrification capacity of the primary anoxic zone appears to have been exceeded as 2,6 mg N/ℓ as nitrate was found in the effluent from this zone.
- Nitrate removal in the second anoxic zone amounted to only 0,7 mg/ℓ compared with 4,2 mg N/ℓ in the sludge blanket in the final clarifier.
- The phosphate removal capability of the plant was not very large and an effluent orthophosphorus of 1,0 mg P/ℓ could not be achieved.
- Adequate phosphorus release appears to have taken place in the anaerobic zone but low DO values are believed to have been responsible for retarding aerobic removal of phosphorus.
- If some uptake of phosphate in the primary anoxic zone could be ensured, this would enhance the overall phosphorus removal capability of the plant.
- Operation under limited oxygen supply conditions encourages high sludge volume indices (SVI's) of 310, with concomitant settling problems.
- When these data are compared to those presented in the previous section one must conclude that the absence of nitrate from the anaerobic zone enhances phosphorus removal.

Increasing the influent COD

The load to the Goudkoppies Works was increased by augmenting the existing flow with that from a low gradient septic sewer containing effluent from the yeast industry. Reference to Table 2 will show a dramatic improvement in nutrient removal. With the enhanced COD of the influent and the fact that it now contained approximately 200 mg/ℓ of volatile acids as acetic acid, denitrification was assured at all times and over a two-year period, phosphorus removal has been such that effluent levels of 1,0 mg o-P/ℓ have been met consistently for 94 % of the time.

Sewage composition modification at the Northern Works

Having demonstrated at the Goudkoppies Works the advantages of readily biodegradable substrate in the influent sewage in the form of the lower molecular weight fatty acids, which confirmed the findings of Ekama, Siebritz and Marais (1983), an experimental programme was designed to modify the composition of the influent sewage to the biological reactors at the Northern Works.

Off-line generation of readily biodegradable additives

Acid fermentation of primary clarifier sludge was carried out on a continuous basis in a digester providing a retention time of 6 days. The supernatant liquor from this digester was added directly to the anaerobic zone over a period of only 4 h per day. Results are depicted in Table 3. Arising from this experiment a number of interesting observations can be made:

- Effluent nitrate concentrations remained low despite the fact that the influent sewage COD remained low for most of the time.

- Considerable quantities of COD must have been adsorbed to the mixed liquor suspended solids (MLSS), as it took approximately 1 sludge age for the oxygen utilisation rate to drop after acid sludge supernatant addition was discontinued. This would suggest that continuous conditioning of the MLSS is not essential.

- Use of this technique ahead of traditional holiday periods such as Easter and Christmas, when the load to works drops drastically, may assist in efficient nutrient removal at these times.

- Under these experimental conditions 15,3 mg P/ℓ was removed but nevertheless, 2,2 mg P/ℓ remained in the effluent.

- Improved performance may have been feasible had it been possible to limit phosphorus release under anaerobic conditions or improve uptake under anoxic or aerobic conditions. Here again, it is suggested that ORP measurements may provide a useful means of control.

The daily variations during this experimental period are given in Figure 2.

Observations derived from Figure 2 are as follows:

- Sustained production of volatile fatty acids (VFA) using a single digester was not possible and it is suggested that the possible reason for this was that a population of methanic bacteria developed using some of the VFA produced for methane production. It is therefore proposed to repeat this experiment using two digesters on a fill and draw cycle of three days each, with each digester being completely emptied at the conclusion of the cycle.

- The lowest concentration of both phosphates and nitrates in the effluent is associated with peak production of VFA.

- There appears to be a lag period between peak volatile acid production and low effluent phosphate concentrations, suggesting that a change in bacterial population may have been taking place before optimal phosphate removal was achieved.

In-line generation of readily biodegradable additives

Raw sludge contains 1 000 – 2 000 mg/ℓ of volatile fatty acids which are normally lost to nutrient removing plants when this material is withdrawn for digestion. By simply recycling this sludge to the head of the primary clarifiers, these acids can be washed out into the liquid phase for onward transmission to the biological reactors. By increasing the retention time of the sludge in the primary settlers, further generation of acids is possible.

Approximately 50 % of the raw sludge at the Northern Works has been recycled to the influent of the clarifiers with results that are recorded in Tables 3(b) and 4. Barnard (1984) has also successfully used this technique, which he has termed "activated primary tanks" at a number of other plants in South Africa.

Comments on performance are offered as follows:

- The COD strength of the primary clarifier effluent was virtually the same as that of the influent, although the suspended solids content of the effluent was lower, thus indicating that more soluble COD was present in the feed to the bioreactors.

- A significantly thicker sludge with up to 7 % solids was finally removed for digestion.

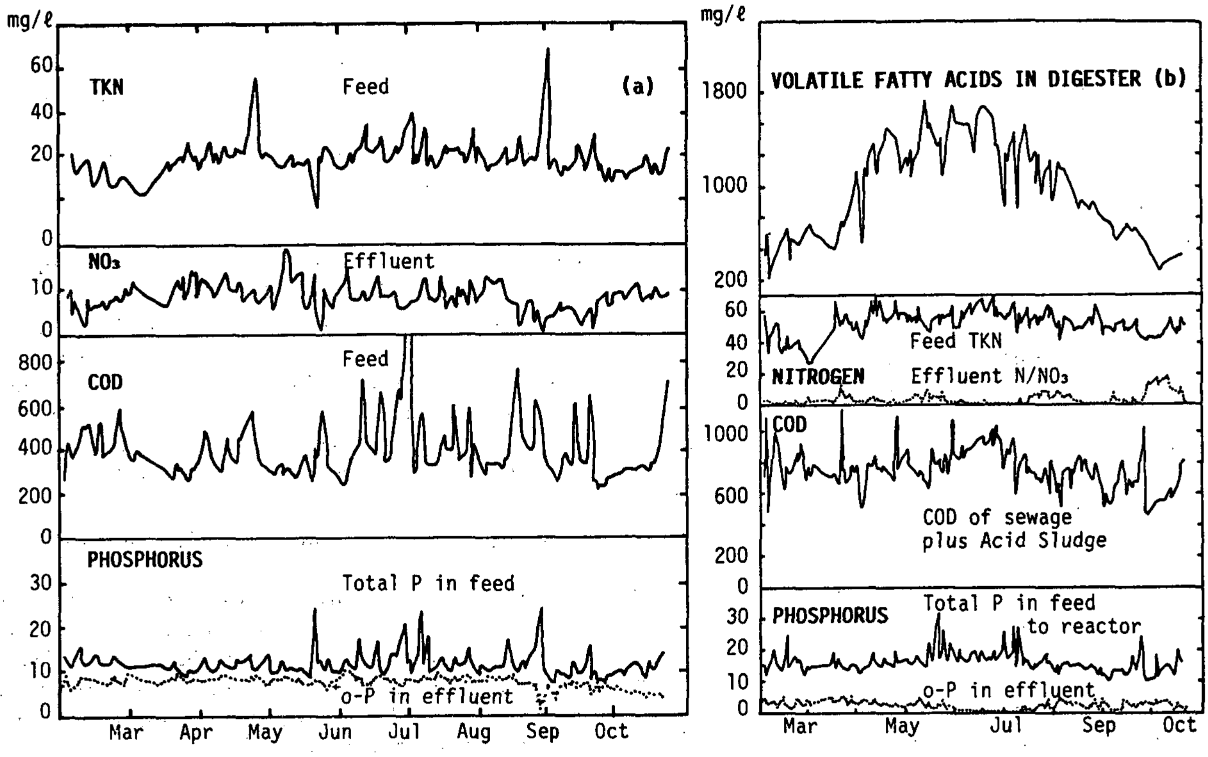


Figure 2
Acid sludge supernatant addition to the Northern Works
(a) Prior to acid sludge supernatant addition
(b) After acid sludge supernatant addition

- Excellent nitrogen removal was recorded with the nitrogen content of the waste sludge rising to 10 – 14 % N/VSS. This is obviously advantageous as nitrogen is not being solubilised to nitrate, with its known potential for adversely affecting phosphate removal.
- Phosphate removal improved and uptake in the primary anoxic zone was also noted, whilst final effluent concentrations approached 1 mg P/ℓ.
- Reasons for the fairly extensive release of phosphorus in the second anoxic zone remain unexplained as it could be reasonably assumed that with DO levels of 2 mg/ℓ in the primary aerobic reactor, very little, if any, soluble and readily biodegradable COD would have been available. Furthermore, it appears that this release occurred in the presence of nitrates.
- Equally confusing is the very rapid uptake of phosphorus in the short retention final aeration basin. It was noted however, that when rapid uptake of phosphorus took place in the primary aeration zone, the same capability usually existed in the secondary aerobic zone.

TABLE 4
THE INFLUENCE OF PRIMARY SLUDGE RECYCLE ON SEWAGE COMPOSITION

		Sedimentation Tank	
		Influent	Effluent
COD	mg/ℓ	630	590
TKN	mg N/ℓ	57	60
Total P	mg P/ℓ	14	16
Suspended solids		360	230

Discussion and conclusions

Full-scale experience with the Bardenpho process in Johannesburg has shown that a number of operating criteria are associated with good biological phosphorus removal. An important one is the need to obviate the recycle of nitrate to the anaerobic zone. This usually means that complete nitrate removal is required. Recent work in Johannesburg has shown that primary sludge recycling can lead to improved denitrification.

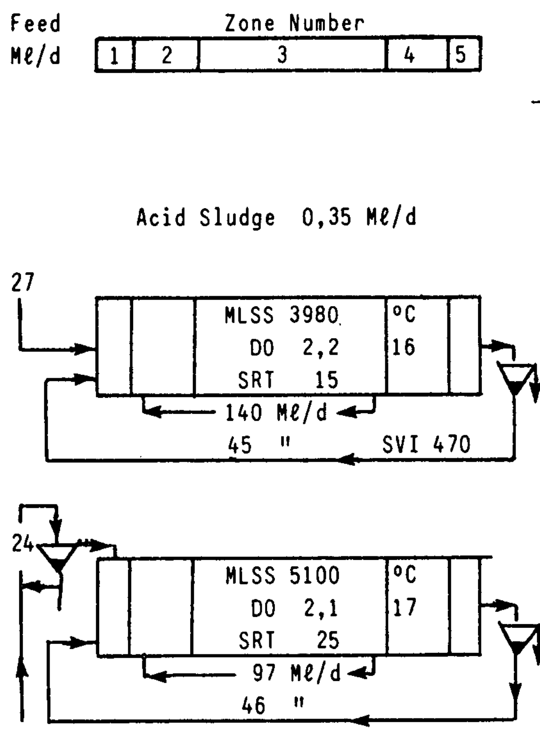
There are also indications that denitrification can be further improved by having plug-flow anoxic reactors, the optimal design of which still needs to be researched.

The successful operation of biological phosphorus removal plants is clearly dependent on the actual composition of the sewage treated. Performance of plants which are achieving poor nutrient removal can be upgraded by the addition of fermentation products produced from raw sludge. Some researchers believe that specific substances such as acetates are important, whereas others have shown that the mixed fermentation products of raw sludge give the best results.

The application of fermentation techniques to nutrient removal plants is a relatively new development. Considerable scope exists to optimise the production of the most suitable compounds and to determine their effect on the micro-environment of specific bacteria and method of absorption into the cell.

To date, considerable attention has been focussed on the reactions taking place in the anaerobic or fermentation zone and

TABLE 3
PERFORMANCE OF THE JOHANNESBURG NORTHERN WORKS



Sample Point	COD	Nitrogen TKN	NH_4	NO_3	Phosphorus Total	ortho
(a) Acid Sludge Addition						
Influent	360	38			11	7,7
Acid Sludge	26000	1180			500	
Mixture	700	53			17,5	
Zone :						
Anaerobic			8,1	0,1		10,5
Anoxic 1			4,9	0,8		6,6
Aerobic 1			2,0	4,0		2,9
Anoxic 2						
Final Effl			1,6	2,8		2,2
(b) Primary Sludge Recycled						
Influent	590	60			14	8,6
Zone :						
Anaerobic			9,9	0,2		12,0
Anoxic 1			4,6	0,9		7,0
Aerobic 1			1,8	4,5		2,3
Anoxic 2			2,0	2,3		8,7
Final Effl	84		1,4	3,5		1,6

it would now appear to be desirable to investigate the conditions required to ensure uptake of phosphates in the primary anoxic zone. Such uptake, even if marginal, may make all the difference with regard to compliance or non-compliance with statutory effluent standards.

There is also a need for the development of simple control techniques to assist operating staff in achieving maximum removal of nutrient. Koch and Oldham (1984) have proposed the use of oxidation-reduction potentials (ORP) for this purpose and it is suggested that the further investigation of this technique under local conditions is warranted.

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