The exceptional simultaneous removal of carbon, nitrogen and phosphorus in a simple activated sludge treatment system at Kingsburgh Wastewater Treatment Works

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Abstract

This paper presents two types of processes at Kingsburgh wastewater treatment works. The West plant was designed as a BNR plant using the UCT configuration. However, due to plant process optimisation, the West plant has been operating for five years without the internal recycle from the aerated zone to the anoxic zone. This treatment system has been operated in a simultaneous nitrification-denitrification (SND) mode following an extended anaerobic zone.

The second treatment process, the East plant is a conventional activated sludge plant which has been recently re-commissioned is being operated as to promote N and P removal by intelligent control of aerator hours, and at the same time the amount of oxygen input.

In both processes SND is obtained by low aeration in which the bulk phase dissolved oxygen is between 0.5 and 0.8 mg/l. The plant performance has been assessed by monitoring nitrate, ammonia and alkalinity. Small dosages of alum are added on a continuous basis to ensure consistent P removal to less than 0.5 mg/l, and with the added benefit of providing process stability.

The effluent discharge standards required by DWAF for this treatment works situated in a designated sensitive area are very stringent, but are consistently attained in a simple operating mode. Those standards are as follows: $NO_3/N < 5$ mg/l, $NH_3/N < 1$ mg/l and $PO_4/P < 1$ mg/l.

The East plant results looks promising but has yet to be operated for a much longer time to confirm the recent results.

Introduction

Kingsburgh Wastewater Treatment Works (KWWTW) treats 3,4 Ml/d average dry weather flow (ADWF) of domestic effluent. This works is situated on the South Coast of KwaZulu-Natal and is run by eThekwini Municipality. The effluent discharge standards required by DWAF for this treatment works are very stringent because it is situated in a sensitive area. The following standards imposed by DWAF are as follows: $PO_4/P < 1$ mg/l, $NO_3/N < 5$ mg/l, $NH_3/N < 1$ mg/l

KWWTW consists of two types of processes. The first being a biological nutrient removal (BNR) process and is originally designed as a UCT configuration but operated in a simple restricted aeration mode. This plant is designed to treat 3.1 Ml/d ADWF of screened and degritted raw sewage. It has been in operation for 5 years and is operating at 10% above capacity at 3.4 Ml/d ADWF.

The second process is an extended aeration plant which is designed to treat 2.75 Ml/d ADWF of screened and degritted raw sewage. This plant was not designed for nutrient removal but as a conventional activated sludge plant and has been recently re-commissioned due to the increased demand for wastewater capacity.

With the extended aeration plant in operation, the BNR plant is being operated at 60% of its hydraulic capacity (1.9 Ml/d) with 1.5 Ml/d being diverted to the extended aeration plant.

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This paper presents results obtained from the BNR plant and the extended aeration plant when treating raw wastewater of consistent load. More emphasis will be placed on the BNR plant focusing on operational mode and process stability from Jan 2000 to Dec 2001. The individual processes, such as phosphorus release/uptake and simultaneous nitrification and denitrification are also discussed.

Results of the capacity modelling, operating method and performance for the extended aeration plant will also be presented.

Wastewater characteristics

In Table 1 are listed typical pH and hydraulically-weighted average concentrations of significant components of the raw wastewater under dry weather conditions.

TABLE 1
Concentrations in mg/l

pH	7.1
COD	815
NH_3-N	37
Alk. as $CaCO_3$	223
Total PO_4-P	14
Soluble PO_4-P	10

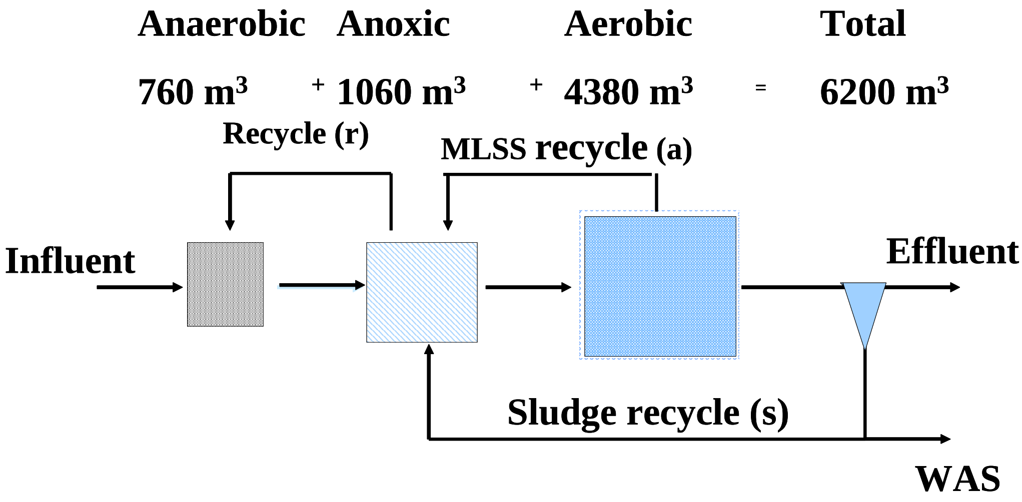


Figure 1
UCT process flow diagram

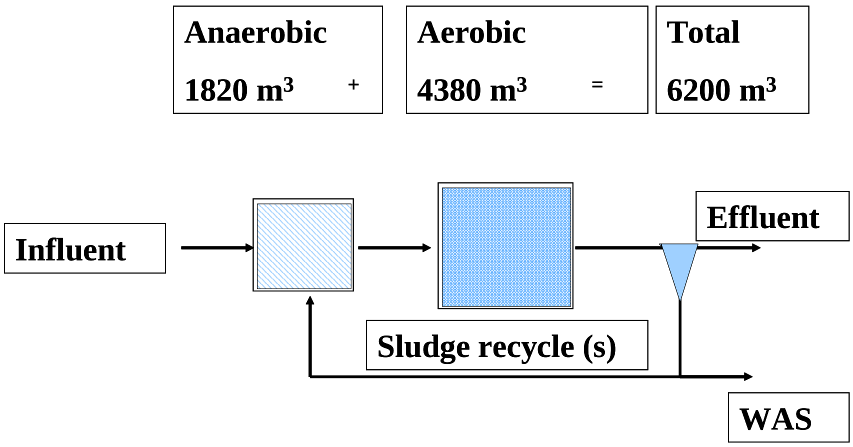


Figure 2
Kingsburgh BNR plant (as operated)

Biological nutrient removal (BNR) plant

TABLE 2
Design specification for the BNR plant

Average dry weather flow (m^3/d)	3 100
Organic load (kgCOD/d)	2 980
MLSS (mg/l)	4 500
Surface aerator (kW)	4 x 37
Mixers (kW)	6 x 37
Clarifier: Volume (m^3)	1 407
Surface area (m^2)	402

Process description

The BNR plant has been optimised and is now operated without the internal recycle from the aerobic to anoxic zone for the past 4 years. The process flow diagram is shown in Fig. 2. This system works exceptionally well, under simple control. Under operating conditions of low dissolved oxygen or restricted aeration in the aerobic zone low concentrations of ammonia (< 1 mg N/l) and nitrate (< 0.5 mg N/l) are observed at the end. Restricted aeration is to provide just enough oxygen to satisfy carbonaceous removal and nitrification/ denitrification process. With the plant producing such good nitrate and ammonia results there is no justification for an internal recycle and, therefore, the combined volume of the anoxic and anaerobic zone (1 820 m^3) is considered to be one large anaerobic zone with a retention time of 13 h at current operating flow.

The BNR plant has a chemical facility to provide low chemical dosages of alum to thicken the clarifier sludge as there is no dewatering facility but only a temporary sludge storage tank. This thickened sludge is tanked daily to Southern Wastewater Works and disposed of. The addition of alum also adds another dimension of stability regardless of the process being reliable and effective as there is always a possibility of process upsets caused by uncontrolled factors.

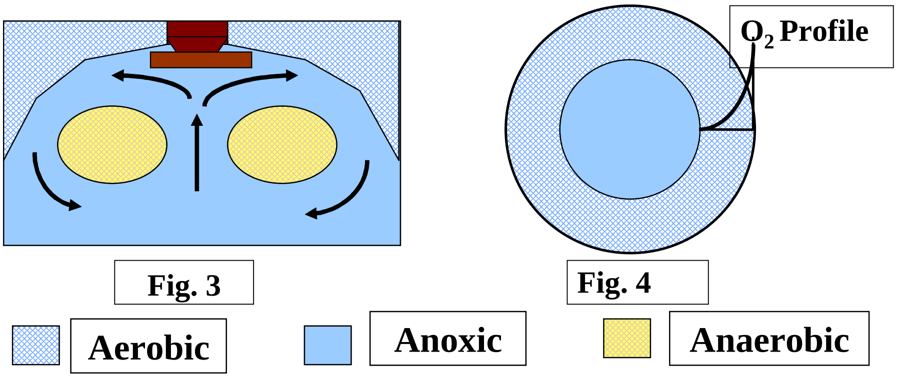


Figure 3
Zones created by surface aerator action

Figure 4
Oxygen concentration profile within a microbial floc

TABLE 3
BNR operational results: Monthly averages from Jan 2000 to Dec 2001

	Range	Average
Inflow (m^3/d)		3 442
Reactor MLSS (mg/l)	3 784 - 6 995	5 389
% MLVSS	57 - 78	72
Aerobic zone: Nominal HRT (h)		30
Anaerobic zone: Nominal HRT (h)		13
SRT (d)	21 - 66	42
RAS MLSS (mg/l)		9 855
kgCODred/kWh		2.45

Simultaneous nitrification-denitrification phenomenon (SND)

This experience of SND is not new (Pochana et al., 1999; Bertanza, 1997) and occurs with low dissolved oxygen (DO) concentrations in the bulk liquid range of 0.5 to 0.8 mg/l. Whether this is a physical phenomenon, i.e. a result of the formation of anoxic regions within an otherwise aerobic environment (due either to surface aerators (Fig. 3), or possibly a result of diffusion limitation into the flocs thus creating an anoxic zone inside the floc leading to denitrification (Fig. 4)), or a biological phenomenon is still questionable.

It has been hypothesised that surface aerators in deep tanks create a vortexing action similar to an internal pump system. With this system aerobic, anoxic and anaerobic zones are created only when DO is at a particular crudely defined concentration.

Discussion

Carbonaceous removal

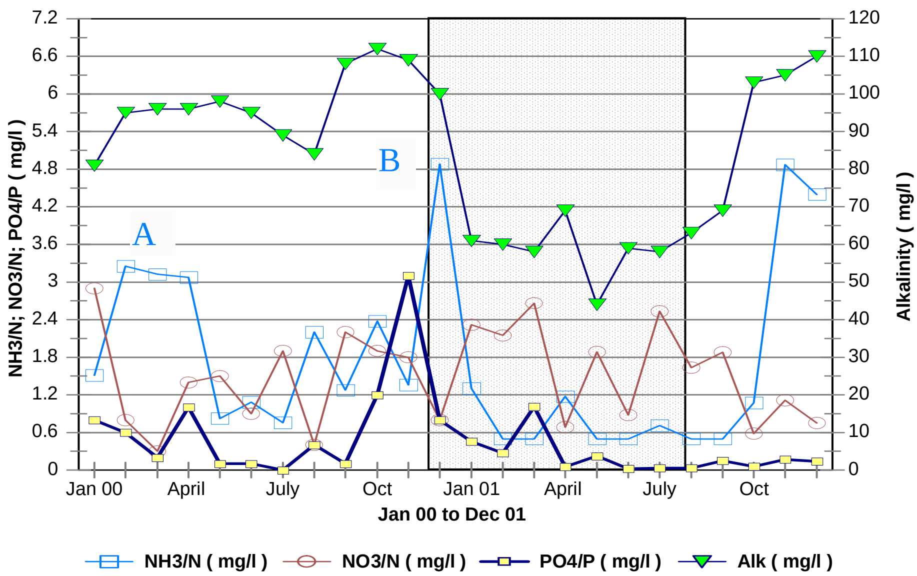
The COD removal was consistently good, with the average clarifier effluent concentration of 57 mg/l. This is equivalent to a removal efficiency of 93%.

Nitrogen removal

The average NH_3/N and NO_3/N concentrations in the clarifier effluent were 1.76 and 0.91 mg/l respectively.

The high NH_3/N concentration at Peaks A and B on Fig. 5 is the result of inadequate nitrification capacity emanating from under - aeration periods on a few occasions for those months. During the festive season, plant loading can increase by as much as 3 times. An overall nitrogen removal efficiency of 92% was achieved.

Figure 5
BNR plant clarifier effluent results from Jan 2000 to Dec 2001



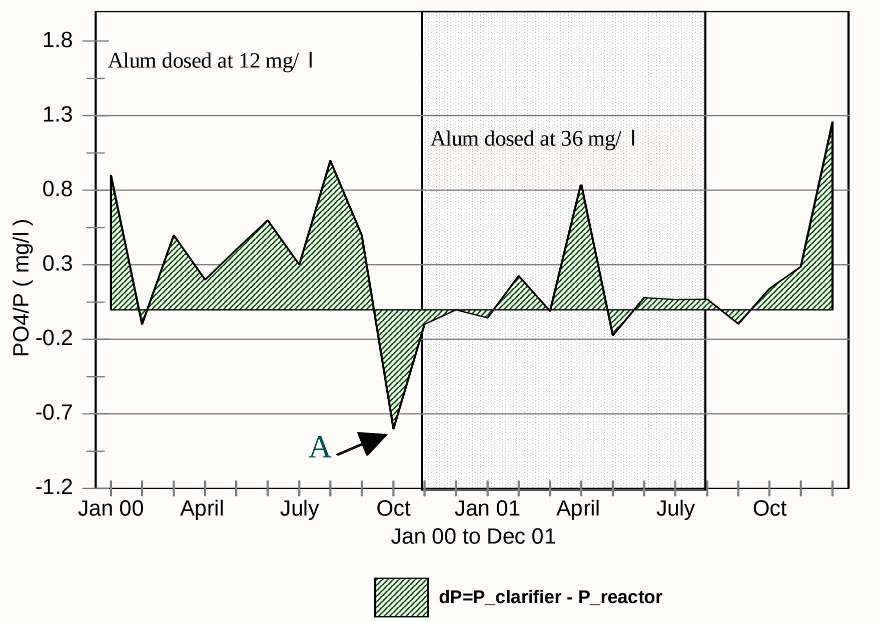


Figure 6
Alum effect on phosphorus release in the clarifier

Oxygen requirement

The oxygenation control is based on ammonia and nitrates or alkalinity results.

Effluent ammonia and nitrate results are provided by our laboratory daily and aeration adjustment is as follows:

If NH_3/N >2 mg/l then the aerator run-time is to be increased by 5%;

If NO_3/N > 5 mg/l then the aerator run-time is to be decreased by 5%.

Alkalinity (Alk) of the effluent stream is equally a quick and easy way of assessing the extent of nitrification and denitrification and can be determined on site by plant operators by titration.

If Alk > 100 mg/l then the aerator run-time is to be increased by 5%;

If Alk < 70 mg/l then the aerator run-time is to be decreased by 5%.

Alum dose effect on alkalinity

From Jan 00 to Dec 00 (12 -15) mg/l of alum was dosed, the alkalinity ranged from (90 -110) mg/l.

From Dec 00 to Sep 01(displayed on Fig. 5 as the shaded region), there is a sudden drop in alkalinity by 40 mg/l and this is due to a 300% increase in alum dose from 12 mg/l to 36 mg/l as 1 mg/l alum consumes 0.5 mg/l alkalinity as $CaCO_3$.

Microbial population

The concentration of solids is being run in an unsteady state due to *ad hoc* wasting caused by the plant not being staffed on weekends/ holidays, or if there are transport problems and the WAS storage tank is full, no wasting is possible. The plant also has a problem of high infiltration of silt due to storm flow, therefore the VSS can go as low as 57%.

Phosphate removal

The system was able to produce clarifier effluent quality of about 0.71 mg/l phosphorus. The alum dosage of between 12 and 36 mg/l was maintained upstream of the clarifiers to minimise phosphorus release from the settled sludge and also to thicken the sludge. Alum does, however, also induce phosphorus precipitation in the clarifier, this is confirmed in Fig. 6 by a negative change of phosphorus concentration between the clarifier effluent and the reactor effluent at Point A. The shaded region of the graph is when alum was dosed at 36 mg/l; there is extremely low phosphorus release during this period.

Extended aeration plant

Process description

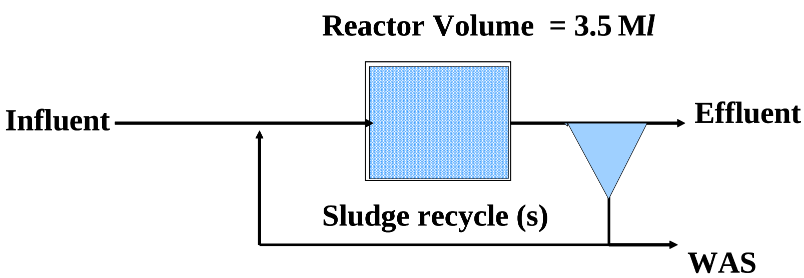


Figure 7
The process flow diagram for the extended aeration plant

The reactor is a 3 500 m^3 capacity, single-compartment, open, rectangular tank 32 m long x 3.5 m deep and 47 m wide. Fixed reactor outlet weir. Aeration equipment: 4 fixed, constant-immersion, vertical shaft, 16 blade turbine-type, 37 kW each and provides 1.2 kgO_2/kWh at sea level.

Clarifier: 1 x 25 m diameter x 3 m deep; RAS flow: 69 l/s

This plant is not designed for BNR treatment; however, it is operated in a similar manner to the BNR plant but in a less controlled operating mode. Much of the success achieved by Kerdachi and Roberts in removing C, N and P at Umhlatuzana Wastewater Works over many years (Kerdachi and Roberts, 1981a, b) using a virtual replica of this plant and also with domestic wastewater, using on/off operating sequence of the surface aerators and using

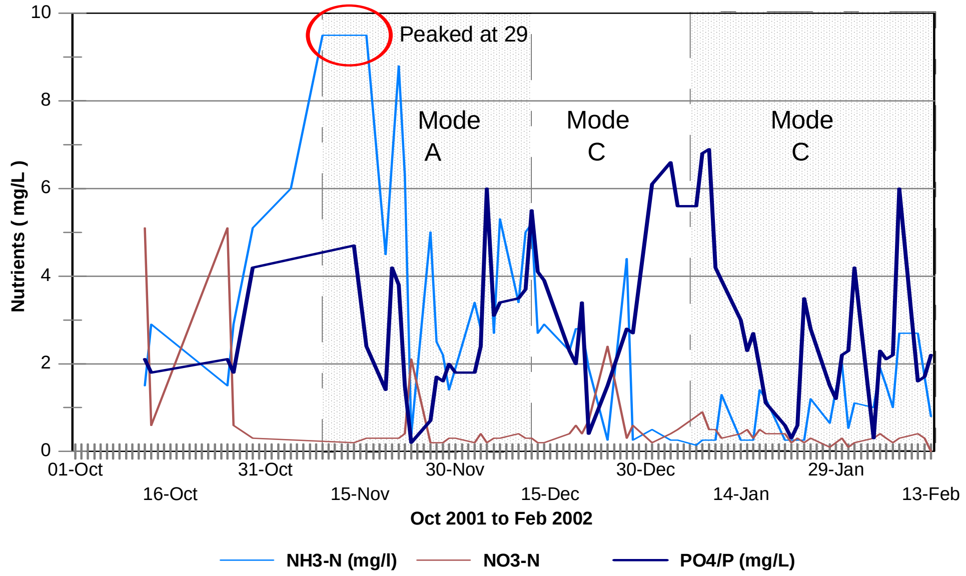


Figure 8
Extended aerationplant clarifier effluent results

TABLE 4 **Design specification for extended aeration plant**	
Average dry weather flow (m^3/d)	2 750
Organic load (kgCOD/d)	1 900
MLSS (mg/l)	4 500

low DO as a control with just enough DO to satisfy the nitrification/ denitrification process.

The numerical model of Kerdachi and Roberts (1981a, b) is an adaptation of the UCT model to the operating conditions prevailing with large non-aerobic mass fraction, and assuming that f_{up} varies with the aerobic solids retention time. This model was calibrated using Umhlatuzana Wastewater Works where more than 90% C, N and P removal was achieved consistently and continuously for months. The results are summarised in Table 5.

TABLE 5 **Predicted operating conditions of extended aeration plant by model**	
Average dry weather flow (m^3/d)	1500
Organic load (kgCOD/d)	1050
Aerobic sludge age (d)	6
MLSS (mg/l)	4500
O_2 required kg/d)	641

Discussion of preliminary results

Prior to Nov 2001, the extended aeration reactor was used as a sludge storage site. Whenever there was no capacity available in the tanker the sludge had to be wasted to the reactor. From Aug 2001 a trickle feed of 264 m^3/d was fed to the reactor. The mixed liquor increased to 10 000 mg/l. When the plant was fully commissioned to capacity of 1 500 m^3/d, the MLSS was gradually brought down to 7 000 mg/l.

TABLE 6
Extended aeration plant operational results from Oct 2001 to Jan 2002

	Range	Average
Inflow (m^3/d)	1 141 - 2 613	1 879
Reactor MLSS (mg/l)	7 184 - 10 920	9 281
% MLVSS	52 - 58	54
Reactor: Nominal HRT (d)		1.9
SRT (d)	62 - 71	67
RAS MLSS (mg/l)	9 690 - 11 720	10 697

The process performance of the extended aeration plant from Oct 2001 to Feb 2002 is presented in Fig. 8.

During operational MODE A (i.e. from 8th Nov 01to 12th Dec 01), the aeration cycle times were:

2 aerators on-line from 07:00 to 16:30 and
all aerators off-line from 16:30 to 07:00.

Nitrates remained extremely low as the oxygen input was lower than demand. Ammonia made a drastic improvement to steady at 5 mg/l and under-aeration was still noticeable at the end of this mode, therefore the aeration hours were increased. The COD in the effluent averaged 70 mg/l and peaked to 136 mg/l due to severely restricted oxygen input. Phosphorus was variable and averaged 3.2 mg/l for this period.

During operational MODE B (from 12th Dec to 7th Jan), the aeration cycle times were:

1 aerator on-line for 24 h with no aerator during all-off period.

There was an improvement in ammonia removal with the ammonia level averaging 1.9 mg/l . Both nitrogen and carbon removal efficiencies were > 90%. The very low ammonia indicated high oxygen input, therefore, the aerator hours were then gradually decreased. Phosphorus once again cycled, this time peaking higher than previous mode to 6.6 mg/l and averaged 3.7 mg/l . This peaking of phosphorus at the end of the operating mode can also be attributed to over-aeration.

During operational MODE C (from 7th Jan 02 to Feb 02), the aeration cycle was adjusted for diurnal loading. After assessing the plant flow charts, it was observed that flow picked up from 6:00 am and reaches a peak at about 11:00am then drops from 4:00 pm to a minimum at 12:00 midnight.

The aeration cycle times were:

1st aerator on from 08:00 - 21:00 while the
2nd aerator on from 10:30 - 23:00.
From 23:00 - 08:00 no aerators are on. During the peak demand the aerators overlap.

Conclusion

The BNR plant simple operation makes the operating mode beneficial as the works has operators with limited knowledge when it comes to process control. High removal efficiencies have been obtained and sustained for carbon, nitrogen and phosphorus removal. Effluent ammonia and nitrate concentrations are good control indicators and is suggested for anaerobic/aerobic mode of operation.

Preliminary full scale trials carried out on the extended aeration plant provides excellent nitrogen and carbon removal while phosphorus removal remains poor. The results are promising but more data is needed to confirm this operating mode.

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