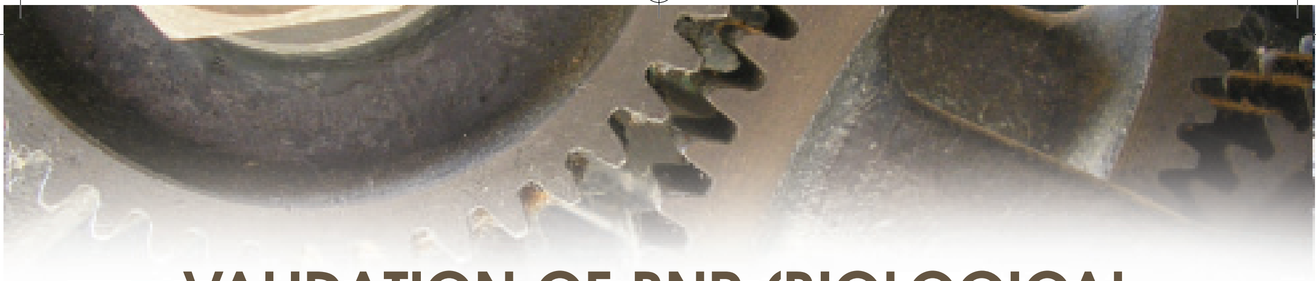

VALIDATION OF BNR (BIOLOGICAL NUTRIENT REMOVAL) PLANT

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ABSTRACT

Llangefni WwTW receives discharge from the rural town of Llangefni and the local industrial estate and to date this is the first and only BNR plant in Wales. The consents from March 2003 included a reduction in ammonia (NH_4-N) to 1.5 mg/l, suspended solids to 20 mg/l (SS) and Biological Oxygen Demand (BOD) to 7 mg/l and included a new Phosphate (PO_4-P) standard of 2 mg/l. The process selected to meet the new consents was Biological Nutrient Removal (BNR) and was unusual as it was for a small, rural wastewater treatment plant that receives about 26% of its flow from an industrial estate.

During commissioning, the plant produced an average phosphate concentration of 1.0 mg/l and an ammonia concentration of 0.7 mg/l. It was confirmed that to achieve consistent phosphate removal a BOD:P ratio greater than 20:1 is required along with a high VFA (Volatile Fatty Acids) concentration of 200 – 300 mg/l.

Key words: ***Biological Nutrient Removal (BNR); commissioning, Phosphate consents; Volatile Fatty Acid;, wastewater.***

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INTRODUCTION

Phosphate is known to be the limiting nutrient in fresh water bodies and can lead to the degradation of water quality as well as ecological diversity from eutrophication. The Urban Wastewater Treatment Directive (UWWTD 91/271/EEC) and the Water Framework Directive (2000/60/EEC) enforce the need to reduce nutrients such as phosphate from entering water bodies. Under the UWWTD a number of water bodies in the UK are classified as 'sensitive' as they are found to be eutrophic (or may become eutrophic) if protective action is not taken [1].

Nutrient removal can be achieved by either chemical or biological means. Biological methods for phosphate removal have several advantages over chemical treatment processes, from both an environmental and business perspective. The Environment Agency (EA) encourages biological processes on the basis that they reduce chemical dispersion into the environment and this is seen as highly advantageous as the concentrated phosphate is recoverable from the sludge with fewer complications. The water discharged from a biological process is also seen to be of a higher quality than a chemical process, as chemical dosing can increase the salt loading on the receiving water body due to the negative ions of the precipitate remaining in the water. Sludge produced from biological processes can in addition be recycled directly to land as an alternative fertiliser and this is often seen as favourable to the water utilities as there are increasing restrictions on sludge disposal routes.

Llangefni WwTW, located on the Isle of Anglesey with a population equivalent of 31,954 (including traders), discharges to the River Cefni and ultimately to the Irish Sea. The new stringent consents enforced in March 2003 by the EA, subsequently made it essential to upgrade the WwTW. The works receive discharge from the local rural town of Llangefni and also the adjacent industrial estate, which includes an abattoir, pharmaceutical/fine chemical company, cheese manufacturer and a chicken processor.

Table 1. Original and new consent levels for Llangefni WWTW

Parameter	Original Consent	New Consent
BOD (5 days @ 20°C) mg/l	12.5	7
Suspended solids mg/l	25	20
NH_3-N mg/l	7	1.5
PO_4-P mg/l	X	2.0
Copper mg/l	0.21	0.13
Zinc mg/l	0.35	0.20
Phenol	0.35	0.22

A BNR (Biological Nutrient Removal) process was selected for Llangefni WwTW after a number of feasibility studies and was designed specifically for the phosphate and ammonium consents, as well as the increased flow of 700 m^3/day expected from the expansion of the industrial estate. Table 1 illustrates the original and new consents for the WwTW.

The BNR process is suggested to be dependent on influent wastewater characteristics, in particular the VFA (Volatile Fatty Acids) concentrations. The principles of BNR require the uptake of VFAs in the anaerobic phase, which induces the release of orthophosphate, this then allows the excessive uptake of phosphate in the aerobic phase of the treatment process. Cooper *et al.* [(2)], suggested that 7.5 mg/l of VFAs are required to release 1 mg/l P and typical concentrations of VFAs in average strength wastewaters are 15 – 40 mg/l. This would imply that between 2 –5 mg/l P can be released in average strength wastewaters and therefore VFA addition is required to increase phosphate release to ensure successful uptake in the aerobic zone.

However, BNR installations in the UK have not been widely adopted, possibly due to the concern for manning levels and the technical input which is required, as the BNR process is a much more sensitive operation than conventional wastewater treatment processes[3]. In order to reduce the difficulty in control and to optimise the BNR process Cooper *et al.*, suggests that the following points should be covered in operator training:

(i) Mechanisms of nutrient removal
(ii) Sampling and monitoring
(iii) Analytical test kits
(iv) Fault-finding procedures

NEW PLANT DESIGN

Originally Llangefni WwTW utilised two high rate filters and a series of humus tanks in the treatment process. The position of the new BNR process in the treatment works is shown in Fig.1. No additional chemical dosing system for the removal of phosphate was installed at Llangefni WwTW and this was largely due to the suitability of the wastewater quality for biological treatment.

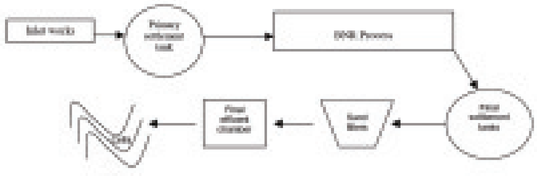

Figure 1. Schematic of Llangefni WwTW Processes.

The treatment plant was designed on the criteria shown in Table 2, these values are based on the designed dry weather flow (DWF) of 5741 m^3/d and 3X the DWF. The industrial estate rarely utilises the full discharge consent of 1886 m^3/d and flows are generally 1540 m^3/d.

Table 2. Design criteria for the BNR at Llangefni WwTW

Parameter	Design Value	Value based on DWF	Extrapolated value as DWF X 3
DWF	5741 m^3/d	~	~
Average BOD	1806 kg/d	314.6 mg/l	943.8 mg/l
Average NH_3-N	65.4 kg/d	11.4 mg/l	34.2 mg/l
Average PO_4-P	26.1	4.6	13.8

The BNR system is a modified version of the University of Cape Town design (UCT) and consists of two lanes. The main modification to the process at Llangefni is to the Returned Activated Sludge (RAS) recycle system shown in Fig. 2. The RAS is recycled back to the inlet distribution chamber where it is mixed with the incoming effluent. Initial studies of the influent showed that there was no nitrate or bound oxygen; therefore there was no reason to protect the anaerobic zone from the RAS. Surplus Activated Sludge (SAS) is removed for disposal via the sludge treatment system along with imported sludges.

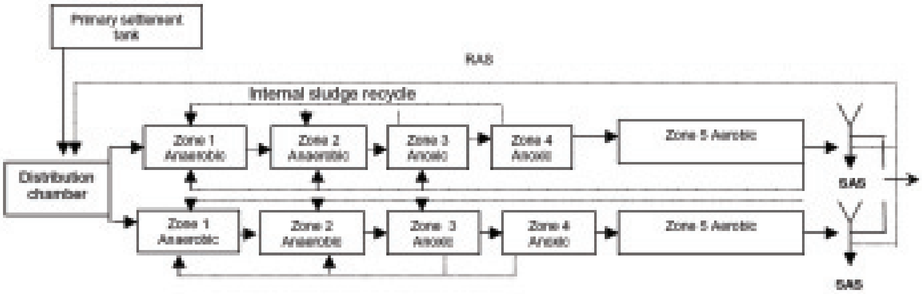

Figure 2. Flow diagram of BNR zones and recycling systems at Llangefni [4].

The water depth in each tank was 6m and baffles were used to separate each zone. There are two anaerobic zones, two anoxic zones and one aerobic zone, which has the longest retention time of approximately eight hours.

As part of the WwTW upgrade a new sludge-handling centre was installed, this was designed to treat primary as well as imported sludge from the local area. Primary and imported sludge is pumped through a rotamat screen before undergoing lime dosing. Additionally, SAS from the final settlement tanks is pumped from the SAS well and poly-dosed, then belt-pressed before lime dosing, where the sludge is held at pH 12 for two hours. The treated sludge is then released from the tank to the centrifuge for dewatering, producing an end product of around 22-25% dry solids.

Llangefni typical wastewater characteristics

Commissioning took place between August 2002 and February 2003 and utilised an interdisciplinary commissioning team. MEICA Process Ltd were the main contractors and the plant design was carried out by WEBS Ltd. Samples were taken daily from November 2002 onwards to monitor the performance of the plant at the onsite laboratory by the University of Wolverhampton. The post-commissioning performance was assessed using a non-intensive sampling protocol (twice a month) followed by analysis at the University of Wolverhampton using standard methods [5].

A summary of the quality of the primary settled wastewater is shown in Table 3. The average BOD:COD ratio of the primary settled wastewater is consistent with values stated in the literature of 0.4-0.6, showing the waste is treatable by biological means[6]. The data indicates the average COD (Chemical Oxygen Demand), BOD, ammonium and phosphate were higher during the non-intensive sampling period and nutrient levels, on average, had more than doubled. The process therefore is susceptible to seasonal changes in wastewater strength so monitoring after commissioning was vital.

Influent VFA samples were taken at Llangefni during 2003 and showed some variation, however, this did not have any major impact on nutrient removal of phosphate as would be expected (Fig. 3). Cooper et al., highlighted that the stronger sewages provided a substantial concentration of the readily available organics required by the bacteria to store organic material and release orthophosphate. Compared with values

Table 3. Llangefni primary settled influent characteristics

Parameters	Intensive (Nov 2002 – Feb 2003)					Non-intensive (Mar – Aug 2003)				
	Average	Max.	Min.	SD.	No .	Average	Max.	Min.	SD.	No .
COD (soluble) mg/l	288.0	625.0	107.0	129.1	60	449.7	830.0	231.0	176.5	11
COD (Total) mg/l	397.6	1069.0	151.0	174.1	70	623.0	1201.0	295.0	253.2	11
BOD mg/l (calculated from COD)	156.8	427.6	61.2	71.7	71	~	~	~	~	~
BOD mg/l (5 days @ 20°C)	~	~	~	~	~	402.0	828.0	22.0	216.6	9
BOD:COD	0.39	-	-	-	-	0.64	-	-	-	-
SS mg/l	93.5	273.0	8.0	45.4	52	129.2	275.0	66.0	64.5	11
PO_4-P mg/l	3.9	23.9	1.2	3.9	63	3.7	5.6	2.1	1.1	11
NH_3-N mg/l	11.4	19.3	0.1	4.7	61	28.0	43.4	17.6	9.4	11
pH	7.40	8.95	6.68	0.37	62	7.07	7.62	5.78	0.49	11

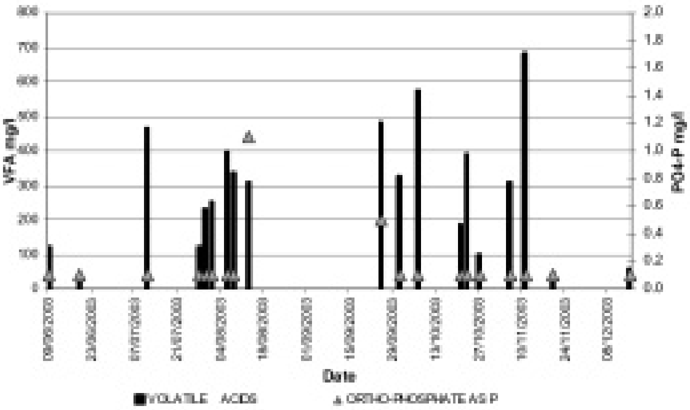

Figure 3. Influent VFA concentrations and Final effluent PO4-Pconcentrations during June-Dec '03.

quoted in the literature the wastewater at Llangefni WwTW has a considerably high concentration of VFAs and based on the principles of BNR, this should contribute to efficient phosphate removal.

Commissioning performance at Llangefni WwTW

During commissioning the quality of the final effluent of the plant was never compromised. In the early phases of commissioning final effluent from the BNR was fed back to the existing plant to ensure compliance. Commissioning the BNR was a three-stage process and initially only 60% of the flow was fed to the BNR. When operating successfully, the BNR received full flow for eight hours a day and by the 21/11/02 the BNR progressed to operating 24 hours a day on full flow. Decommissioning of some of the existing processes (e.g. the high rate filters) was initiated once the BNR was operating satisfactorily and DCWW accepted handover of the site once the new consents came into force in March 2003.

A rapid initiation of the BNR process was accomplished by utilising 'seed' or activated sludge from a local wastewater plant. Initially lane one of the BNR process was seeded with activated sludge from Treboth WwTW (North Wales) on 31/10/02 and lane two was subsequently seeded on 07/11/02. The MLSS (Mixed Liquor Suspended Solids) of each lane were monitored daily during the commissioning period, to ensure the population of micro-organisms were increasing at a sufficient rate, this data is presented in Fig. 4. When MLSS of 3000 mg/l were achieved the process was considered to be operating successfully. For this plant, BNR lane one achieved satisfactory levels after 39 days and BNR lane two after 23. On average the biomass sludge had good settling qualities and the average Stirred Sludge Volume Index (SSVI) value during commissioning was 105.1 ml/g.

The food to mass ratio (F:M) describes the amount of food available, measured as kg of BOD, to the population of biomass, measured as kg of SS; the lower the ratio the more efficient the process. The shut down of lane one for maintenance work on the 04/02/03 until the 07/02/03 resulted in an increase in the F:M ratio as seen in Fig. 5. As a result of the loss in micro-organism population there was an increase in the level of ammonium in the final effluent as shown in Fig. 6, however there was no observed effect on phosphate removal.

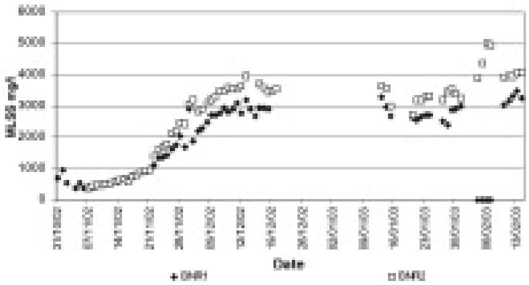

Figure 4. Growth of biomass in the BNR measured as MLSS.

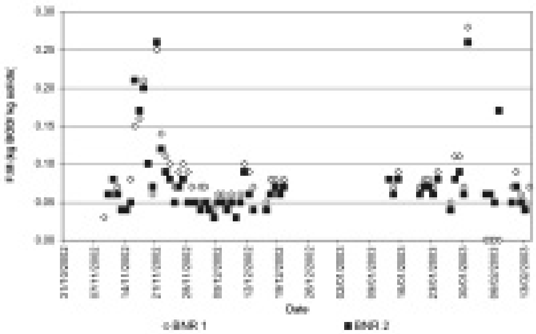

Figure 5. F:M ratio for the BNR throughout commissioning.

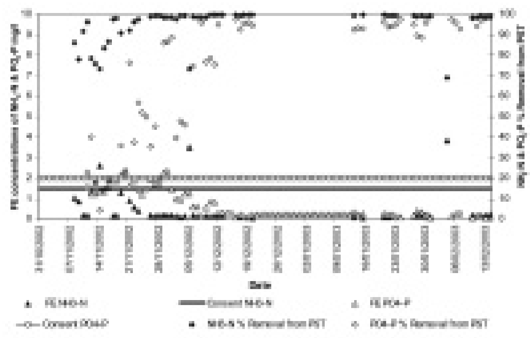

Figure 6. Ammonium & Phosphate removal throughout the commissioning (intensive monitoring) for final effluent (FE).

Ammonium removal was generally consistent throughout the commissioning period (Fig. 6), however some occasions occurred when the removal efficiency was reduced.

The variable removal efficiency can be a result of the initial start up of the BNR process. This is coupled with operational factors which may have affected ammonium removal and these were:

(i) A decrease in MLSS levels
(ii) A corresponding peak in the F:M ratio
(iii) An increase in SS in the FE
(iv) An increase in the concentration of ammonium entering the works, possibly from the chicken processors or pharmaceutical company on the industrial estate

The percentage of phosphate removed from the primary settled wastewater to the final effluent increased in relation to an increase in biomass growth throughout the commissioning period. From 01/12/02 onwards the consent was consistently met (as shown in Fig. 6); this is within 31 days from the start-up of the whole process. Other plants have taken a greater length of time to achieve phosphorous removal. Northampton WwTW was modified to a UCT configuration and aimed to treat a PE of 2850. It was commissioned in the winter of 1993-4 and it was only from March onwards that consistent phosphorous removal was achieved[3]. Severn Trent Water's Derby plant, which also operated under a UCT configuration, achieved BNR within two months of seeding.[7]

IMPACT OF SEASONAL CHANGES ON BNR PERFORMANCE

The effectiveness of the BNR

Seasonal changes were shown by an increase in the average temperature of the Mixed Liquors (ML) between the intensive and non-intensive periods, as shown in Table 4. Commissioning took place during the winter months with ML temperatures at an average of 13.7°C and an average of 21.7°C for the non-intensive sampling period (spring and summer).

The results showed that the BNR performance was more effective during the non-intensive period (spring and summer), when the final effluent ammonium and phosphate levels from the primary settlement tanks improved; however, the nutrient removal was still adequate at low temperatures. Ydstebø *et al.*, [8] concluded that organic loading had a greater effect on nutrient removal than temperature. At Llangefni, phosphate concentrations in the effluent were also observed to increase during the non-intensive sampling, but consents were generally met.

Maintaining the process with variable wastewater strength

The removal of nutrients in the final effluent was effective during the non-intensive period (Fig. 7) and both consents were met. During this non-intensive sampling period final effluent phosphate concentrations ranged from 0.0 mg/l to 1.0 mg/l illustrating some variability. The average phosphate load for this period was 3.7 mg/l and the average final effluent concentration was 0.4 mg/l which is within the consent limit and indicates the capability of the plant to perform with some variability in phosphate loading.

Janssen *et al.* [9] indicates that a higher BOD:P ratio assists with the removal of phosphate. Other researchers such as Mulkerrins et al. [10], state that for efficient phosphate removal the influent to the anaerobic zone must have a BOD:P ratio

Table 4. Characteristics of nutrients in the final effluent during intensive and non-intensive sampling periods

Nutrient mg/l	Intensive sampling period					Non-intensive sampling period				
	Average	Max.	Min.	SD.	No.	Average	Max.	Min.	SD.	No.
NH_3-N	0.7	0.0	10.6	1.51	65	0.3	0.0	1.5	0.47	11
% removal NH_3-N from PST	94.8	/	/	/	/	98.3	/	/	/	/
PO4-P	1.0	0.0	4.1	0.96	58	0.4	0.0	1.0	0.36	11
% removal PO_4-P from PST	74.5	/	/	/	/	97.3	/	/	/	/
Temperature	13.7	/	/	/	/	21.7	/	/	/	/

greater than 20:1.

The occasions when phosphate concentrations increased

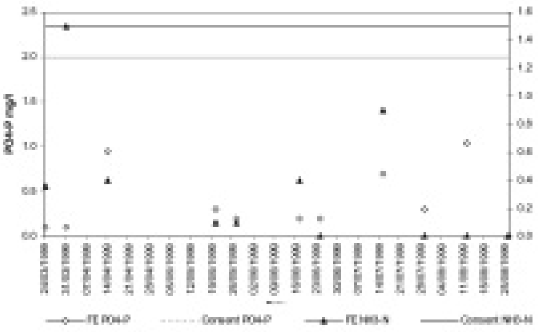

Figure 7. Nutrient levels in the final effluent during post-commissioning.

slightly in the final effluent, but were within the phosphate consent, occurred on the 15.04.03 (1.0 mg/l), 16.07.03 (0.7 mg/l) and 13.08.03 (1.0 mg/l). Plant performance was not compromised on the 16.07.03 due to a high BOD:P ratio producing a final effluent phosphate concentration of 0.7 mg/l. Although limited VFA data is available, it does highlight that high VFAs on the 16.07.03 (465 mg/l) and a high BOD:P ratio (65.2:1) may have assisted the BNR performance despite an increase in the strength of the wastewater and a reduction in MLSS on this date. This confirms the work of Cooper *et al.*, who emphasised the need for a BOD:P ratio of at least 20:1 together with the availability of a carbonaceous substrate, primarily VFAs, to ensure a consistent performance by the bacteria and to prevent consent failures.

On the 15.04.03 and 13.08.03 the BOD:P ratios were 37.8:1 and 32.0:1 respectively, although this is above 20:1 it still had an impact on final effluent quality compared with previous data where the BOD:P ratio was higher. Upton et al. [11], discussed similar problems with regards to a rural plant in Stratford upon Avon stating the addition of short chain fatty acids were required to ensure consistent phosphate removal despite having a BOD:P ratio above 20:1. However, in general BOD:P ratios are above 20:1 and VFA concentrations are typically greater than 100 mg/l at Llangefni WwTW.

LLANGEFNI WWTW PERFORMANCE A YEAR AFTER COMMISSIONING

The plant has now been in full operation for 17 months and Tables 8 and 9 summarise the quality data from April 2003 (shortly after hand over) to May 2004. Some of the samples included in this section were taken at similar times as the post-commissioning survey, although not on the same day. Phosphate and ammonium concentrations in the influent are similar to those recorded during the commissioning period (Table 3). The plant also receives adequate VFA concentrations which are required by the BNR process to operate successfully.

Table 9 illustrates the final effluent quality from Llangefni WwTW from April 2003 to May 2004. The table shows that phosphate removal was efficient (above 90%) and consistently within consent guidelines. Ammonia removal was generally within the consent limits on all, but a few occasions, indicating the implementation of the BNR process was successful.

Table 8. Llangefni WwTW Crude Combined Quality Data April 2003 – May 2004

Parameter	Average	Max.	Min.	SD.	No.
pH	7.87	6.70	10.60	1.06	38
BOD	482.6	160.0	1290.0	242.6	44
COD	1022.0	456.0	2750.0	506.9	51
NH_3-N	28.3	7.2	57.4	9.9	51
TSS	271.0	12.0	1480.0	217.7	51
PO_4-P	4.5	1.7	7.8	1.3	38
VFAs	235.5	30.0	680.0	178.6	26

Table 9. Llangefni WwTW Final Effluent Quality Data April 2003 – May 2004

Parameter	Average	Max.	Min.	SD.	No.
pH	7.69	6.70	8.10	0.26	83
BOD	3.6	1.0	54.8	6.7	107
COD	47.4	120.0	438.0	51.7	71
NH_3-N	0.6	0.3	2.6	0.5	99
TSS	13.0	1.5	340.0	43.9	102
PO_4-P	0.1	0.1	1.1	0.1	62
VFAs	21.9	20.0	45.0	6.7	14

Phosphate loading during commissioning and throughout the monitoring period was variable, with minimum values of 1.2 mg/l and maximum values of 23.9 mg/l. However, these high values were transient and the average values were lower at 3.9 and 3.65 mg/l for the commissioning and monitoring period respectively. In the subsequent period up to May 2004 the maximum phosphate value recorded was 7.8 mg/l, the final effluent quality on this occasion was 0.1 mg/l.

Overall the plant has been able to cope with fluxes within the feed water quality, an example of which was on the 23.10.03 when 99% removal was experienced for COD value of 2750 mg/l and TSS value of 1480 mg/l in the settled sewage. In addition, the concentration of phosphate on this occasion was 4.30 mg/l, which was reduced to 0.1 mg/l in the final effluent.

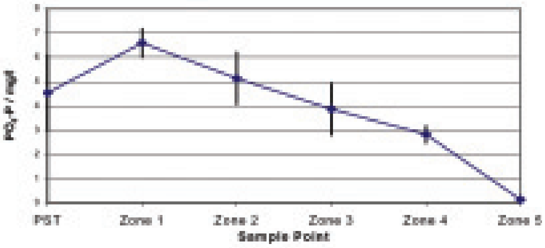

Figure 8. Phosphate profile through the BNR plant.

Confirming the principles of the BNR process

Phosphate profiles can be used to confirm the principles of the BNR process by analysing the phosphate levels in each zone of the BNR. It is generally seen that this plant is verifying the principles of the BNR process by the initial release of phosphate in zone one followed by the progressive removal of phosphate to below consent requirements in zones two to five.

The standard deviation for the data in Fig. 8 is shown as error bars. Error bars were greater for zones two and three, this may be due to difficulties in sampling the wastewater from the separate zones, due to the arrangement of the baffles and weirs.

The periodical determination of phosphate uptake provides information on the biological activity over time and can predict changes in the Bio-P activity from various factors. Janssen et al. discusses the use of phosphate uptake and release tests to provide information on phosphate removal by the Bio-P process and the capacity of the sludge under aerobic conditions. Changes in the Bio-P activity can possibly be assigned to seasonal variations. They predicted the true capacity would be lower, due to the limited oxygen level. Table 6 describes the classification of the sludge based on the calculated uptake rates as proposed by Janssen *et al.*

Table 6. Classification of Bio-P sludge based on P release and uptake rate (Janssen et al.*)* [(3)]

Release or uptake rate (mg P/g VSS.hour)	Classification
<3	Moderate
3-7	Good
>7	Very Good

Modified phosphate uptake tests based on Janssen et al. were performed to evaluate the Bio-P activity from Llangefni WwTW. The method was simplified to

simulate plant conditions. Once all the phosphate was removed by the aerated sludge a solution of phosphate (KH_2PO_4) was dosed and the phosphate levels were monitored. The calculation of the phosphate uptake rate was based on the removal of phosphate from solution.

Uptake rates calculated for two samples were given a 'very good' classification for the Bio-P activity for the original uptake of phosphate in solution (shown in Table 7). The literature states this does not necessarily mean the Bio-P system is completely efficient, as wastewater characteristics are influential.

Table 7. Phosphate uptake rate results

Sample	TSS g	Phase 1- Not dosed uptake rate mg P/g TSS.Hour	Dose of phosphate mg/l	Phase 2-After dosing uptake rate mg P/g	Dosed total phosphate removed mg/g of TSS TSS.Hour
1	3.905	8.19	20	7.45	447.0
2	3.745	8.62	40	8.54	512.4

The amount of phosphate removed per gram of TSS (Total Suspended Solids) is calculated using uptake rates (not dosed and after dosing). The data indicates that the original uptake rates are similar for both samples and total phosphate removed after dosing is an average of 479.7 mg/g TSS. Increasing the dose of phosphate did not result in a notable change in the phosphate uptake rates, indicating the microbial population was at its full capacity. These preliminary experiments could be developed further to assist in determining the Bio-P activity of BNR sludge.

CONCLUSIONS

1. The BNR plant was successfully commissioned within a few months and in advance of the implementation of the new consents.
2. An inter-disciplinary commissioning team was utilised comprising of engineers, operators and managers, with additional scientific input from the University of Wolverhampton.
3. The utilisation of this team provided efficient commissioning and handover. The operation of the new BNR process was also successfully achieved ensuring the transfer of knowledge to the operational staff.
4. Despite receiving variable quality influent, the plant produced a final effluent that was able to meet the discharge consents on all but a few occasions.
5. Nutrient removal, in terms of ammonia and phosphate, is above 70% for the commissioning period and above 95% for the post-commissioning period.
6. A further year of full operation has shown that the BNR can operate consistently and effectively by achieving above 95% ammonia and phosphate removal.

7. A BOD:P ratio greater than 20:1 does not always ensure an efficient process as stated by Upton et al., preliminary results show high VFA concentrations are also required; 200-300mg/l ensures efficient phosphate removal.
8. Additional optimisation may still be required to ensure consistent performance in terms of key operational parameters e.g. MLSS and dissolved oxygen.
9. It is essential to ensure effective operational practice is also maintained, including assessment of quality data and a review of any changes to plant performance over time.

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