3. Process configurations

Biological phosphorus removal is carried out in a numerous of activated sludge systems. Biofilm processes are at present studied in pilot scale investigations, but are not yet developed in full-scale applications. However, it is likely that biofilm systems also will be developed in full scale applications in the near future. This paper focuses on the activated sludge systems and only briefly comments on the development of biofilm systems.

Increased understanding of the mechanisms involved in bio-P removal has since the start in the sixties led to a fast development of process configurations. Concurrently commercial interests concerning patenting of the processes have led to a numerous of different trademark names which are built on more or less the same concept.

Biological phosphorus removal without nitrogen removal is the least complicated bio-P process still, in most cases, combined bio-P/N removal configurations are used. To day we normally divide bio-P configurations in two major groups called sidestream and mainstream systems.

Sidestream processes

In sidestream configurations the release of phosphorus occurs in the sludge recycle stream. After the anaerobic treatment of the sludge recycle stream the phosphate is removed either chemically, as in the Phostrip process, or biologically, as in the OWASA process (figure 2). These are the two main variants of sidestream processes, but many other configurations exist.

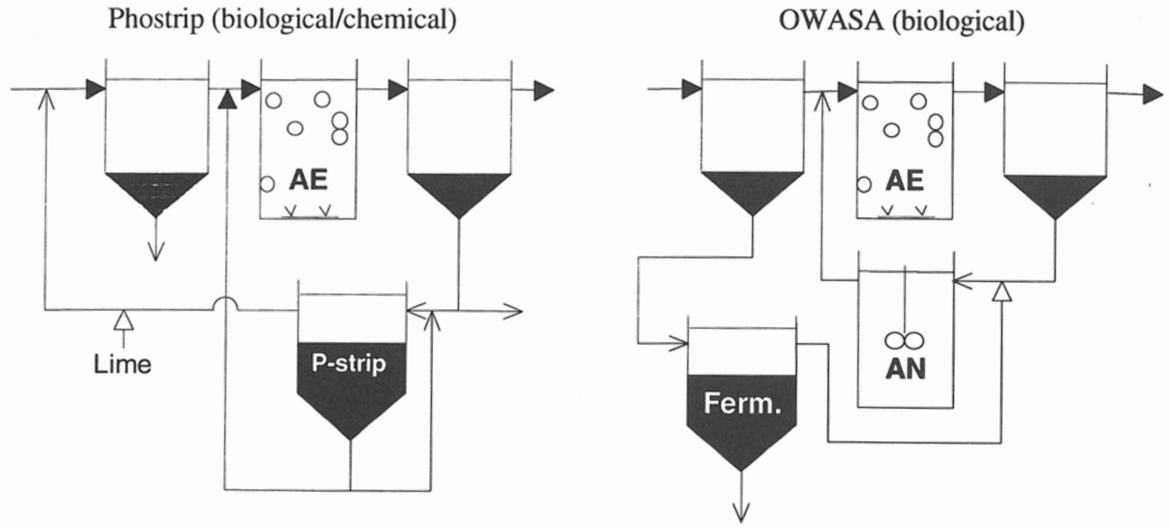

Figure 2. Examples of sidestream processes (biological/chemical- and biological phosphorus removal)

Mainstream processes

Figure 3 shows some examples of single mainstream biological phosphorus removal and combined phosphorus and nitrogen removal configurations. These examples are not meant to constitute a complete list of single mainstream configurations, but should be representative for the most common configurations that are in use world-wide. In addition there are some two-sludge systems or combined activated sludge and biofilm systems, but they are not commonly in use.

For all configurations, the basic process-stages for bio-P/N removal are:

- Firstly an anaerobic stage (selector) in order to utilise the VFA in the influent waste water
- Before the clarifier, an aerobic stage to ensure efficient P-uptake and avoid secondary phosphorus release.
- Some configuration like the UCT-processes pay special attention to avoid nitrate recycling to the anaerobic stage. These configuration involve a second internal recirculation from the anoxic stage back to the anaerobic stage simultaneous with the recirculation of the RAS to the same (or prior) anoxic stage. The modified UCT-process provides better protection of the anaerobic stage from nitrate recycling. Because RAS (+ effluent from anaerobic stage) is first denitrified and recirculated back to the anaerobic stage before the consecutive anoxic stages for denitrification of the nitrate recirculation from the aerobic stage. The modified UCT-process may also be a favourable process for the denitrifying poly-P bacteria (alternating anaerobic and anoxic conditions). Another method to avoid nitrate recycling from RAS to the anaerobic stage is to have a pre-anoxic stage for removal of nitrate from RAS and incoming wastewater or a separate anoxic stage only for RAS before entering the anaerobic stage.
- Bio-N removal is generally based on pre-denitrification (or combined pre- and post-denitrification as in the low loaded 5-stage Bardenpho process). This means that the incoming waste water (or endogenous respiration in post-denitrification) is used as carbon source for denitrification. Anoxic stages are therefor placed ahead of the aerobic nitrification stage from where nitrified water is recirculated back to the anoxic stage.
- Alternating processes involve the same basic processes, but with these configuration the need for internal recirculation pumps are reduced. They have a high degree of flexibility (e.g. anaerobic, anoxic and aerobic cycles lengths). Disadvantages with some of these configurations may be the need for a control system and that the actual recirculation rates might be difficult to control.

Some general characteristics of the different process configurations are given in table 1. Results from some plants might be different from the characteristics given in this paper because the waste water composition and the running conditions, for example, may have been favourable or not.

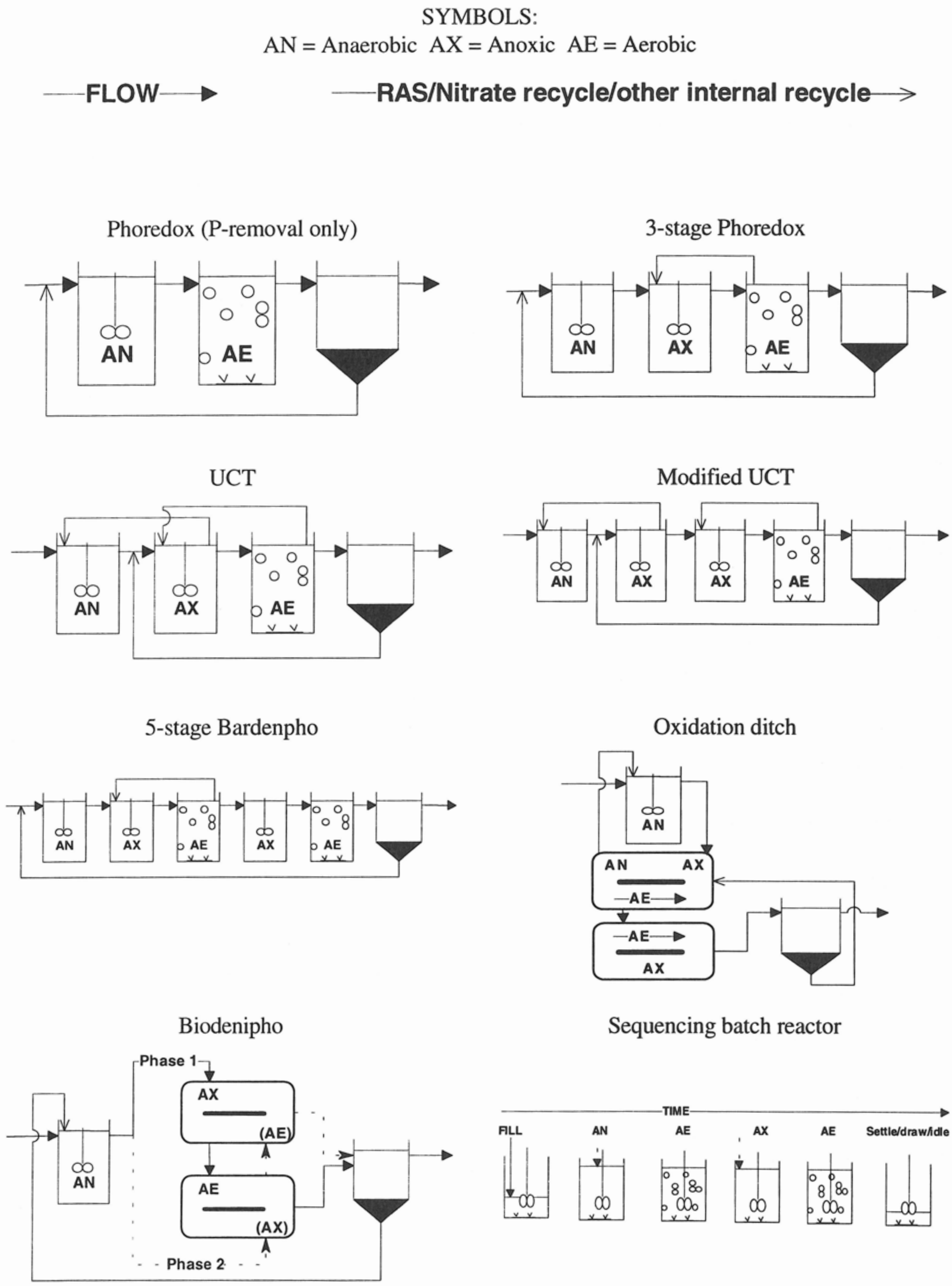

Figure 3. Examples of biological phosphorus removal and combined phosphorus and nitrogen removal technologies. Single mainstream and alternating processes.

Table 1. General characteristics of common process configurations for bio-P and bio-P/N removal

Configuration	Typical retention time/sludge age (h/d)	Complex config. (Low, Medium, High)	Nitrification (Yes,no)	Sensitivity for poorly buffered WW (Low, Medium, High)	N-removal potential[1] (None, Medium, High)	Sensitivity for inhibition due to nitrate- (or oxygen-) recycle to anaerobic stage (Low, Medium, High)	Bio-] remov potenti (Low Mediu High
Phostrip	2-4/4[3]	M	No	L	N[4]	L (H if high temp.)	H
OWASA	2-4/4[3]	M	No	L	N[4]	L (H if high temp.)	H
Phoredox	2-5/4-5	L	No	L	N[4]	L (H if high temp.)	H
3-stage Phoredox	8-12/15-20	M	Yes	H	M	H	L/M
UCT	10-12/15-20	M/H	Yes	M	M	M	M/H
Modified UCT	11-13/15-20	H	Yes	M	M	L	H
5-stage Bardenpho	12-20/20-25	H	Yes	H	H	H	L/M
Oxidation ditch	12-20/20-25	L	Yes	H	H	H	L/M
Biodenipho	8-15/15-25	M	Yes	H	H	H	L/M
SBR[5]	broad range	H	optional	Dependent of chosen operating condition			

[1] The nitrogen removal strongly depend upon the C/N-ratio in the anoxic stage and the sludge age. The N-removal potential is given to compare the different configurations, provided the same incoming waste water with medium C/N-ratio and sludge ages as described.

[2] Achievable phosphorus removal strongly depend upon the VFA/P-ratio in the anaerobic stage. The P-removal potential is given to compare the different configurations, provided the incoming waste water is the same with BOD/P-ratio above but close to 20 (in order to achieve efficient bio-P removal).

[3] Retention time for the aerobic stage. Retention time for the anaerobic stage = 1-10 h

[4] No removal except for metabolism-N and physical removal, typically 10-15%

[5] SBR systems are operated with a high degree of flexibility.

Additional process units to optimise bio-P(/N) removal

All process configurations which are described above have the potential to remove a significant amount of phosphorus, but it must be emphasised that removal efficiency strongly depend on the waste water composition (e.g. VFA/P-ratio) and operating conditions at the plant (e.g. sludge treatment, anaerobic/aerobic retention times and sludge age, and nitrate/oxygen recycling to the anaerobic stage).

With favourable influent BOD/P ratios, the bio-P removal alone may lower the total phosphorus concentration in the effluent to about 0.5-2.0 mg P/l. However, experimental data from plants have shown that it is possible to achieve effluent concentrations below 0.5 mg/l only with secondary settling (Randall et al., 1992). In general an efficient final clarification or tertiary granular media filtration is needed for such a low total concentration in the final effluent.

However, in many cases the waste water composition is not favourable for bio-P removal and/or the effluent phosphorus concentration criteria is too stringent to be achieved by bio-P removal alone. If the incoming BOD/P ratio is below 20 then chemical precipitation should be recommended for achievement of efficient P removal.

If the incoming waste water BOD/P ratio is above 20, but with lack of VFA, there are many optimisation methods which can be recommended to achieve efficient phosphorus removal. Among these, primary sludge fermentation, standby equipment for chemical precipitation and/or tertiary filtration will be commented further in the following.

One of the most common optimisation processes for bio-P removal is primary sludge fermentation for production of VFA. The supernatant from primary fermentation can be fed into the anaerobic selector, regardless of chosen configuration, to improve phosphorus removal efficiency. Primary sludge fermentation can be carried out in numerous of ways, but with different efficiency. The simplest way, and with least efficiency, is to allow a sludge blanket to form within the primary clarifier and to slowly recycle the sludge to the inlet. Other alternatives is to include a separate fermenter/thickener at the treatment plant. Typical fermenter alternatives are static fermenters / thickeners, complete mix fermenters, separate complete mix + thickeners/fermenters and finally combined complete mix + thickeners/fermenters. In a study done by Dawsen et al., (1994), comparison of the VFA production between a static, a complete mix and a complete mix + thickener/fermenter indicated that significantly more VFAs are produced from a complete mix + thickener/fermenter. However, fermenter selection must also include site-specific and economic considerations.

Stand-by chemical precipitation for simultaneous precipitation is a common strategy for plants which have stringent effluent requirements. This will assure necessary low concentration of phosphorus at all time regardless of variation in incoming VFA or possible malfunction/shut-off of a part of the plant. The combination of bio-P removal and chemical precipitation could in many cases be a optimal solution to achieve the best synergetic effects, and is common in use.

When stable effluent concentrations lower than 0,5 mg P/l is required, tertiary filtration and/or chemical precipitation is in general recommended. Even though low soluble phosphate concentrations are obtainable, it is not likely to have stable effluent concentrations below 10 mg SS/l after final clarification. Depending on the phosphorus content of the excess sludge the maximum effluent suspended solids to achieve less than 0.5 mg particulate P/l in the effluent would be in the range of 5-10 mg SS/l.

Research within biofilm technology

During the last 5-6 years there has been some research connected to bio-P removal using biofilm technology (Nordeidet et al., 1996).

Experiments with an upflow floating biofilter (BIOSTYR), showed that it was possible to adapt a biofilter to obtain bio-P removal. One or more anaerobic contact periods were introduced during the filtration period between two backwash procedures of the same biofilter.

Results from pilot scale showed a phosphorus removal of 70-90 %; giving effluent residuals around 2 mg P/l (Goncalves et al. 1994).

In a biofilm sequencing batch reactor with Pall-Rings as biofilm support, achieved removal of COD, phosphorus and ammonia-nitrogen were 89, 75 and 87 % respectively (Marco et al. 1996). The high removal efficiencies of P and N were obtained thanks to the establishing relationship between nitrifying bacteria and poly-P bacteria.

Biofilm technology is generally believed to need a stricter process control compared to activated sludge systems in order to achieve efficient phosphorus removal (Henze, 1996). Pilot scale investigations have shown that it is possible to achieve fairly high phosphorus removal of the order of 70-80 %, but stable, low effluent concentrations (< 1,0 mg P/l) have still not been reported. However, with further research it might be that in the future alternating biofilm processes may be able to compete with (or even show to have some advantages compared to) activated sludge systems.

4. How to choose the optimal process configuration?

The optimal choice of process configuration depends upon many factors such as:

- Waste water composition
- Required effluent quality (organic matter, phosphorus and nitrogen)
- Site-specific and economic considerations

Waste water composition

The wastewater composition at the inlet of the waste water treatment plant is dependent on the sources delivering waste water to the sewer system (especially industry), type and condition of the sewer system, presence or absence of oxygen in the sewers, climate, typography and soil conditions.

The performance of a bio-P and bio-P/N system is strongly affected by the characteristics of the influent wastewater as well as the wastewater influent to each zone of the process (with special attention to different recycle streams within the plant). The main parameters affecting choice of bio-P/N removal configurations are the resulting amount and type of biodegradable organic matter (especially VFA and BOD), ratios between organic matter and phosphorus/nitrogen, temperature, and concentrations of oxygen and nitrate in (the influent to) each zone. Mass balance calculations should be performed for each individual process configuration to give an estimate of the conditions in each single biological process unit. These basic data calculations facilitate the evaluation of the different configurations.

Required effluent quality

Requirements to effluent quality and the formulation of the effluent claim vary from plant to plant and are dependent on different conditions related to the recipient. The more stringent requirements the more complex process configuration must be planned and the higher safety factor must be included.

As illustrated in table 1, the different process configurations have unequal potential for removal of nitrogen and phosphorus. A rule of thumb is that the configurations which are operated with the highest hydraulic retention time and sludge age and have more than one anoxic stage/cycles, will have the highest potential to remove nitrogen. Regarding phosphorus, the configurations with special attention to avoid nitrate and oxygen recycle to the anaerobic stage and at the same time have flexible zone-sizing/phase lengths, will have the highest phosphorus removal potential. These configurations will of course also have the highest capital and operating expenditures.

The choice of configuration must therefore be based on a cost-effective solution which is sufficient to cope with the existing effluent requirements claim and at the same time be suitable for any future extension. This means that if nitrogen removal is not required, configurations like sidestream-processes and Phoredox should be evaluated. However, if stringent effluent requirements are claimed for both phosphorus and nitrogen, then process configurations similar to modified UCT or 5-stage Bardenpho should be evaluated.

Site-specific and economic considerations

When suitable process-configurations are compared, the solution resulting in the lowest possible capital and operating expenditures most often will be the first choice. Although, it should be stressed that costs connected to treatment and disposal of sludge may result in substantial changes in the total calculations of long term operating costs. Comparison of process configuration should therefore include the total plant, as well as future planning.

If the area available for a high grade waste water treatment plant is limited, this will have consequences for the choice of treatment solution. With limited space, configurations with emphasis on advanced process control possibilities should be evaluated. If nitrogen removal is required then biofilm systems, specially for the nitrification process, may be suitable. Combined systems with biological phosphorus removal and denitrification in activated sludge and nitrification in a separate biofilm unit may also be interesting alternatives.

Finally the operators competence and experience, together with local/national practice will to some extent also affect the choice of configuration.

Since the above mentioned factors will vary considerable from site to site, it is obvious that there are no general solution to the choice of the "optimal" process configuration. An evaluation must be done separately in each case taking special precautionary measures against using other plants experience and achieved effluent quality uncritically.

5. Optimisation of bio-P/N processes

Compared to conventional activated sludge and chemical precipitation plants, bio-P/N treatment plants are more dependent on satisfactory operation. This, of course, has to do with the fact that some of the microbiological processes active in the different basins of the bio-P/N plant are very sensitive to swift changes in the composition and quantity of the incoming wastewater. This is especially the case for nitrifying bacteria and liberation of phosphorous from poly-P bacteria, a process that is dependent on low redact potentials in the sewage.

Optimisation of bio-P/N processes require proper operation and the introduction of new process units with the aim to optimise the chosen main process configuration.

5.1 Optimisation through proper operation

The main driving forces for attach weight to optimum operation including instrumentation, control, and automation is:

- Technical:
  - increased knowledge about load variations and how they affect the treatment processes;
  - increased knowledge about the different microbiological processes and the possibilities to describe (and simulate) these mathematically;
  - successful technological development of software, sensors and control equipment;
- Central and local government administration:
  - pressure on the economy; request for more compact plants and reduced operation and maintenance costs;
  - stricter nutrient effluent requirements; often based on a combination of environmental considerations and best available technology.

The different control strategies may be separated into four defined categories (from simple to advanced level) viz.:

1. Manual, limited use of on-line sensors
2. Manual, active use of on-line sensors
3. On-line control based on data from on-line sensor
4. On-line control based on data from on-line sensors, verified and controlled by different forms of computer-systems/models.

Manual control with limited use of sensor device

Manual control most often apply PLS-systems which normally are based on registrations of water flow and oxygen concentrations in the aerobic basins. Changes of the set-points are done manually.

The benefits of manual control systems are mostly connected to their simplicity and low investments costs. Three main limitations are:

1. Operation will never be optimal due to delayed input from laboratory analysis
2. Due to difficulties in predicting shifts in diurnal variations, broad control limit values must be accepted
3. Periodically operation costs may be high due to periodically a) high recycling ratios, b) high aeration and c) high dosing of chemicals

Manual control through active use of on-line instruments - "off-line operation"

By use of on-line instruments, real time analysis may be accomplished in different stages of the bio-basins. The information from such on-line analysis may be used to describe variations through the day, week or season. The operation may still be manual, but changes in the operations control system are based on data from the on-line instruments.

Off-line operations are beneficial due to the possibilities they give for careful study of critical situations with high loading of organic matter, nutrients or water. Set-points may be pre-set after normal operation throughout the day or week, but it must be stressed that unforeseen situations, for instance due to high ratios of industrial waste water at the inlet of the treatment plant or severe events of precipitation will not be covered up in treatment plants with "off-line operation".

Automatic control based on use of on-line instrumentation

The operating control system receives signals from on-line instruments and convert them into relevant actions, for instance changes of recycling ratios or to dosing pumps for chemicals. The operation will continuously be adjusted to oblige the conditions in the basins, which could be manifested through a) lower set points for oxygen concentration during nights and weekends and b) elongation of the denitrification periods in alternating treatment plants or lower recirculation ratios in recirculation plants due to reduced C/N-ratios.

The benefits in using on-line operation are first of all reductions in operation costs, provided there are satisfactory sensors maintenance routines (cleaning and calibration) at the plant.

On-line control, verified and controlled by different forms of computer-systems/models

Operation of bio-P and bio-P/N plants based on powerful and complex expert systems has only to a limited extent been applied in large scale plants. Fuzzy logic and Neural network are building stones in complex controllers, prepared to take care of uncertain information or to recognise certain patterns for instance in diurnal changes of sewage quality.

These systems are expected to gain an increased popularity in the coming years, provided that the rather high investment costs connected to the total control-system (included capital costs for necessary construction plant) can be justified by increased purification efficiency and cost savings.

Conclusion

The choice of operation level, which often will be a combination of the above mentioned main levels, is dependent on the plants size, effluent requirements, load conditions and consumption of factor inputs (energy, chemicals etc.). The optimal choice of operation level must be evaluated in each case and will strongly be affected by local conditions.

5.2 Optimisation measures

Optimal running of bio-P and bio-P/N plants can be obtained through a series of optimisation measures. Some of the most relevant measures are listed below:

- Equalisation of influent flow and/or nutrient loads.
- Influence the composition of the wastewater to the influent of different biological stages, for instance by:
    - Control of recirculation streams
    - Internal carbon source production by sludge hydrolyses
    - Treatment of supernatant liquor from sludge treatment
- Introduce possibilities for volume (or time) ratio of anaerobic, anoxic and aerobic reactors (phases). Aim at plugflow in biological reactors by introducing tanks in series for each main zone (anaerobic, aerobic and, if relevant, anoxic zones).
- Measures related to increased control of sludge age (sludge pumps, suspended solids sensors etc.)
- Measures related to increased control of oxygen concentrations in aerobic reactors
- Oxygen and nitrate control of recirculated sludge to the anaerobic zone.
- Tertiary filtration to ensure low suspended solids in effluent.
- Stand-by, or if necessary continuously, polishing chemical precipitation (simultaneously, post or in filters).
- Sludge treatment: Surplus sludge taken from aerobic reactor followed by flotation (avoid secondary phosphorus release).

Conclusion

Which optimisation measures that should be chosen and the prioritisation of theses will strongly be affected by the plants chosen process configuration (incl. pre-treatment and sludge handling), flexibility in the construction, design of each single process unit, wastewater composition and variation, effluent requirements and the potential for increased purification efficiency and/or reduction of running costs. Planning of new plants or retrofitting of existing plants should therefore also focus on future needs so that the chosen solution facilitate future requirements.

Since the development within wastewater treatment processes are moving towards more complex configurations and increasing amount of process units, another important issue is the need for detailed control strategies. This can be achieved by preparing detailed manuals which cover the most important plant operations tools at the plant and likely operational challenges, or by use of sophisticated soft-ware for more detailed event analysis ("what if" situations).

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BIOLOGISK FOSFOR OG NITROGENFJERNING I GRIMSTAD
Inntrimming, optimalisering og drift 1996

Leif Ydstebø, Norwet a.s, Vingveien 2, 4050 Sola, Norge
Torleiv Bilstad, Høgskolen i Stavanger, Box 2557, 4004 Stavanger

SAMMENDRAG

Groos RA har vært i drift som Norges første bio-P og BNR anlegg siden 2. oktober 1995. Anlegget har i gjennomsnitt hatt en rensegrad for fosfor på 91 %, tilsvarende 0,57 mg/l Tot-P i utløpet. Ved råvannstemperatur mellom 3 °C og 15 °C har løst fosfor vært 0,1 mg/l P i utløpet. Nitrogenrensingen har ikke vært stabil, men har til tider vist over 90 % fjerning; i.e., lavere enn 4 mg/l Tot-N i utløpet. Organisk stoff målt som hhv. KOF og TOC i utløpet har henholdsvis snitt på 65 og 17 mg/l. SS i utløpet, hovedsakelig i form av skum, har bidratt til redusert renseeffekt for fosfor og organisk stoff. Målinger på løste fraksjoner av fosfor og organisk stoff viser at den biologiske prosessen fungerer. Slammets sedimenteringsegenskaper viser gjennomsnittlig SVI på 89 ml/g. Anlegget har vært drevet med MLSS opp til 8000 mg/l ved høy hydraulisk belastning uten tegn til slamflukt. Avløpsvannet i Grimstad inneholder mer organisk stoff enn forutsatt. Dette har bidratt til både høy slamproduksjon og god fosfor og nitrogenfjerning. Sammenlignet med kjemisk felling er bio-P slamproduksjonen 50-60 % beregnet som kg TS/ kg fjernet fosfor eller organisk karbon.

INNLEDNING

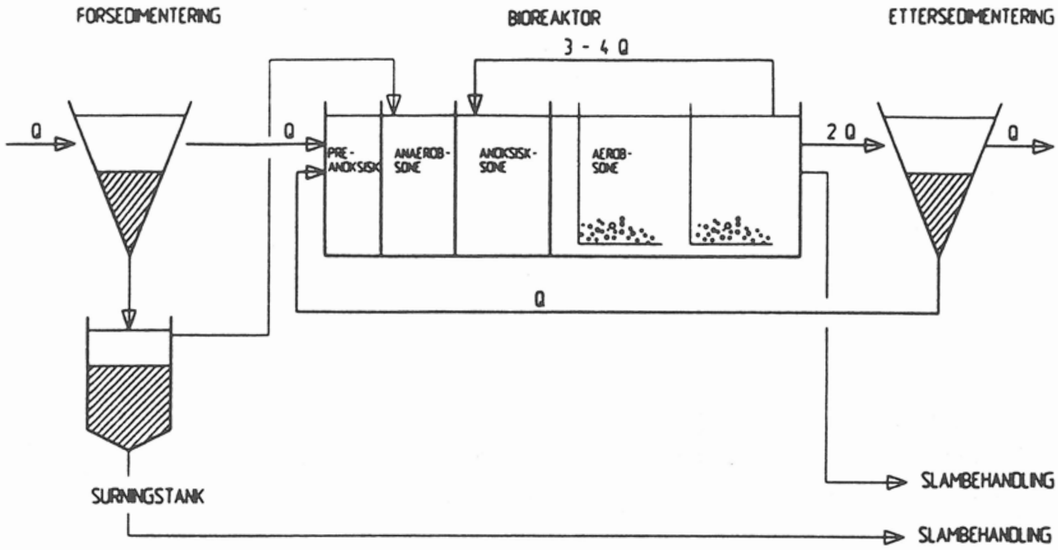
Groos Renseanlegg ble satt i drift 2. oktober 1995 som Norges første anlegg dimensjonert for biologisk fjerning av fosfor og nitrogen. Siden 1. januar 1996 har NORWET, hovedkonsulent for anlegget, sammen med Grimstad kommune stått for inntrimming og driftsoptimalisering. Anlegget kan drives med bare fosforfjerning (bio-P) eller både fosfor- og nitrogenfjerning (BNR). Myndighetenes rensekrav varierer som vist i Tabell 1.

Tabell 1. Rensekrav for Groos Renseanlegg (mg/l middelverdier i utløp)

Parameter	Biologisk fosforfjerning uten nitrogenfjerning	Anlegg med fosfor og nitrogenfjerning
Tot-P, mg/l P	90 %	1 (75 %)
Tot-N, mg/l N		8 (70 %)
KOF, mg/l	50	50
TOC, mg/l	15	15
SS, mg/l	20	20

ANLEGG- OG PROSESSBESKRIVELSE

Vannbehandlingsdelen består av rist, sand og fettfang som var det opprinnelige renseanlegget bygget i 1989. Den nye delen inkluderer biologisk fosfor og nitrogenfjerning (Figur 1) og består av forsedimentering, bioreaktor og ettersedimentering. Slambehandlingen består av fermentor, flotasjonsfortykker og sentrifuger. Anlegget er dimensjonert for 16.000 pe iht. SFT's retningslinjer for dimensjoneringskriterier presentert i Tabell 2.



Figur 1. Skisse over Groos renseanlegg

Tabell 2. Dimensjoneringskriterier for Groos renseanlegg

Q_{min} Tørrværvannføring	m^3/d	5000
Q_{dim} Dimensjonerende vannføring	m^3/d	6500
$Q_{max\ dim}$ Maks dim. vannføring	m^3/d	13000
Total suspendert stoff i råkloakk	mg/l	256 @ Q_{min}
KOF-belastning	kg/d	2100
Nitrogenbelastning	kg/d	192
Fosforbelastning	kg/d	27,2

Etter rist og sandfang fordeles avløpsvannet i to forsedimenteringsbasseng dimensjonert for 2,1 m/hr overflatebelastning. Primærslam pumpes inn i fermentoren tilsvarende 12 % av gjennomsnittlig tørrværvannføring. Fermentoren er dimensjonert med 4-8 døgn slamalder for produksjon av fettsyrer. Overløpet fra fermentor ledes til første anaerob sone i bioreaktor. Fortykket primærslam med 5 % TS pumpes til sentrifuge. Bioreaktoren består av to parallelle linjer hver oppdelt i sju soner; en preanoks, to anaerobe, to anokse og to aerobe; Tabell 3.

Tabell 3: Reaktorvolum (m^3) og oppholdstider (hr)

Sone	Volum	HRT ved Q_{min}	HRT ved $Q_{max\ dim}$
Pre-anoks	80	0,38	0,15
Anaerob	200	0,96	0,37
Anoks	520	2,50	0,96
Aerob	1600	7,68	2,95
Total	2400	11,52	4,43

Anokse soner har ulike funksjon avhengig av om anlegget drives som bio-P eller BNR. Ved bio-P kan anoks sone gjøres anaerob eller aerob. Ved BNR fungerer sonen som denitrifiseringsreaktor. Overskuddslam tas ut fra aerob sone og ledes til flotasjonsfortykker hvor TS oppkonsentreres fra 0,5 % til 4 %. Det fortykkede slammet lagres i en luftet tank før sentrifugering. Slammet fra bioreaktorene holdes aerob for å unngå frigjøring av fosfor.

DRIFTSBETINGELSER

Det første driftsåret har vært preget av mekaniske problem som har påvirket renseprosessen. Spesielt periodene 1. - 15. mars, 16. mai - 15. juli og 1. - 15. september medførte dette problemer med å opprettholde rensingen. Periodene som har vært upåvirket av mekaniske problemer har jevnt over gitt gode renseresultater. På tross av de mekaniske problemene har mikroorganismene fungert bra. I september ble riktignok slammet utsatt for en «forgiftning» som spesielt påvirket bio-P kulturen. Nitrogenfjerningen ble også hemmet, mens fjerning av organisk stoff var nærmest upåvirket.

Inntrimmingen deles i to perioder: mellom januar og mai ble anlegget drevet som et biologisk fosforfjerningsanlegg (bio-P) og fra juni til desember med både fosfor- og nitrogenfjerning (BNR). Analyser på stikkprøver og døgnblandprøver er gjort på renseanlegget med HACH-utstyr og ukeblandprøver er analysert på eksternt laboratorium.

RESULTATER

Driftsforholdene i form av hydraulisk belastning og stoffbelastning er presentert i Tabell 4 og Figur 2, 3 og 4. Tørrværvannføring er i snitt 3737 m^3/d og de høyeste verdiene i Figur 2 skyldes regnvær.

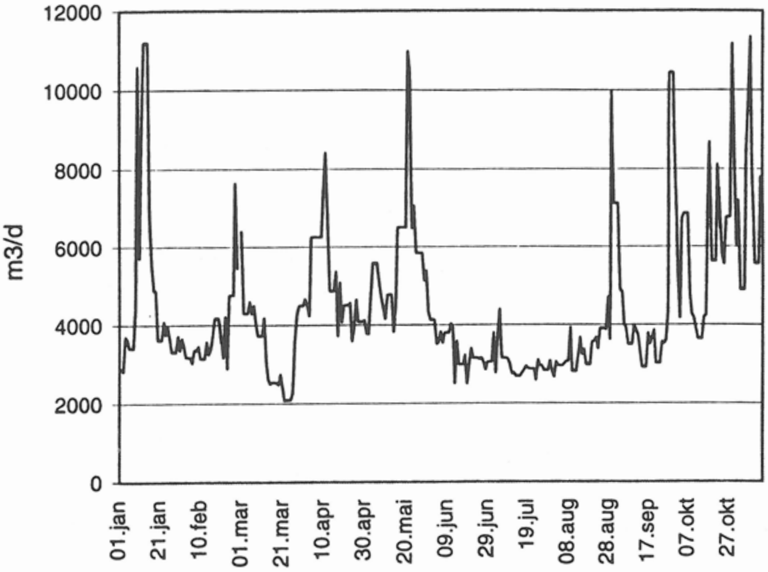
Tabell 4. Hydraulisk, organisk og fosforbelastninger samt KOF/P forhold i innløp

	Hydraulisk belastning m^3/d		Organisk belastning kg KOF/d		Fosforbelastning kg Tot-P/d		KOF/P kg/kg
	Snitt	Maks.	Snitt	Maks.	Snitt	Maks.	
Januar	5235	11197	2597	4026	18,7	23,9	139
Februar	3833	7644	2294	4400	17,9	37,3	128
Mars[1]	3366	6406	2481	5279	20,9	43,0	119
April	5112	8419	2155	5184	23,4	45,7	92
Mai	5672	10980	1735	4229	14,9	21,0	116
Juni[1]	3384	4131	1523	3326	17,7	34,2	86
Juli[2]	3015	4401	1118	2064	15,1	31,2	74
August[2]	3684	9990	2839	6453	19,8	39,1	143
September	4555	10450	3091	4071	22,5	38,7	137
Oktober	6019	11175	3262	6100	21,2	31,0	154
November[3]	6982	11342	4194	6781	22,0	26,0	191

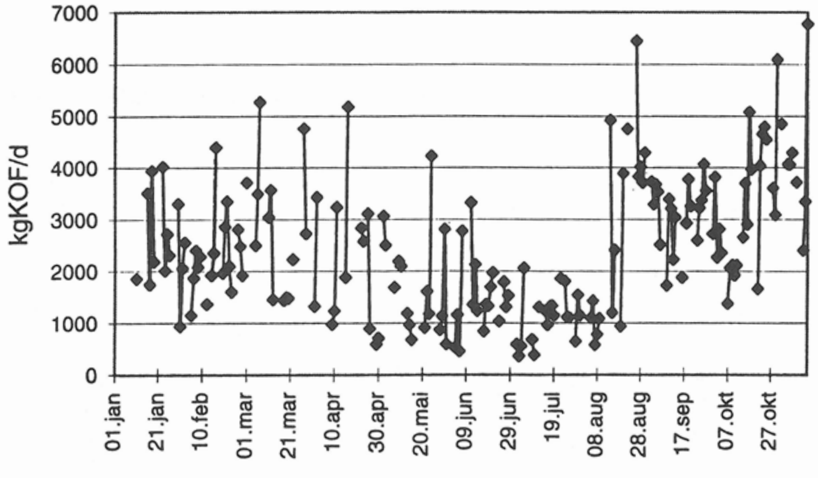
1. Vedlikeholdsarbeider, linjene periodevis ute av drift 2. Linje 1 ute av drift 17. juli - 30. juli, Linje 2 ute av drift 31. juli - 25. august, 3. data fra 1.-13. november

De store og varierende KOF belastningene vist i Figur 3 tilskrives stort sett industrielt spillvann fra næringsmiddelindustri. KOF-belastningen utgjør en snittkonsentrasjon på 561 mg/l i innløpet. Ukeblandprøver hver 2. uke viser et snitt på 90 mg/l TOC i innløpet.

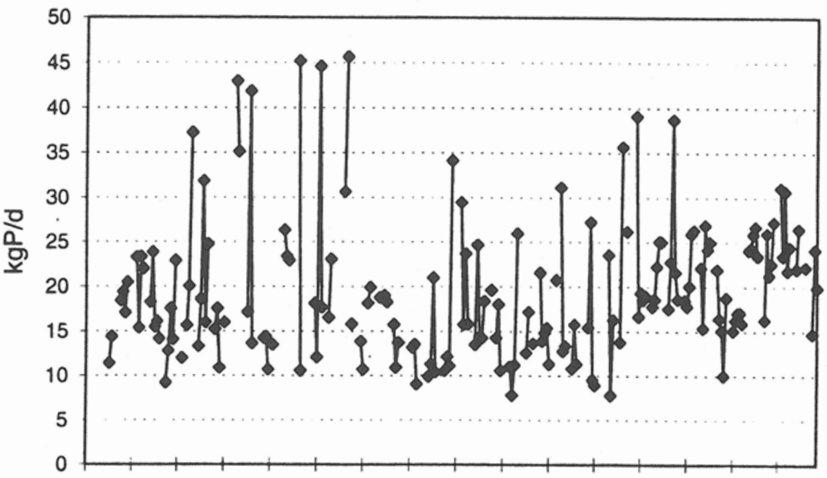
Anlegget er dimensjonert for 27,2 kg P/d (Tabell 2). Dimensjonerende belastning utgjør i snitt 4,7 mg/l P i innløpet mens faktiske tilførsler viser 6,2 mg/l P (Figur 5).



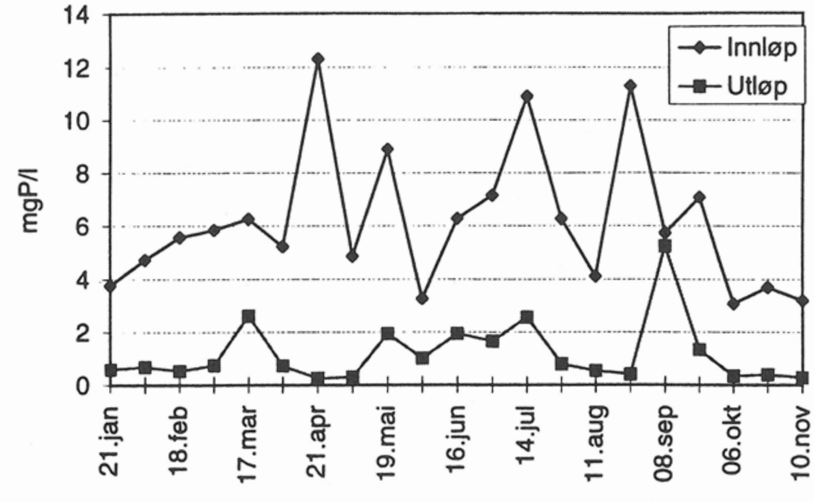
Figur 2. Hydraulisk belastning 1996



Figur 3. Organisk belastning 1996



Figur 4. Fosforbelastning 1996



Figur 5. Tot-P konsentrasjoner i inn og utløp (ukeprøver) 1996

Biologisk fosforfjerning

Biologisk fosforfjerning fungerer bra i Grimstad. Hovedgrunnen for det gode resultatet tilskrives høyt innhold av tilgjengelig organisk stoff i innløpsvannet inkludert fettsyrer fra fermentor. Den biologiske prosessen fjerner ortofosfat til 0,1 mg/l P. Tot-P har vært noe høyere på grunn av suspendert stoff i utløpet. Resultatene er dessuten variable på grunn av mekaniske problem. Tabell 5 oppsummerer utløpskonsentrasjoner av fosfor basert på ukeblandprøver tatt hver andre uke.

Tabell 5. Utløpskonsentrasjon av Tot-P for linje 1 og 2 (mg/l)

Dato	Januar	Februar	Mars	April	Mai	Juni[3]	Juli[3,4]	August[4]	Sept[5]	Oktob	Novem
1 - 15	0,6	0,5	2,6[1]	0,2	0,3	1,0	2,6	0,5	5,25	0,33	0,27
16 - 30	0,7	0,7	0,7	0,3	1,9[2]	1,9	0,8	0,4	1,33	0,38	

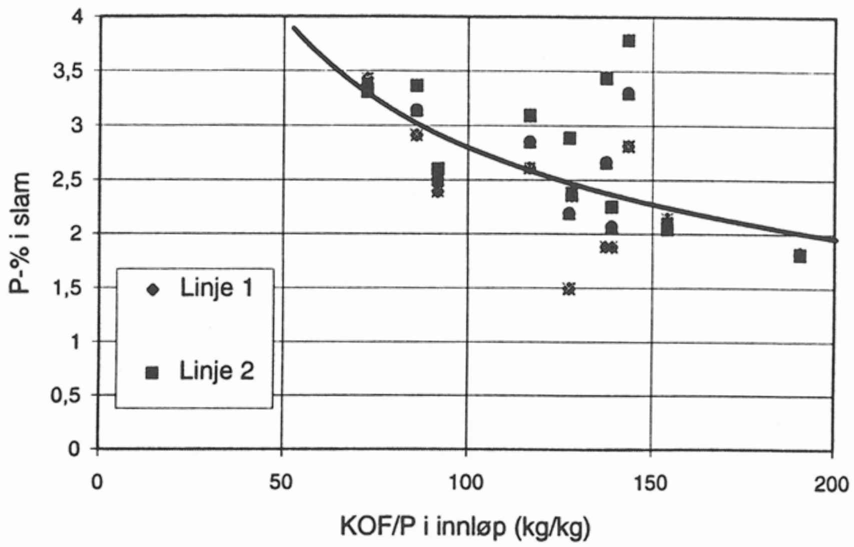
1. Reparasjonsarbeider 2. Overlufting og skum 3. Uten omrøring i anoks sone 4. En linje ute av drift 5. «Forgiftning»

Snittet for Tot-P i utløpet er 1,2 mg/l for hele perioden. Dette tilsvarer en rensegrad på 81 %. For periodene med minst driftsforstyrrelser var utløpskonsentrasjonen 0,56 mg/l P i snitt, tilsvarer en rensegrad på 91 %.

I Tabell 6 er fosforinnholdet i slam presentert og verdiene indikerer at anlegget har høy organisk belastning i forhold til fosforbelastningen; jfr. KOF/P forhold i Tabell 4. Figur 6 indikerer sammenheng mellom organisk belastning og fosforinnhold i slammet.

Tabell 6. Fosforinnhold i slam (%)

	Januar	Februar	Mars	April	Mai	Juni	Juli	August	Sept	Oktob	Novem
Linje 1	1,88	2,48	1,55	2,62	2,39	3,16	3,34	2,86	1,95	2,14	1,84
Linje 2	1,89	2,40	1,85	2,57	2,90	3,24	3,06	2,21	3,40	2,04	1,84



Figur 6. Fosforinnhold i slam som funksjon av KOF/P i innløpet

Reduksjon av organisk stoff var i snitt over året 89 %, som tilsvarer 65 mg/l KOF i utløpet. For periodene uten driftsforstyrrelser var rensegraden 90 % eller 57 mg/l KOF i utløpet. Rense-kravet for KOF er 50 mg/l. Basert på analyser av TOC viste dette i gjennomsnitt 17,6 mg/l i utløpet, tilsvarende 81 % renseeffekt. Rensekravet for TOC er 15 mg/l.

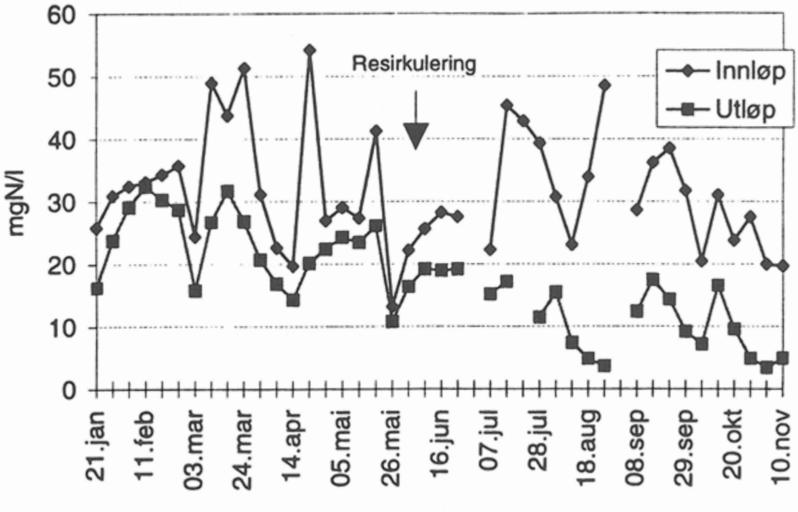
Biologisk nitrogenfjerning

Erfaring med kombinert biologisk nitrogen og fosforfjerning er fra juni. Resultatene indikerer at anlegget kan håndtere lang slamalder (høy MLSS) og derfor nitrogenfjerning ved lav temperatur (8 °C i november) samt høy organisk belastning.

Nitrifisering ble observert i slutten av mai med vanntemperatur på 11 °C. I midten av juni ble det observert merkbar total nitrogenfjerning. Fram til 23. juni manglet omrøring i anokse soner. Den organiske belastningen var også relativt lav. Fra 23. juli ble alt innløp tilført bare en linje av bioreaktoren; i.e., halve det totale reaktorvolum. Dette viste seg å gi merkbare forbedringer på renseresultatene både for fosfor og nitrogen. Driften fortsatte med bare en linje til 23. august med gode renseresultater. Nitrogenfjerningen ble opprettholdt utover høsten. På tross av en «forgiftning» i september ble det oppnådd lavere enn 4 mg/l N i utløpet i november med temperatur på 8 °C og organisk belastning på mer enn dobbel av dimensjoneringskriteriene. Renseresultatene for nitrogenrensing er presentert i Tabell 7 og Figur 7.

Tabell 7. Total nitrogen i inn- og utløp (ukeprøver)

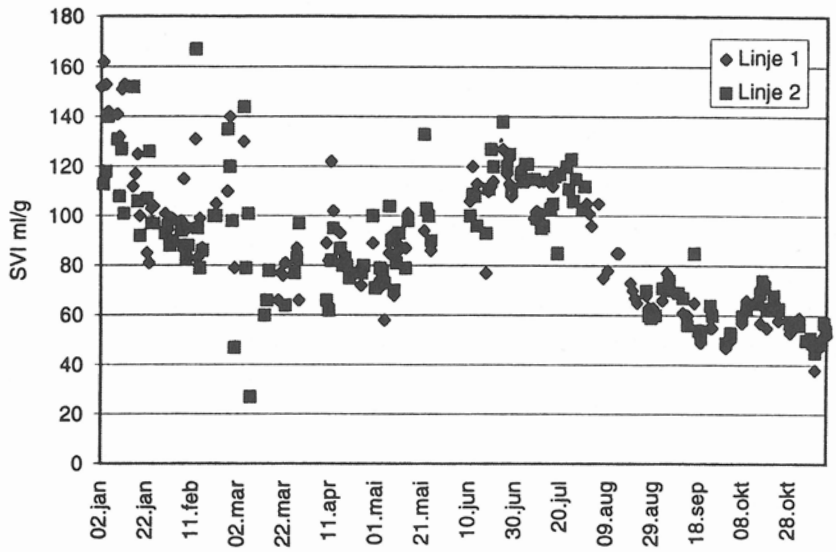
	Innløp, mg/l	Utløp, mg/l	Rensegrad %
1. jan. - 11. nov.	32,0	17,9	44
23. juli - 15. nov	31,8	9,9	69
12. aug.- 31. aug.	41,2	4,3	90
22. okt.- 11. nov.	22,4	4,4	80



Figur 7. Konsentrasjon av Tot-N i inn og utløp (ukeprøver) i 1996

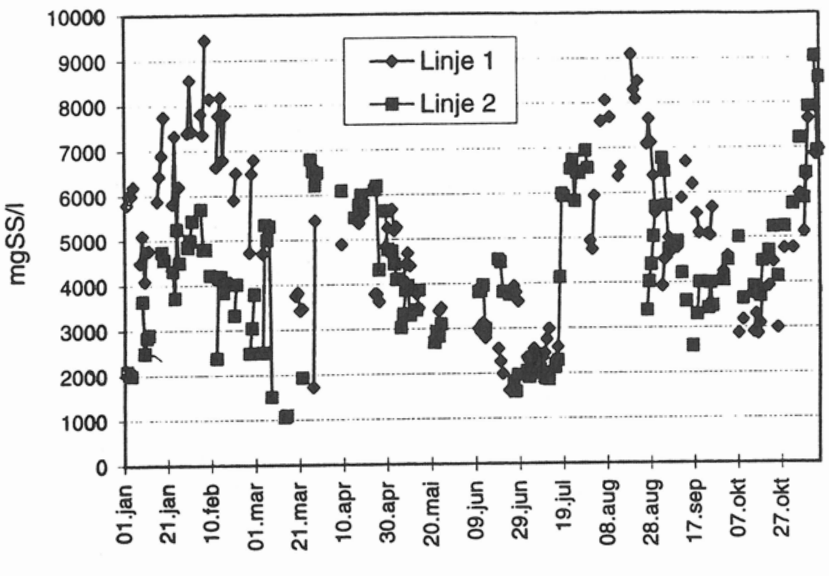
Slamegenskaper

Slammet har gode sedimenteringsegenskaper som vist ved SVI i Figur 8. Tilhørende slamkonsentrasjoner i bioreaktor er vist i Figur 9.

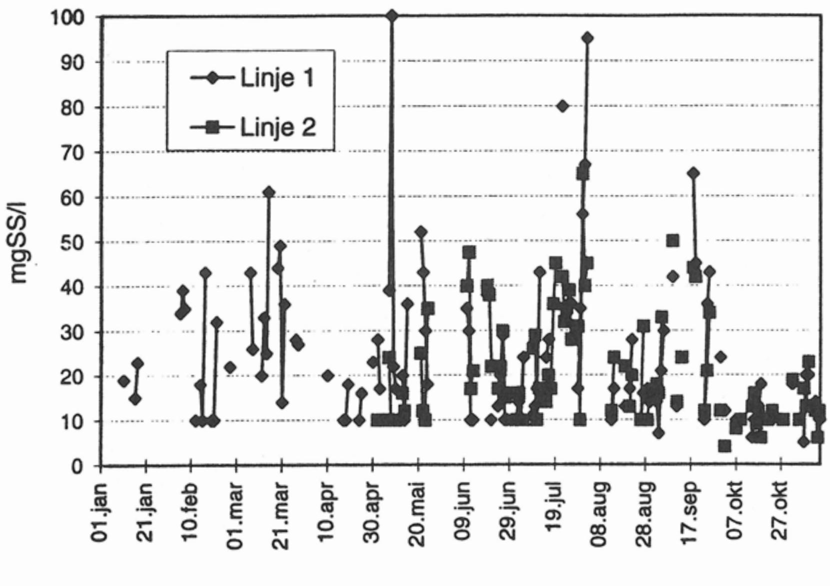


Figur 8. Slamvolumindeks

Det har imidlertid vært høye konsentrasjoner av SS i utløpet (Figur 10). Dette har til tider resultert i for høye konsentrasjoner av Tot-P og KOF i utløpet. TS i utløpet er oftest i form av skum på overflaten. Tiltak er iverksatt for å redusere dette. Noen reell utvasking av biologisk slam har ikke forekommet.



Figur 9. Slamkonsentrasjon i bioreaktoren



Figur 10. Suspendert stoff i utløpet

Slamproduksjon

Groos renseanlegg har hatt forholdsvis høy slamproduksjon på grunn av høy organisk belastning. I Tabell 7 er det gjort en sammenligning av slamproduksjon på Groos med anlegg som har kjemisk fosforfjerning (VEAS Oslo og SNJ Stavanger).

Tabell 7. Karakteristikk av innløpsvann, rensegrad og slamproduksjon på VEAS, SNJ og Groos

	Innløp TOC, mg/l	Rensegrad, %	Innløp P, mg/l	Rensegrad, %	Slamprod. kg TS/ kg TOC_{RED}	Slamprod. kg TS/kg P_{RED}
VEAS	49,5	67	3,10	97	5,2	56
SNJ	26,8	61	1,77	85	4,3	47
Groos[1]	86,7	81	6,7	85	2,5	30

1. Data fra januar - juli

Fermentor

Fermentoren har vært i drift siden midten av april og produsert inntil 250 mg/l fettsyrer (Hac) i overløpet. Slamalderen har vært 5-8 døgn. Temperatur og råvannskvalitet er bestemmende parametre for syreproduksjon.

DISKUSJON

Høy hydraulisk belastning har ikke vist negativ effekt på fjerningen av fosfor og organisk stoff. Kort hydraulisk oppholdstid kompenseres med lett omsettelige organiske forbindelser og høy slamkonsentrasjon i bioreaktoren. Nitrogenfjerning er mer problematisk ved høy hydraulisk belastning. Imidlertid drev anlegget i perioden 22. okt. til 11. nov. med gjennomsnittlig hydraulisk belastning på over 7100 m^3/d, temperatur på 8 °C, organisk belastning over dobbelt av dimensjonering og med over 80 % nitrogenfjerning. Dette bl.a. fordi MLSS var over 6000 mg/l.

Høy organisk belastning I innløp gjør at fettsyrer fra fermentor ikke er avgjørende for fosforfjerning. Sammenligning av fosforfjerning i de to reaktorlinjene med og uten fermentoroverløp viste imidlertid noe bedre rensegrad i linjen med tilsetting. Bio-P aktiviteten, målt som fosforfrigjøring i anaerob sone, var dessuten mye høyere i linjen med fermentoroverløp. Det tyder at en høyere bio-P populasjon kan fungere som en buffer mot høyere utløpskonsentrasjoner av fosfor ved økt fosforbelastning. Fosforinnholdet i slammet var imidlertid høyest i linjen uten fermentortilsetting fordi denne linjen hadde lavere KOF/P forhold og tilhørende lav slamproduksjon (Figur 6). Det høye KOF/P forholdet regulerer bio-P aktivitet og bio-P akkumulering i anlegget.

Økt behov for organisk stoff for kombinert fosfor og nitrogenfjerning i sommerferien medførte at en bioreaktorlinje ble tatt ut av drift. Dette gav markert bedre renseresultater både for fosfor og nitrogen. Høyt utbytte av fettsyrer fra fermentor kompenserte for den lave organiske belastningen i råvannet. Næringsmiddelindustrien var ikke i drift i ferien.

Etter at næringsmiddelindustrien igjen startet i august fikk en markert bedre rensegrad for både fosfor og nitrogen. Resultatene for nitrogen indikerte denitrifikasjon i aerob sone fordi nitratproduksjonen var betydelig lavere enn ammoniumreduksjonen. Dette kan ha en sammenheng med mye lett omsettelig organisk stoff og svingninger i oksygenkonsentrasjonen som gjør deler av bio-fnokkene anokse. Dette reduserer således nitratkonsentrasjonen i returslammet med tilhørende negative effekter for fosforfjerning.

For å opprettholde nitrogenfjerning om høsten ved fallende temperatur ble slamalderen forlenget fra 5-6 døgn i slutten av august til 18 døgn i november. Dette gav 8000 mg/l MLSS uten at det medførte noe problem. Selv maksimum vannføring under et regnvær førte ikke til slamflukt. Bioreaktorens konstruksjon med sju soner oppretter en substratgradient fra innløpet mot utløpet som fremmer veksten av ikke-filamentøse bakterier. SVI var i første del av november mellom 50 og 60 ml/g med klar vannfase over slammet.

Returslampumpingen (RAS) er konstant og justeres manuelt i forhold til innløpsmengden. Variasjoner i innløpet medfører varierende akkumulering av slam i sedimenteringsbassenget. I sommer ble returslampumpingen redusert fra $1Q_{INN}$ til $0,5Q_{INN}$ for å minimalisere returen av nitrat. Dette førte i kortere perioder til økning i konsentrasjon av ortofosfat i utløpet, sannsynligvis på grunn av anaerobe forhold i sedimenteringsbassenget med tilhørende frigjøring av P. Nitratkonsentrasjonene i utløpet er vanligvis så lave at høyere returslampumping ikke spiller noen vesentlig rolle. Høy KOF i innløpet reduserer negative effekter av nitrat i returslammet.

KONKLUSJON

Biologisk fosforfjerning har gitt Tot-P utløpskonsentrasjoner ned mot 0,2 mg/l P, og med 0,56 mg/l i snitt under stabile driftsforhold. Prosessen har vist seg å fungere bra ved temperatur rundt 5 °C. Høy organisk belastning har bidratt til god fosforrensing.

Biologisk nitrogenfjerning sammen med biologisk fosforfjerning gav utløpskonsentrasjoner for nitrogen ned mot 4 mg/l for temperaturer mellom 8 °C og 15 °C og med organisk belastning dobbelt av dimensjoneringen. Kontroll av nitrat i returslammet om sommeren er viktig med hensyn på fosforfjerningen. Høyt innhold av lettomsettelig organisk stoff og lave oksygenkonsentrasjoner medførte denitrifisering i aerob sone og lav nitratkonsentrasjon i utløpet.

Utløpskonsentrasjoner av organisk stoff og suspendert stoff har vært i overkant av rensekravene, hovedsakelig på grunn av konstruksjonsmessige forhold. Det er også mer å hente på driftssiden for disse parametrene. Organisk stoff i utløpet er 65 mg/l som KOF og 16 mg/l som TOC (krav hhv. 50 og 15 mg/l). Belastningen av organisk stoff har i mesteparten av perioden vært langt over dimensjoneringskriteriene for anlegget.

Slamproduksjonen er høy på grunn av høy organisk belastning. Sammenlignet med kjemiske renseanlegg er slamproduksjonen på Groos 50-60 % basert på kg TS/ kg fjernet fosfor eller organisk stoff.

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Biological phosphorus and nitrogen removal using alternative process configurations at an activated sludge plant

Heikki Kiuru, Kiuru & Rautiainen Ltd, Finland

1 Development of and introduction to the HUT-Savonlinna-process

The Laboratory of Environmental Engineering at the Helsinki University of Technology (HUT) has carried out two successive research and development projects at the Pihlajaniemi WWTP of Savonlinna in the full-scale during 1991-1995. The 1st project (1991-1993) was directed to nitrogen removal from municipal wastewater. The 2nd project (1994-1995) concerned biological nutrient removal or, in other words, combined phosphorus and nitrogen removal.

The results of these projects have been presented in the report 18 "**Biologinen ravinteiden poisto suuren biomassakonsentraation aktiivilietelaitoksessa** " ("**Biological Nutrient Removal at an Activated Sludge Plant with High Biomass Concentrations**") of the Laboratory of Environmental Engineering at the HUT (Kiuru et al. 1996). This report has been written in Finnish, but there is an English abstract as well as quite a long English summary included in the publication having 169 pages in total.

The activated sludge process of this plant has been operated since 1987 as a very low-loaded process (the sludge loads of 0.02-0.06 $kgBOD_7/kgMLSS \times d$) with the sludge concentrations of 6-10 $kgMLSS/m^3$ depending on the wastewater temperature in the aeration tanks as well as on the wastewater flow. Those are the main factors, when a total nitrification has been implemented. The sludge loads were counted for the biomass included in the aeration tanks, only.

This plant has been modified in 1991-1995 for biological nutrient removal by means of the own organic carbon content of wastewater without any extension of the process. The plant had been fitted in 1984 with a tertiary stage by flotation filters. The plan as well as the profile of the plant are presented in fig. 1. The technical specification of the plant is as an appendix of this paper. There is also a brochure on the plant available in this conference.

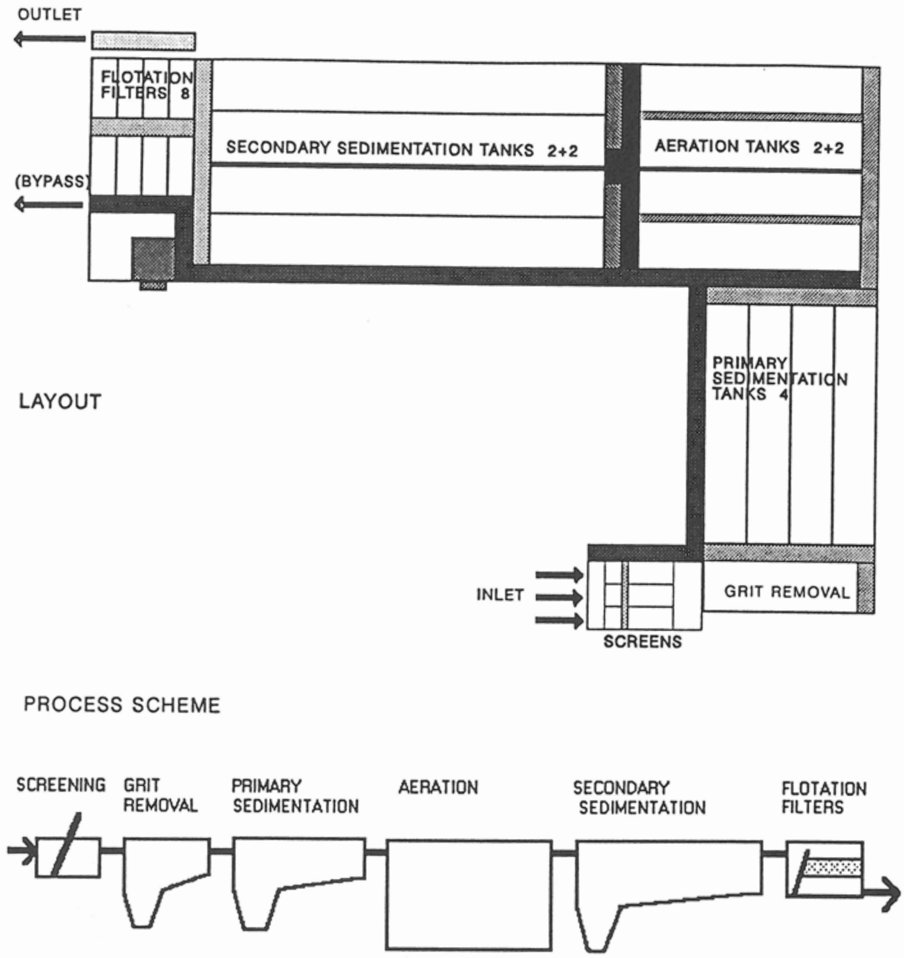

Figure 1. The Pihlajaniemi Waste Water Treatment Plant

The plant has been operated with biological nutrient removal since 1994 resulting in the following average records (the quality of tertiary treated wastewater as well as the reductions achieved in the treatment process):

	Concentration mg/l	Reduction %
BOD_7	< 5	> 95
Total phosphorus, P_{tot}	< 0.3	> 95
Total nitrogen, N_{tot}	< 10	> 70
Suspended solids SS	< 5	> 95

The activated sludge process of this plant is operated flexibly according to the conditions affecting on biological treatment, it is to say, mainly according to the wastewater temperature as well as to the wastewater inlet flow. The wastewater temperature varies at the range of 5-20 °C. The usual range (except some few days per year) of the wastewater temperature is 7-18 °C.

When operating at this range, the process can always be kept as a completely nitrifying one, so that the extent of the aerobic zone of the reactors for biological treatment is adjusted to be large enough for the wastewater temperature and flow to be dealt with in any operational circumstances. The main principle of operation is to keep an amount of biomass large enough (kgMLSS) in the aerated use. The content of ammonium nitrogen (NH_4-N) in the secondary treated wastewater is analyzed by a continuous automatic analyzer.

The rest volume of the reactors which is not needed for nitrification, is used for an anaerobic zone as well as for one or two anoxic zones for biological nutrient removal. It is a specialty of this process that the secondary sedimentation tanks are used as an active anoxic reaction volume for denitrification. It has been counted that about 40 % of the total denitrification capacity of the activated sludge process is located just in the secondary sedimentation tanks.

When the process is operated with high sludge concentrations in the reactors, it cannot be avoided that there are also quite thick sludge beds on the bottom of the secondary sedimentation tanks. There is always plenty of nitrate in the water/sludge-mixture (mixed liquer) coming there from the reactors. In this way, the anoxic conditions prevail in the secondary sedimentation tanks.

The operation of this process with high sludge concentrations including the use of the secondary sedimentation tanks as an anoxic reaction volume is based on the very good settleability of the activated sludge. This, in turn, is based on the very low-loaded biological treatment. When taking in account also the amount of sludge in the secondary sedimentation tanks which is in an average as large as that in the reactors, the real sludge load of the process is only a half of that counted for the sludge amount in the reactors only as usually.

In this way, the sludge load of the process is 0.01-0.03 kgBOD_7/ kgMLSS x d only, depending on the wastewater temperature. The total sludge age of the process is conversely 20-60 d. When the sludge is removed as the excess sludge from the process, it is almost black and the share of the active or living organic part of biomass is less than 10 % of the organic fraction of sludge which, in turn, is about 65-70 % of the total amount of sludge. This is to say, that 30-35 % of sludge is inorganic matter which consists mainly of mineralized organic substances.

The activated sludge process of the plant modified for biological removal of phosphorus and nitrogen is titled the **HUT/Savonlinna**-process. When expressing all the process alternatives for biological nutrient removal included in the process with block letters in different zones, A = anaerobic, D = denitrification or anoxic, N = nitrification or aerobic, the following alternatives are included in the process (figure 2):

A/D/N/D-process

A/D/N-process

A/N/D-process

N/D-process

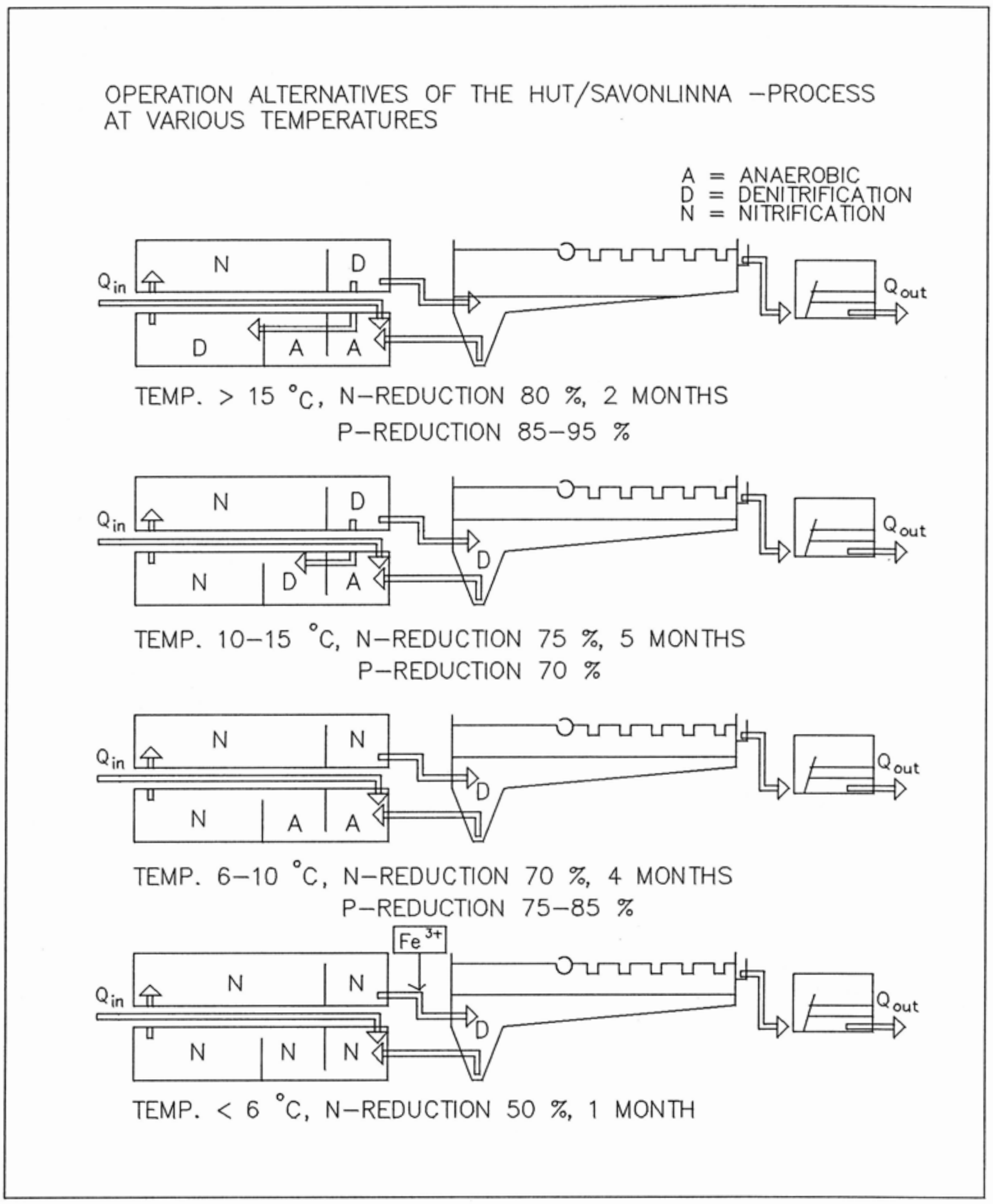

Figure 2. The alternative process concepts of the HUT/Savolinna -process

The last one is for the ultimate conditions in which the waste-water temperature is lower than 6 °C. In this process the whole volume of the reactors is in the aerated use. Denitrification takes place in the secondary sedimentation tanks only. There is no anaerobic zone at the beginning of the reactors. This means that phosphorus is removed in this process alternative, which is used temporarily only, by chemical precipitation.

There is also a lot of different variations of the first three or the main process concepts in wich the extents of the various zones of the process can be changed easily according to the short-time variations of operational circumstances. The last modification measures of the plant are under construction just now. This is to say, that the final arrangements of the reactors and improving the pre-treatment as well as the by-pass/cross-flow arrangements between the primary, secondary and tertiary stages will be done.

The 3rd or final project concerning the completion of biological nutrient removal will be started in March 1997. The target is to improve the efficiency of biological nutrient removal by the own organic carbon content of wastewater with a little addition of external organic carbon (ethanol) as well as with a flexible use of all the unit operations and treatment stages of the plant. It seems now to be quite possible to create a new generation of the activated sludge process, when this project has been carried out.

2 Operational experiences with the HUT/Savonlinna-process

Biological nutrient removal at the Pihlajaniemi WWTP including also the biological removal of phosphorus was started in July 1994 after an almost half-year long transition period for elimination of the influence of the chemical precipitation of phosphorus as well as starting of the biological phosphorus uptake to be carried out by biomass. The efficiency of biological phosphorus removal varied at quite a large range during the second half of 1994. The efficiency of nitrogen removal was very stable all the time.

Since the breaking in period for biological phosphorus removal was over in the beginning of 1995, the operating of the Pihlajaniemi WWTP has been on quite a stable basis. There have been very long periods during 1995-1996, when no addition of the precipitation chemical ($FeSO_4$) has been needed at all for achieving the total phosphorus content P_{tot} less than 0.3 mg/l in the tertiary treated wastewater. The content of dissolved phosphorus (PO_4-P) of the secondary treated wastewater is analyzed by a continuous automatic analyzer.

It seems to be so that, when the wastewater retention time in the reactors is longer than 7 h, and the wastewater retention time in the anaerobic zone of the reactors is at least 1.5 h with a sludge concentration of 6-10 kgMLSS/m^3, both the removal of phosphorus and nitrogen can be carried out quite effectively. The total nitrogen content N_{tot} of the teartiary treated wastewater has been usually less than 10 mg/l.

When the activated sludge process has been operated according to the A/N/D-concept, there is no anoxic zone for pre-denitrification in use in the reactors. This means that no internal circulation of sludge is needed in the reactors for nitrogen removal. Regardless of that the process is still working rather effectively both for phosphorus and nitrogen removal. Always when possible, there is a small anoxic zone in the end of reactors for elimination of oxygen as well as for starting post-denitrification.

The secondary sedimentation tanks are used as an active reaction volume for biological treatment or, in other words, as an anoxic reaction volume for the implementation of the main part of post-denitrification. This is carried out by means of the endogenious respiration of heterotrophic bacteria taking place in the thick sludge beds on the bottom of these tanks. The organic carbon which is needed for post-denitrification is taken from the intracellular carbon stocks of these bacteria.

The rate of post-denitrification is controlled, so that the return sludge pumping from the secondary sedimentation tanks back to the reactors for biological treatment is adjusted according to the content of nitrate nitrogen (NO_3-N < 1 mg/l) in the return sludge to be let flow into the reactors. The content of nitrate nitrogen in sludge is analyzed by a continous automatic analyzer. In this way, the rate of post-denitrification can be maximized.

There is also a remarkable advantage on the almost total absence of nitrate nitrogen in the return sludge from the point of view of biological phosphorus removal. No special arrangement is needed for elimination of nitrate nitrogen in the ananerobic zone located in the beginning of the reactors. This means that the return sludge can be let flow directly to the anaerobic zone without disturbing the absolutely anaerobic conditions needed for the release of phosphorus in this zone.

The HUT/Savonlinna-process at the Pihlajaniemi WWTP is operated flexibly according to the variations of conditions, so that all the process alternatives presented above are used almost annually. The process alternative is choosen according to the temperature and flow of wastewater. The main principle in operation is to keep nitrification going on completely independing on the temperature and flow of wastewater.

This means that the degradation of organic compounds of wastewater in the process goes practically to the very end. This, in turn, is probably the main explanation for a very stable settling of sludge in the secondary sedimentation tanks, when operating with the high sludge concentrations of 6-10 kgMLSS/m^3 in the reactors.

When operating according to the principles presented above, it is clear that, depending on the temperature and flow of wastewater, the sludge concentration in the reactors for biological treatment must be high enough, and the extent of the aerobic zone of these reactors must be large enough to keep nitrification being able to go on complelety in all conditions.

When the wastewater temperature is 6-10 °C during the dry-weather daytime flow, it is possible to use sludge concentrations of 8-10 kgMLSS/m^3 in the reactors and to keep the anaerobic zone of 1/4 or 25 % of the total reactor volume in use in the beginning of that for biological phosphorus removal. It is to say, that the A/N/D-process alternative can be used about for 4 months per year. As mentioded above, operation with this process alternative is very simple, because no internal circulation of sludge in the reactors is needed.

This also means that the N/D-process alternative, in which there is no anaerobic zone in use (the wastewater temperature < 6 °C) and phosphorus must be removed by chemical precipitation, is used less than 1 month per year. Nitrogen removal by post-denitrification in the secondary sedimentation tanks can be carried out also in this process alternative rather effectively (reduction of N_{tot} more than 50 % in any case). Internal circulation of sludge in the reactors is not needed in this temporary process alternative, either.

When the wastewater temperature is 10-15 °C during the dry-weather daytime flow, let us say about 5 moths per year, it is possible to use the A/D/N/D-process alternative. In this concept, there are in use an anaerobic zone of 1/8 or 12,5 % of the total reactor volume and an anoxic zone of the same size after that for pre-denitrification. There is also in use, when possible, an anoxic zone in the end of the reactors for post-denitrification which is exactly of the same size as the anaerobic and anoxic zones in the beginning of those.

The main part of post-denitrification takes place, in any case, in the secondary sedimentation tanks always, when the A/D/N/D-process is used. The sludge concentrations of 6-8 kgMLSS/m^3 are used in the reactors mainly, when operating the activated sludge process with the A/D/N/D-concept. In this concept, it is necessary to use the internal circulation of sludge in the reactors in order to carry nitrate nitrogen into the anoxic zone for pre-denitrification.

When this anoxic zone is located between the anaerobic and aerobic zones, the internal circulation of mixed liquer must bypass the anaerobic zone in the beginning of the reactors and let into the anoxic zone for pre-denitrification. The internal circulation is carried out by the submerged propeller pumps for it. Those are located in the end of the reactors.

Because the anoxic zone for post-denitrification is in use just there in the end of reactors always, when possible, there is no dissolved oxygen (O_2) left in mixed liquer which is circulated into the anoxic zone for pre-denitrification. In this way, there are absolutely anoxic conditions present in this anoxic zone. This is to say, that pre-denitrification can be carried out effectively.

When the wastewater temperature is more than 15 °C, let us say, about 2 months per year, only 3/8 or 37,5 % of the total reactor volume is needed to operate in the aerated use for implementation of the complete nitrification. This means that both the extent of the anaerobic zone and that of the anoxic zone in the beginning of the reactors may be 1/4 or 25 % of the total reactor volume, which is to say, that 1/2 or 50 % of the total reactor volume or the whole 1st halves of the twin-tanks are operated unaeratedly. It also means that there may be in use the anoxic zone (1/8 or 12,5 % of the total reactor volume) in the end of reactors.

Because the sludge concentration in the reactors is in this case 5-6 kgMLSS/m^3 only, there are very thin sludge beds on the bottom of the secondary sedimentation tanks. Post-denitrification takes place only with no remarkable rate in the secondary sedimentation tanks. This is why, the actual process concept is the A/D/N-one, although it seems to be the A/D/N/D-process. The anoxic zone for post-denitrification in the end of the reactors has no significant role in nitrogen removal.

The main task of it is the elimination of dissolved oxygen from the mixed liquer which is circulated internally in the reactors. Regardless of that, this process alternative is the most effective one both for the removal of phosphorus and for that of nitrogen. In this process alternative, there are the anaerobic and anoxic zones in the beginning of the reactors which are large enough for a very effective removal of phosphorus and nitrogen.

This means that the content of total phosphorus P_{tot} in the secondary treated wastewater, when using this process alternative, actually the A/D/N-concept, is always less than 0.5

mg/l and mainly less than 0.3 mg/l. The content of total nitrogen N_{tot} in the secondary treated wastewater is always less than 8 mg/l and in the best case less than 6 mg/l.

The average retention time of wastewater as well as that of mixed liquer in both of those zones is about 2 h or 4 h in total. The average retention time in the aerobic zone is about 3 h and the average retention time of the anoxic zone in the end of reactors is about 1 h resulting in the actual average retention time of the whole reactor volume of about 8 h. The average retention time of wastewater in the secondary sedimentation tanks is about 10 h. The average sludge retention time in the secondary sedimentation tanks is less than a half of that or, in other words, 3-4 h.

As remembering from the page 3, the minimum time for retention of wastewater in the reactors for biological treatment in order to carry out an effective removal of nutrients at the Pihlajaniemi WWTP is 7 h. When taking in account the biological activities taking place in the secondary sedimentation tanks during its SRT of 3-4 h in the different process alternatives, this means that always in the dry-weather conditions there is a sufficient reserve for operation of the activated sludge process in order to carry out an effective biological removal of nutrients.

When operating the activated sludge process of the Pihlajaniemi WWTP flexibly using all the possible process alternatives and their variations in the way presented above, this process is always in an effective use for biological nutrient removal. This means that there is never any ineffective or partially effective volume in the reactors from the point of view biological nutrient removal. This means that no addition of precipitation chemical is usually needed for improving the biological phosphorus removal.

The main factors affecting on this fact are the high volumetric reaction rates of biological activities in the process achieved through the high biomass concentrations used in the reactors and the low rate of the total circulation of biomass in the process. The rate of the total circulation of biomass in the process is 70-300 % of the wastewater flow to be treated only, depending on the process alternative in use.

It has been observed that, if the rate of the internal circulation of sludge in the reactors, when exploiting pre-denitrification in nitrogen removal, is increased over the maximum rate of 250 % of the flow of wastewater to be treated, the effieciency of nitrogen removal will be decreased slowly but inevitably.

When exploiting post-denitrification in nitrogen removal, the rate of the return sludge pumping should, if possible, be decreased to the minimum rate of about 50 % of the flow of wastewater in order to be able to maximize the efficiency of post-denitrification. This, however, is not possible with the existing return sludge pumps.

3. Future prospects

After having studied several municipal WWTP´s in Finland in order to impelement biological removal of nutrients, it seems to be, so that it either is not necessary to extend the plants at all, or in any case, to extend those very moderately only, if exploiting the HUT/Savonlinna-process. The secondary sedimentation tanks of these plants have been dimensioned with that low hydraulic loading, and the plants are actually that much underloaded, so that it seems to be possible to use the sludge concentrations of 6-10 kgMLSS/m^3 in the aeration tanks which are to be modified to the reactors for biological treatment according to the HUT/Savonlinna-process.

It must be remembered that the HUT/Savonlinna-process has been developed by modifying a conventional activated sludge plant for biological removal of nutrients. The tertiary stage or, in other words, a filtration or flotation filter plant is not necessary for securing the working of the activated sludge process.

If planning a new WWTP for biological removal of nutrients, the solution, when exploiting high biomass concentrations in a very low-loaded activated sludge process, could be rather different from that of the Pihlajaniemi WWTP and probably much simpler than it. If the secondary sedimentation tanks of that plant are planned especially for operation with high biomass concentrations, the concentration of sludge in the reactors could probably be at the range of 10-15 kgMLSS/m^3. But this will be an other story.

APPENDIX

PIHLAJANIEMI WASTEWATER TREATMENT PLANT
Town of Savonlinna

Phases of implementation:

Phase 1 = 1978,	an activated sludge plant fitted with simultaneous precipitation of phospohorus
Phase 2 = 1984,	tertiary treatment plant with flotation filters
Phase 3 = 1993,	modification of the activated sludge process for nitrogen removal
Phase 4 = 1995,	modification of the activated sludge process for combined biological removal of phosphorus and nitrogen

TECHNICAL SPECIFICATION (1.2.1997)

TYPE OF THE TREATMENT PLANT:
A very low loaded activated sludge plant, biological removal of phosphorus and nitrogen.
A tertiary stage after the activated sludge plant, flotation filters as the treatment units.

DIMENSIONING DATA:

Dimensioned inlet flow q_{dim}	=	1 100 m^3/h
Dimensioned BOD_7-load	=	3 300 kgBOD_7/d
Person equivalent number	=	33 000

TREATMENT TARGETS (quality of the treated wastewater):

Biochemical oxygen demand BOD_7 =	< 5 mg/l
Content of total phopshorus P_{tot} =	< 0.3 mg/l
Content of total nitrogen N_{tot} =	< 10 mg/l
Content of suspended solids SS =	< 5 mg/l

PROCESS STAGES AND UNIT OPERATIONS:

<u>Screening:</u>
Mechanical step screen, 1 unit, free distance between the plates 3 mm
Mechanical bar screens, 2 (reserve) units, free distance between the bars 10 mm

<u>Removal of sand and grease:</u>
1 aerated long-retention unit

Volume of the tank =	300 m^3
Dimesioned retention time =	15 min
Average retention time =	> 30 min

Mechanical vagon scraper, 1 unit
Sand pump, 1 submerged vortex-flow pump

Primary sedimentation:
4 squadrat tanks, 5 m x 29 m = 145 m²,
average depth 2.5 m and volume 1 400 m³ in total
Dimensioned surface load 2.0 m/h
Average surface load < 1.0 m/h
Chain-type sludge scrapers
Raw sludge pumps, 1 unit per tank = 4 units a´ 12 l/s,
submerged centrifugal pumps
Throughs for clarified wastewater, 1 unit per tank,
1 overflow weir for clarified wastewater in the end of the tanks
Adjustable surface sludge throughs, 1 unit per tank

Pre-sedimentation is bypassed during the normal or, in other words, dry-weather flow. The pre-treated wastewater is let directly to the activated sludge process. During the top-flows, the amount of pre-treated wastewater which exceeds the flow of 200 l/s or 700 m³/h, is treated by chemical precipitation and let into the pre-sedimentation tanks. Wastewater is let evenly into the activated sludge process only 200 l/s or 700 m³/h. Biological and chemical treatment are operated in this situation parallely.

Biological treatment with the activated sludge process:
2 U-formed twin-tanks or 2 x 2 squadrat tanks, 6 m x 30 m = 180 m², depth 4.5 m, volume 3 000 m³ in total
Tanks have been delt into five separate departments fitted with their own bottom-aerator fields as well as with propeller mixers as follows: The 1st, 2nd and 5th departments, each 1/8 or 12.5 % of the total tank volume as well as the 3 rd departments 1/4 or 25 % oh the total tank volume are operated alternatively aeratedly or unaeratedly. There is one propeller mixer in the 1st, 2nd and 5 th departments. There are two propeller mixers in the 3rd departments.
The 4 th departments 3/8 or 37.5 % of the total tanks volume are always operated aeratedly. There are no propeller mixers in the 4 th departments.
Original dimensioned sludge concentration 3.0 kg MLSS/m³
Average sludge concentration 6-10 kgMLSS/m³
Original dimensioned sludge load 0.3 kgBOD₇/kgMLSS x d Average sludge load 0.02-0.06 kgBOD₇/kgMLSS x d
Average retention time in the twin-tanks 8 h
Fine-bubble bottom aeration, rubber membrane disc aerators, submersion depth 4.5 m
Air compressors, 4 units, rotating screw compressors,
2 050 -8 000 m³/h, automatic stepless control of flow according to the oxygen need of the departments, and
4 350 m³/h by a manual steering
Vertical shaft flow propeller mixers, 5 units per tank and 10 units in total
Pumps for the internal sludge circulation of the tanks, 1 unit per tank and 2 units in total, submerged propeller pumps, stepless control of flow 100-400 l/s or 360 - 1 440 m³

Secondary sedimentation:
4 squadrat tanks, 6 m x 48 m = 288 m², average depth
3.5 m and volume 4 000 m³ in total
Dimensioned surface load 1.0 m/h
Average surface load < 0.5 m/h
Average retention time 10 h
Chain-type sludge scrapers
Return sludge pumps, 2 units per tank and 8 units
in total, submerged centrifugal pumps, stepless control of flow 75-600 l/s or 270 - 2 160 m³/h
Throughs for clarified wastewater, 5 unit per tank
1 overflow weir in the end of the tanks
Adjustable surface sludge throughs, 1 per tank, which
can also be used as throughs for clarified wastewater, if needed.

The secondary settled wastewater may also be let bypass the tertiary stage, if needed, directly to the outlet pipe of the treatment plant. Then the mechanically-chemically treated (the primary settled) wastewater is let into the tertiary stage in which it may be treated either mechanically only (removal of the unsettled fine-coarse suspended solids) or chemically and mechanically (contact filtration or, if needed, post-precipitation)

Flotation filter tertiary stage:
8 units, space for flotation 2.75 m x 6.80 m = 18,7 m²
and for sand filter 2.75 m x 6.30 m = 17.3 m²
Depth of the filter bed 100 cm
Grain size of the filter sand 2-3 mm (D_{10} = 2.1 mm
Flotation is operated by an automatic on/off-principle steering according to the turbidity of the secondary settled wastewater. The flow of dispersion water, 60-180 m³/h, is controlled automatically stepwise according to the flow and turbidity of the secondary settled wastewater.
Filtration is operated continuously by a down-flow control. The backwash of filters is carried out automatically according either to the amount of the filtered wastewater or to the lenght of filtration intervals
Dispersion water pumps, 2 units a´ 48 m³/h and 1 unit
a´ 96 m³/h, pressure head 75 mwp
Dispersion air compressor, 1 unit, 560 l/s x 10 bar
Bacwash water pumps for filters, 158 m³/h and 414 m³/h
Air scour compressor, 1 unit, 1 040 m³/h.

BIOLOGICAL TREATMENT:
A very low-loaded activated sludge process. There are following process alternatives and treatment phases for biological treatment in the actual reactors:
1) anaerobic, anoxic, aerobic and anoxic (A/D/N/D)
2) anaerobic, anoxic and aerobic (A/D/N)
3) anaerobic and aerobic (A/N)
4) totally aerobic (N only)

There are always the anoxic conditions present in the secondary sedimentation tanks which means that quite a lot of post-denitrification takes place in those.

OPTIONS FOR CHEMICAL TREATMENT:
Precipitation of the suspended and colloidal organic matter as well as that of phopshorus included in the wastewater to be let to bypass the activated sludge process and to be let into the primary sedimentation tanks, precipitation chemical ferric sulphate $Fe_2(SO_4)_3$, feeding into the distribution channel of the primary sedimetation tanks.

Compeletion of the biological removal of phosphorus, if needed, in the tertiary stage by contact filtration or by post-precipitation to be carried out with flotation, precipitation chemical ferric sulphate $Fe_2(SO_4)_3$, feeding into the distribution channel of the flotation filters.

In reserve, simultaneous precipitation of phosphorus in the activated sludge process, precipitation chemical ferrous sulphate $FeSO_4$, feeding into the sand and grease removal unit or into the distribution channel of the secondary sedimentation.

Adjusting the pH-value of wastewater to be let into the activated sludge process, if needed, by hydrated lime $Ca(OH)_2$, feeding after the sand and grease remova unit or after the primary sedimentation.

If needed, the improving of biological phosphorus and nitrogen removal with ethanol CH_3CH_2OH to be feeded to the beginning of the reactors for biological treatment or into the distribution channel of the tertiary stage.

DISINFECTION:
If needed, to be carried out with chlorine gas Cl_2, feeding into the distribution channel of the tertiary stage.

SLUDGE TREATMENT:

Pumping of sludge to the sludge treatment as well as in the sludge treatment:
Raw sludge pumps in the primary sedimentation tanks,
4 units a´ 12 l/s, submerged centrifugal pumps
Excess sludge pumps in the pumping station to be connected alternatively with the distribution channel of the secondary sedimentation tanks as well as with the return sludge channel, 2 units a´ 9 l/s, submerged centrifugal pumps,
Pumps for the thickened sludge, 3 units a´ 2.5-13 m^3/h,
spiral screw pumps

Thickening of sludge:
2 round tanks, diameter 12 m, volume 600 m^3 in total,
rotating thickening mechanisms

Conditioning of sludge:
Adjusting of the pH-value with hydrated lime $Ca(OH)_2$, feeding into the mixing vessel in front of the sludge thicknening units
Adding of polymer for dewatering of sludge, feeding after the sludge thickening

Dewatering of sludge:
Filter band presses, 2 units, a´ 13 m^3/h and 1 000 kgTS/h

Composting of sludge:
Mechanical mixing of subtances, composting in cones on the asphalted field sewered to the treatment plant

STORING OF CHEMICALS:

Ferrous sulphate:
Storing and dissolving tank, volume 80 m^3
Feeding tank, 2 m^3
Feeding with membrane dosing pumps

Hydrated lime:
2 silos, each 40 m^3, volymetric dry dosing of lime, feeding as lime milk into wastewater and into sludge before thickening

Ferric sulphate:
Storing in reinforced plastic tanks, feeding as the factory-made liquid

Ethanol:
Storing in reinforced conts, feeding as the factory-made liquid

Polymers:
Storing in paper sacks, automatic preparing of liquid, feeding with membrane dosing pumps

Chlorine gas:
Storing only, if needed, in pressure vessels of steal

Experience with the implementation and optimization of biological phosphorous removal in the municipality of Aarhus, Denmark

John Sørensen, Municipality of Aarhus, Denmark

Abstract

Biological P-removal has been implemented and optimised at four waste water treatment plants in Aarhus, Denmark. The amount and quality of organic matter in the waste water was identified as the most importent parameter for the process. If the amount of ready degradable organic matter is high, it is demonstrated, that a stable biological P-removal process could be obtained in a traditional BIO-DENITRO systems without anaerobic tanks. The bio-P process can be controlled by an on-line control system. The process can be improved by adding hydrolysate, produced internal at the plant from biological sludge. The yield varies from 8-14 % of the total filtered COD in the waste water. This internal carbon source stabilised the biological P-removal, and the organic matter in the waste water was used for optimising the denitrification. Nitrate was reduced in the effluent by 20 % when using hydrolysate. Due to the biological P-removal, it was possible to run the plants with a molar ratio of 0.3 - 0.4.

Keywords

Biological phosphorous removal, hydrolysis of biological sludge, on-line control.

Introduction

The Danish Action plan for the Water Environment from 1987 has resulted in many new Waste Water Treatment Plants (WWTP) and in renewal of other plants, as many plants should obtain full nitrogen and phosphorous removal. Traditionally, phosphorous has been removed from the waste water by chemical precipitation. The biological P-removal process has been known for many years, but has not been used very much in Denmark. During the last few years more and more plants use the process for phosphorous removal, often in combination with chemical precipitation to secure an effluent quality of 0.5-1 mg P/l. The biological P-removal process needs good quality of carbon to run efficient. Therefore the process runs most effective at plants, with high concentrations of ready degradable carbon (VFA). The process runs in two steps (Henze et al., 1995). First the bio-P bacteria releases posphorous during uptake of organic matter in an anaerobic environment. Often this happens in separate tanks - AN tanks. In the second step the bio-P bacteria gain energy from the degration of stored organic matter under anoxic/oxic conditions and use the energy to take up phosphorous from the waste water.

In this paper the biological P-removal is compared on four WWTP´s in the Municipality of Aarhus, Denmark. It is discussed, how biological P-removal can be establised at a BIO-DENITRO plant without separate anaerobic tanks simultaneous with the nitrogen removal, and it is discussed how the process can be controlled under these conditions by an on-line control system. The biological P-removal process can be optimized by hydrolysis of primary sludge (Andreasen et. al, 1996). After hydrolysis, sludge is separated from the hydrolysate. Sludge is pumped to the fermentation tanks, and the hydrolysate, which contain a high amount of ready degradable carbon, is pumped to the biological tanks to optimize the biological P-removal and the denitrification. This paper shows, that hydrolysis of biological return sludge from the clarifiers gives similar results, and that it is much easier to operate. It is also discussed how the P-removal process can be improved by reducing internal sources of phosphorous load to the biological tanks, eg. from reject water.

Materials and methods

Description of the treatment plants

The four treatment plants in this investigation differ all in construction. The key data for the plants are shown in table 1. Egå WWTP is operated according to the nitrate recirculation method and is constructed with selectors and anaerobic tanks.

Table 1. Key data for investigated waste water treatment plants

	Marselisborg	Viby	Åby	Egå
Design load, kg COD/d	26.500	10.000	11.000	11.000
Actual load, kg COD/d	30.000	3.500	6.600	8.800
Biological volume, m3	16.000	14.500	22.000	25.000
Operation method	BIO-DENITRO	BIO-DENIPHO	BIO-DENIPHO	Recirculation
Anaerobic	No	Yes (hydrolysis)	Yes	Yes (hydrolysis)
Presetling	Yes	Yes	No	No
Filtered COD, % *	77	67	36	52
COD/N	11	8	12	10

Remark : * Filtered COD in % of total COD to the biological part.

There are no primary treatment at the plant. The load is 80% of the design load. Viby , Åby and Marselisborg WWTP´s are operated according to the alternating method (BIO-DENITRO and BIO-DENIPHO) (Bundgaard et al., 1991). Marselisborg WWTP has primary treatment, but no separate anaerobic tanks. It was original designed for denitrification only during summertime, but has been operated with full denitrification the whole year. The COD load is 120 % of the design load. Viby WWTP has primary treatment, and is constructed with separate anaerobic tanks. The load is 35 % of the design load due to a shut down of industries in the area. Åby WWTP has no primary treatment and is constructed with anaerobic tanks. The load is 60 % of the design load. On plants operated according to the alternating method, the nitrogen removal is controlled by an on-line control system.

Chemical analyses

Most of the chemical analyses was carried out using test kits (Dr. Lange). Filtered COD was determined as the dissolved COD measured after filtration through a GF/A filter. Phosphate release rate was carried out in the laboratory on water samples from the selectors 1-4 that was mixed with sludge from the plant and stirred. Samples were taken from the mixture each 10 minutes, filtered and analysed for ortho-phosphate. The phosphate release rate was calculated after measuring the content of MLSS in the test chamber. Phosphate release rate on water with acetate was used as control.

Results

Influence of temperature and organic matter

At Viby WWTP there are seasonal variations in the P-release as it is depending of the temperature (figure 2). The lowest chemical addition (low molar ratio) and the highest P-release is measured in the anaerobic tank during summertime.

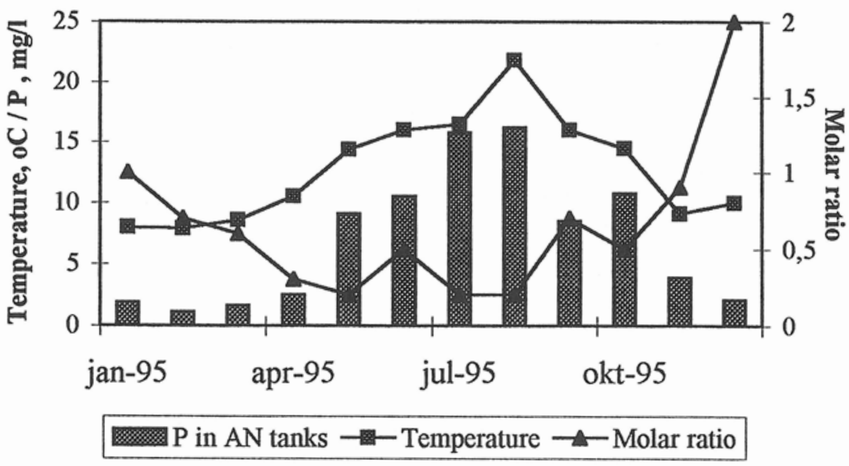

Figure 2. Seasonal variations in biological P-removal, Viby WWTP.

This indicates, that phosphorous is removed biologically. At decreasing temperatures the P-release decreases, and gradually more and more chemicals are needed for the P removal. During periods with low temperatures, most of the phosphorous is removed chemically.

At Egå WWTP, where the retension time in the selectors is about one hour during dry wether, the P-release ends after less than one hour of contact between the raw waste water and the return sludge, (figure 3). The P-release rate is highest in selector 1, and lowest in selector 3. In selektor 4, no P-release is registered. Filtered COD was measured to 101 mg/l in selector 1 and 55 in selector 4. This

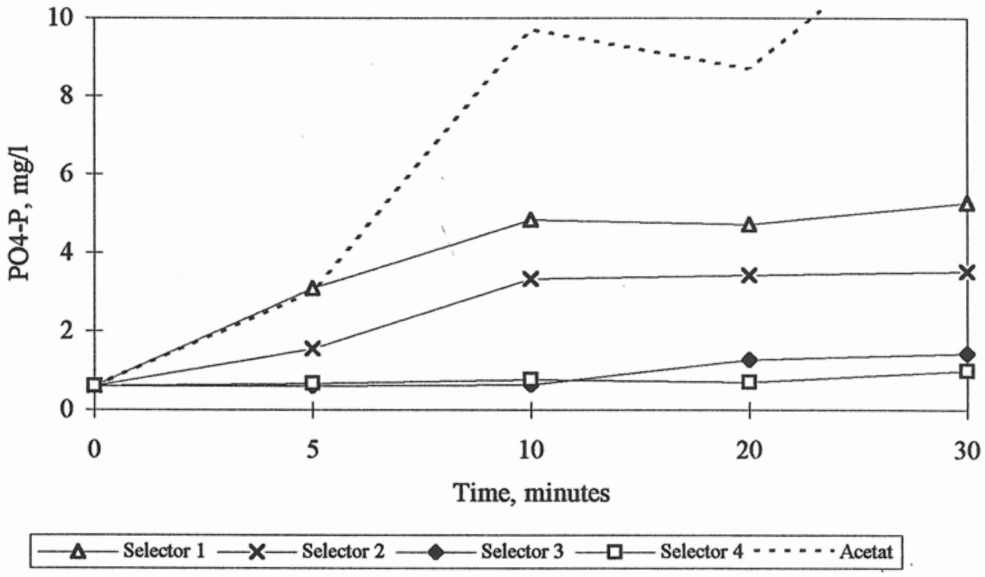

Figure 3.Relative P-release in selector 1-4 at Egå WWTP.
Acetate is used as control.

indicates, that the easily degradable carbon is taken up very fast, and that there might be a lack of easily degradable carbon after passage of the first 3 selectors. The P-release rate varies from 1.6 to 0.1 mg P/g MLSS/hr during passage through the selectors.

Phosphorous is taken up in the aerated tanks. The P-uptake starts immediately when aeration starts (figure 4). The P-uptake rate is slower when the phosphorous

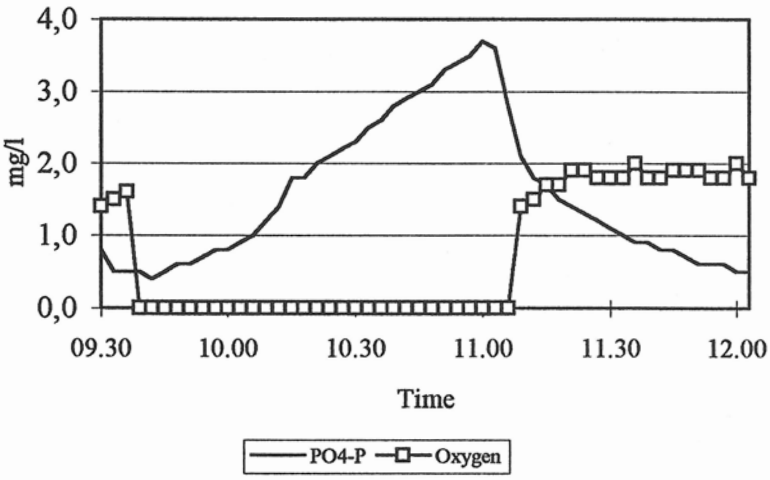

Figure 4. Dynamics of the P-uptake, Egå WWTP.

concentration is low, even if the oxygen concentrations in the water is high (2 mg/l).

Dynamics of biological P-removal

The biological phosphorous removing bacteria has advantage on plants constructed with an anaerobic tank, but the bacteria can also function in the normal biological tank simultaneous with the denitrification (Figure 5). It is seen, that biological P-removal is responsible for 52 - 73% of the total P-removal.

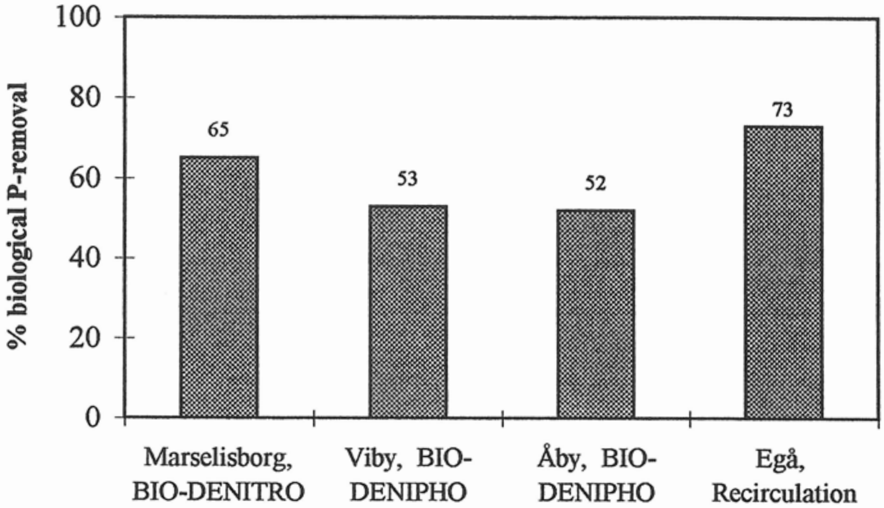

Figure 5. Biological P-removal at four WWTP's.

On all four plants, the COD/N ratio is between 8 and 12. A COD/N ratio of 8 is considered satisfactory for N-removal. On Marselisborg WWTP, the degree of biological P-removal is nearly as high as on Egå where separate AN tanks are present. Marselisborg WWTP recieves waste water from among others a dairy, a brewery, a slaugtery and an oilmill. The dynamic between P-release and P-uptake in one tank at Marselisborg WWTP is shown during some hours on figure 6. It should be noted, that due to the BIO-DENITRO system, there are only outlet from the tank during P-uptake periods (indicated with arrow lines). The effluent quality that day was 0.7 mg P/l. From figure 6 it is seen, that the release and uptake is relatively fast (1 mg P/g MLSS/hr), giving a dynamic biological P-removal. This indicates, that the anaerobic phases should be kept short to avoid too high concentrations of released phosphorous in the tank, and to avoid that the time in the following aerated period becomes too small to take up all the released phosphorous.

An on-line nitrogen removal control system, described in Sorensen et al. (1994), has been running at Marselisborg WWTP for 6 years. After the introduction of biological P-removal, the control system has been extended so, that it also controls the P-release and the P-uptake.

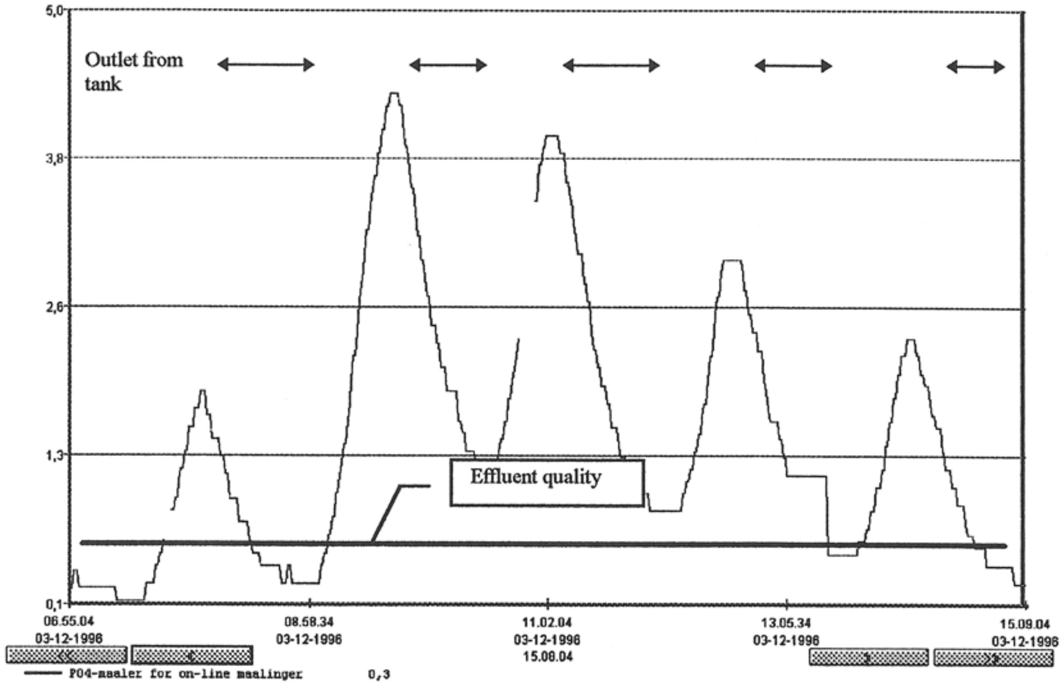

Figure 6. Dynamics of biological phosphorous removal at Marselisborg WWTP.

Nitrogen and biological P-removal in the same tank

At Marselisborg WWTP, a large amount of filtered COD at the inlet to the biological tanks has made it possible through optimization to implement biological P-removal in the same tanks as the nitrogen removal, without influencing these processes (table 3). Due to biological P-removal, the molar ratio has successive been reduced from 0.8 to 0.4 during the last 3 years.

Table 3. Average effluent values of nutrients at Marselisborg WWTP.

	1993	1994	1995	1996
Flow, m3/d	40.500	45.600	39.700	33.600
Ammonia, mg/l	1,5	2,5	1,7	0,7
Nitrate, mg/l	2,1	2,3	1,7	2,1
Phosphorous, mg/l	0,5	1,1	1,9	1,4
Molar ratio	0,8	0,7	0,3	0,4

Hydrolysis of biological sludge

In order to obtain a stable and efficient biological P-removal it is important not to loose readily degradable carbon, that comes with the waste water. If however there is a lack of carbon, it is possible to produce it internal at the plant by hydrolysis of primary sludge or biological sludge. Both methods has been tested at Viby WWTP.

Using hydrolysate from hydrolysis of primary sludge results in a stable and efficient biological P-removal (Andreasen et al. 1996). The operation of the proces however, is time consuming, as sludge and hydrolysate has to be separated before use for the biological processes.

At plants with separate anaerobic tanks for biological P-removal, return sludge and the raw waste water is mixed at the inlet to the anaerobic tanks and phosphorous is released in the anaerobic tanks (figure 7). At Viby WWTP the inlet has been

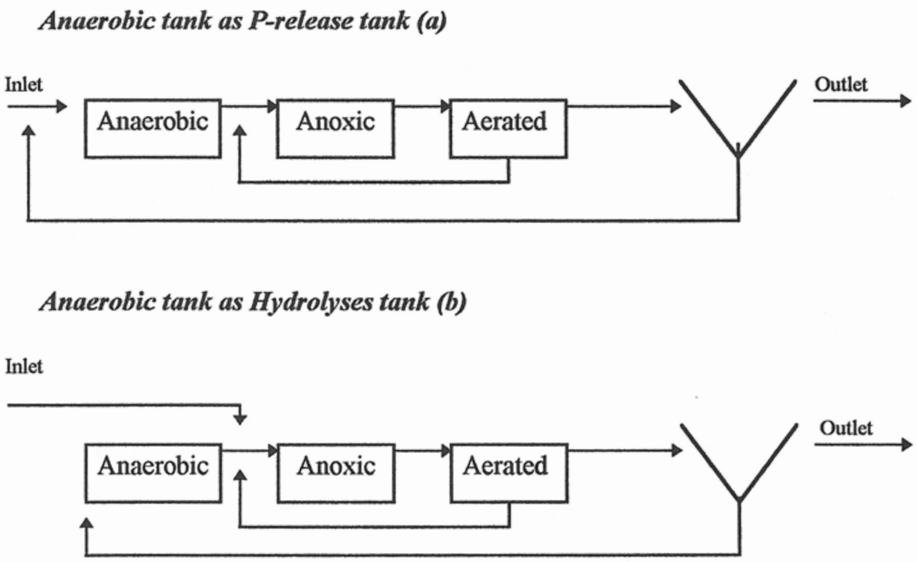

Figure 7. Anaerobic tanks as P-release tanks(a) and as hydrolysis tanks(b).

changed, so that only return sludge runs through the anaerobic tanks and the waste water is led to the anoxic tanks. In this way a hydrolysis of biological sludge has been obtained. A similar hydrolysis has been implemented at Egå WWTP, but only a part of the return sludge is hydrolysed.

Compared to the hydrolysis of primary sludge, the hydrolysis of biological sludge has advantages, as no separation of sludge and hydrolysate is necessary.

Table 4. Hydrolysis of biological sludge at Viby and Egå WWTP's.

	Viby	**Egå**
Volume, m3	5.500	5.000
MLSS, kg/m3	9 - 10	9 - 10
Retension time	10 - 20 hours	10 days
Sludge in hydrolysis tank	All return sludge	Part of return sludge
Produced COD, kg/d	240-300	290
Prod. COD in % of inlet COD	10-14	9-10
P-released, kg/d	140-200	48

The COD produced from hydrolysis was similar whether hydrolysis was from primary sludge or from biological sludge. The COD yield with both methods was 8-14 % of the COD in the inlet. At Viby WWTP, the COD excess production varied between 240-300 kg COD/d (table 4) depending of the retension time in the anaerobic tanks. At Egå WWTP, the excess COD production was 290 kg/d. The released P amount at Viby WWTP was140-200 kg PO_4-P/d depending on the retension time. At Egå WWTP it was 48 kg/d.

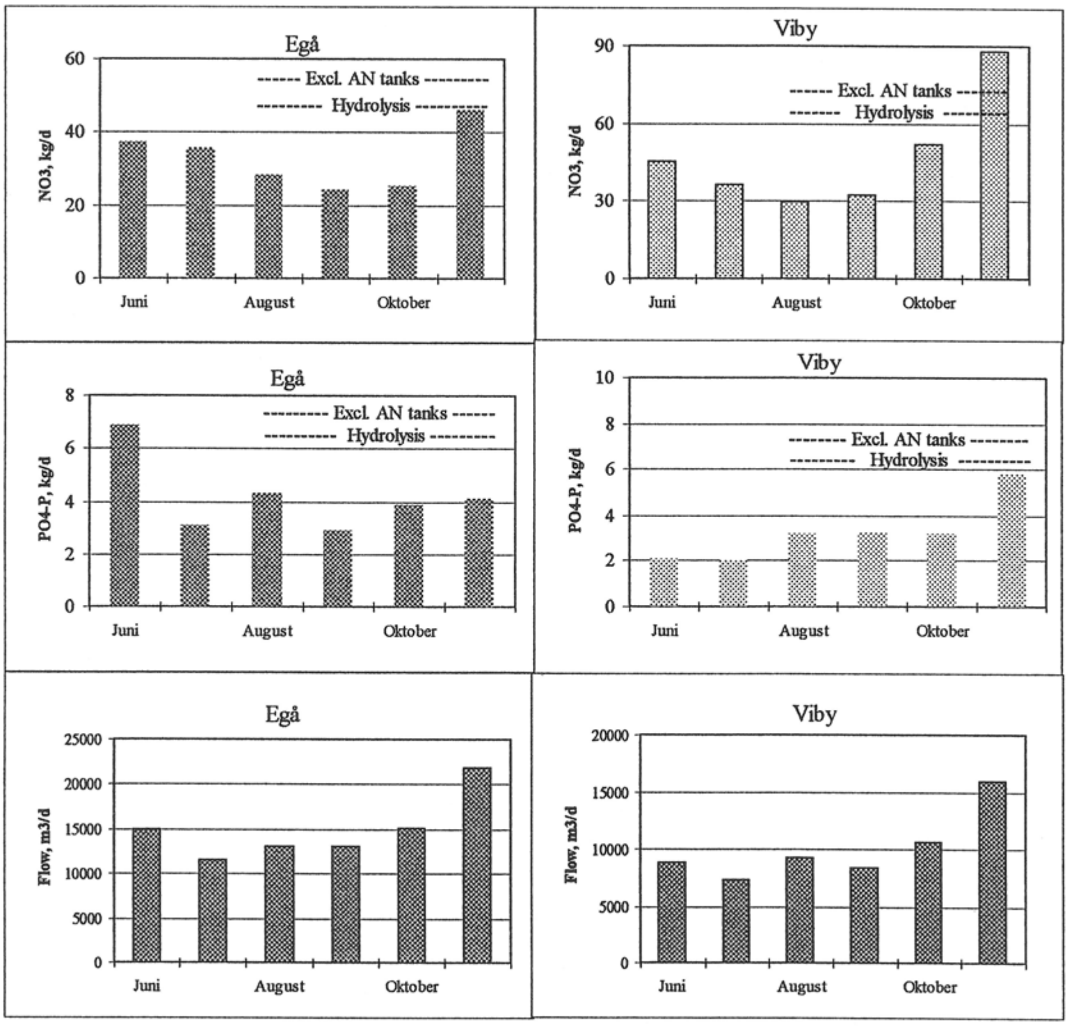

Figure 8. Effect of hydrolysis at Egå and Viby WWTP's. Average values per month.

The effect of the hydrolysis is shown in figure 8, where the flow and the effluent values of nitrate and phosphorous are shown from june-november. At Egå WWTP the amount of NO_3 in the effluent decreased, when the hydrolysate was added to the biological tanks. In november the nitrate amount increased proportional with the flow. The amount of phosphorous in the effluent has been low since july, but the biological P removal process has been more stable from day to day since the hydrolysate was added. At Viby WWTP, there is a decrease in the amount af NO_3 in the effluent in august/september as a consequense of the hydrolysate addition. In october a soft water factory closed, so the waste water quality at Viby WWTP changed and NO_3 concentrations increased in the effluent. The biological P-removal was only influenced sligthly. In november, the nitrate and phosphorous amounts increased proportional with the flow.

Phosphorous in reject water from dewatering of sludge with biological P-removal can reach high concentrations (table 5). A storage of sludge is seen to give the highest P-load to the plant from reject water. At plants with anaerobic digestion of primary and biological sludge, phosphorous will be released under anaerobic conditions. However an aeration for some hours before the sludge is pumped to dewatering seems effective in reducing the P-load of the plant. Dewatering of fresh sludge gives only little load of phosphorous through the reject water.

Table 5. P-load from reject water.

	Marselisborg	**Viby**	**Åby**	**Egå**
Anaerobic digestion of biol. sludge	Yes	Yes	No	No
Aeration before dewatering	None	Aeration	None	None
Storage of sludge	No	No	Yes	No
COD, kg/d	104	43	79	63
NH4, kg/d	206	91	14	1
PO4-P, kg/d	11	2	25	2
% P of influent load	3	4	25	2

Discussion

Biological P-removal is a process, that can run on most plants. Like all other biological processes, it is influenced by temperature, as it is most effctive during summertime with high temperatures in the waste water. Therefore biological P-removal normally is used in combination with chemical precipitation.

When the biological P-removing bacteria within the first hour of contact with the waste water has taken up most of the easily degradable carbon, the carbon quality, that is left over for denitrification is of poorer quality, and may result in lower denitrification rates and higher NO_3 values in the effluent.

On most activated sludge plants, however, there often is a certain degree of biological P-removal on plants without an anaerobic tank, as molar ratio´s around 0.8 often is seen. On BIO-DENITRO and BIO-DENIPHO plants with high amount of organic matter, especially easily degradable carbon, it is possible to have full nitrogen removal and a high degree of biological P-removal in the same biological tanks.

At Marselisborg WWTP the release rate is seen so fast, that the main problem is to control or reduce the release. This has been done by reducing the amount of carbon at the inlet to the biological tanks and by controlling the time used for denitrification/P-release through an on-line control system. The introduction of an on-line nitrogen removal control system resulted in about 20 % longer denitrification time and lower nitrate in the effluent (Sørensen, et al. 1994). The on-line nitrogen and phosphorous control system has not changed the time distribution between aerated and unaerated time at the plant radically. Therefore, the nitrogen removal has not been influenced after introduction of biological P-removal. Thus it has been possible to make space for the biological P-removal process at the plant without influencing the other processes. The reason for this is, the extreme good quality of carbon at the plant. It should be noted, that the load of the plant has increased about 30-40 % in the period 1993 to 1996.

It is possible to produce and use internal carbon sources to improve the biological P-removal. At Viby and Egå WWTP ´s, results showed, that phosphorous was released within one hour of contact with the waste water. The anaerobic volume was not needed for P-release, so now the AN tanks are used as hydrolysis tanks. The yield of filtered COD from the hydrolysis was 8-14 % of the organic load in the inlet. Similar results has been obtained in another study from hydrolysis of primary sludge.The hydrolysis of biological sludge is however much easier to operate. The internal carbon source coming from hydrolysis is used for P-release. The excess COD from the hydrolysis is, together with the incomming waste water, used for denitrification. Thus hydrolysis of return sludge is a useful way to improve the nutrient removal at a WWTP. At Egå it was possible to reduce the NO_3 amount in the effluent by 20% even if 20 % of the biological volume (the AN tanks) was taken out of traditional use.

On Egå, only part of the return sludge is used for hydrolysis. At Viby WWTP, all the return sludge is pumped continously through the tanks controlled by the inlet flow meter. The hydrolysis at Egå has a retension time of 10 days while it is 15-20 hours at Viby. The tanks are similar, but the two tanks differ in the amount of phosphorous released. At Viby the P-release is 3-4 times higher than at Egå. The reason for this might be that the bigger flow through the tanks at Viby makes it possible for a larger amount of bacteria to release phosphorous and take up the produced ready degradable carbon.

Another way of optimizing the biological P-removal is to reduce the internal load of phosphorous from the reject water, by aerating it before dewatering and during storage. The reject water was found to be responsible for 2-25 % of the total P-load to the biological system.

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BIOLOGISK FOSFORPROCESS VID ÖRESUNDSVERKET

Lars-Erik Jönsson och Peter Magnusson, VA-verket, Helsingborgs stad, Sverige

Sammanfattning

En till två av Öresundsverkets fyra linjer har sedan år 1993 drivits med biologisk fosforreduktion i kombination med fördenitrifikation och primärslamhydrolys. Filtrerad totalfosfor i utgående vatten från slutsedimenteringen i bio-P-linjerna har varierat mellan 0,33 - 0,83 mg/l räknat som årsmedelvärden.

Bio-P-processen har visat sig relativt stabil. Funktionen kan tappas mera långvarigt under nederbördsrika vintrar samt i anslutning till industrisemestrar, möjligen beroende på kort anaerob kontakttid. Vid sådana tillfällen har efterfällning med järnklorid tillämpats utan att bio-P-funktionen efter avslutad dosering har tappats. Avgörande faktorer för funktionen är tillräcklig tillgång på lättillgänglig kolkälla (VFA) och en COD_{tot}/P_{tot}-kvot större än cirka 40 i inkommande vatten till anaerobzonen.

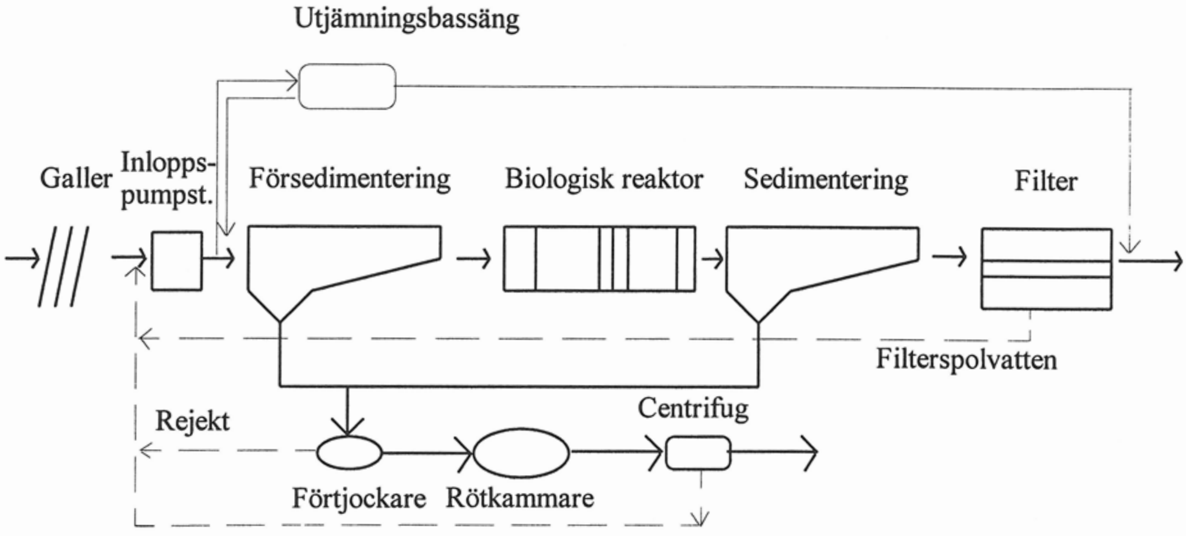
Kortvarig funktionsförsämring i bio-P-processen har hanterats genom polering med järnklorid på filter. Fosforläckage från upplagrat slam i bassängerna i slutsedimenteringen är obetydligt.

Genom primärslamhydrolys i försedimenteringsbassängerna genereras VFA. För att styra hydrolysen används en enkel titrermetod för analys av summa VFA i försedimenterat vatten.

Inledning

Öresundsverket, Helsingborgs Stads avloppsreningsverk, byggdes under 1990 - 1991 ut för att uppnå långtgående kväve- och fosforreduktion. Anläggningen utformades med fördenitrifikation och med möjlighet att testa biologisk fosforreduktion.

Öresundsverket är en aktivslamanläggning vars utformning framgår av figur 1. Verket har fyra linjer från inloppspumpstationen fram till filterna vilket gör det möjligt att parallellt använda olika processer för fosforavskiljning.



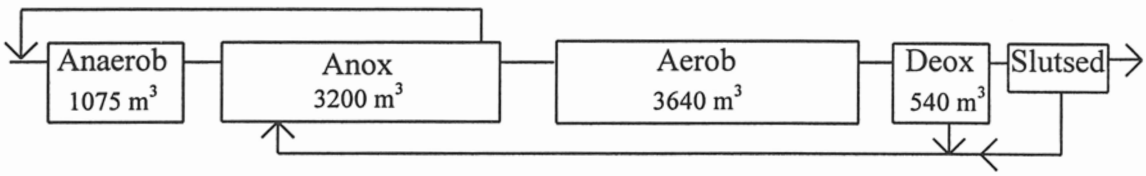
Figur 1. Processchema för Öresundsverket.

Medelvärden för inkommande vatten till Öresundsverket beskrivs i tabell 1.

Tabell 1. Medelvärden för inkommande vatten.

	Flöde (m^3/d)	Totalfosfor (mg/l)	COD (mg/l)
1993	53900	5,7	419
1994	61200	4,5	372
1995	55700	4,6	377
1996	45400	6,5	470

Biologisk fosforreduktion har bedrivits i en s.k. UCT-process, se figur 2. Den anaeroba kontakttiden har varit 0,65 - 0,75 h, baserat på högsta torrvädersflöde 600 - 800 m^3/h och ett slamrecirkulationsflöde på 810 m^3/h. Den rekommenderade kontakttiden uppges till 0,75 - 1,0 h under gynnsamma betingelser för bio-P-processen (1).



Figur 2. Biostegets konfiguration vid biologisk fosforreduktion.

Utsläppsvillkoren för Öresundsverket framgår av tabell 2. Prövotidsvillkoren gäller som årsmedelvärden.

Tabell 2. Utsläppsvillkor Öresundsverket.

	Prövotidsvillkor fram till 1997-04-01	Målsättningsvärden
Totalkväve	12 mg/l	8 mg/l
Totalfosfor	0,3 mg/l	0,3 mg/l
BOD_7	10 mg/l	10 mg/l

I tabell 3 visas resultat från Öresundsverket.

Tabell 3. Reningsresultat Öresundsverket, årsmedelvärden.

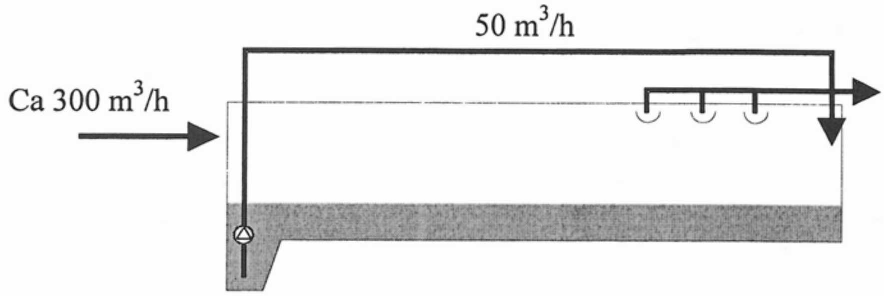
	Utgående total-fosfor hela verket (mg/l)	Utgående total-kväve hela verket (mg/l)	Filtrerad totalfosfor efter slutsed. Bio-P (mg/l)
1993	0,36	8,4	0,83
1994	0,33	6,9	0,38
1995	0,39	6,6	0,77
1996 (nov.)	0,25	7,8	0,33

Kolkälla för bio-P-bakterier i försedimenterat vatten

En avgörande faktor för funktionen av en bio-P-process är tillgången på lättillgänglig kolkälla för bio-P-bakterierna. Särskilt viktigt är mängden flyktiga organiska syror (Volatile Fatty Acids, VFA) framförallt ättiksyra, propionsyra och smörsyra samt fermenterbar organisk substans. Denna senare fraktion av det organiska materialet omvandlas i det anaeroba steget av fermenterande bakterier till ytterligare VFA. Som ett centralt förlopp i bio-P-processen tas dessa syror upp av bio-P-bakterierna i det anaeroba steget samtidigt som ett fosforsläpp sker. I en VA-FORSK-rapport (2) har påvisats att den huvudsakliga mekanismen för fosforreduktionen vid Öresundsverket var biologisk, och att maximalt 10% kunde hänföras till kemiska fällningsreaktioner.

Primärslamhydrolys

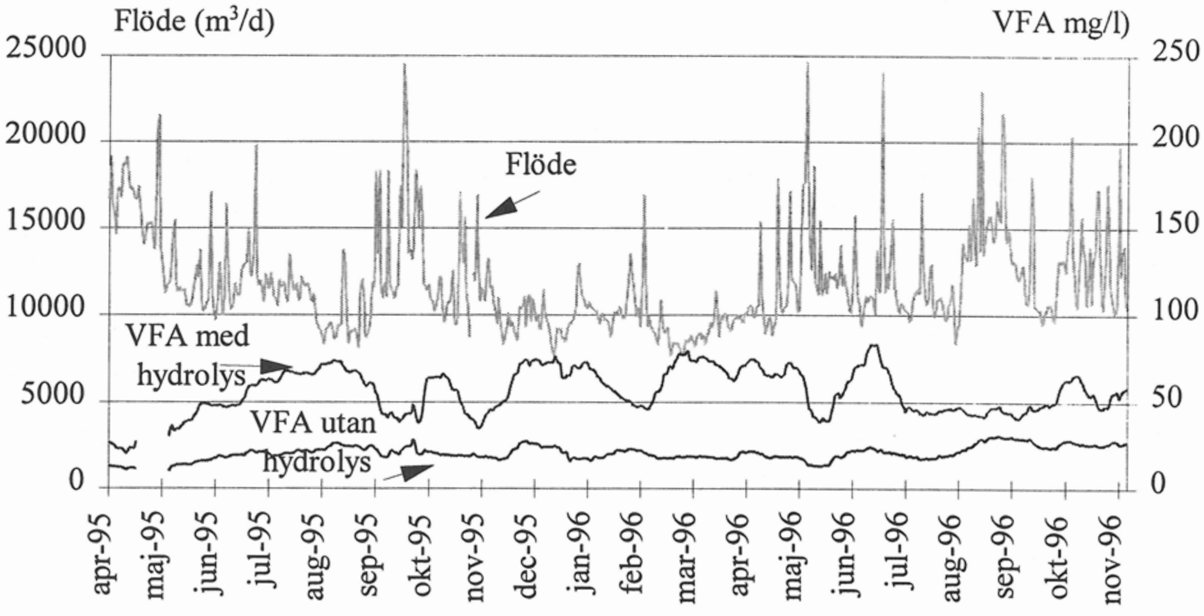
Det konstaterades i slutet av 1992 att mängden lättillgänglig kolkälla i försedimenterat vatten vid Öresundsverket var för liten för god bio-P-funktion. Därför beslöts det att en enkel process för hydrolys av primärslam skulle provas. Hydrolysen utförs i befintliga försedimenteringsbassänger genom att slammets uppehållstid i bassängerna ökas, och de flyktiga syror, VFA, som bildas i slamtäcket tvättas ur genom en rundpumpning av slammet. Rundpumpningen sker med ca 50 m^3/h per bassäng. Medelflödet till varje bassäng är ca 300 m^3/h, se figur 3.



Figur 3. Schematisk bild av primärslamhydrolysprocessen i försedimenterings-bassängerna.

Slammängden i försedimenteringsbassängerna styrdes inledningsvis genom att slamnivån lodades. Lodningen var emellertid ej tillförlitlig, eftersom vattnet svartfärgades av hydrolysprodukterna. I stället har en enkel analysmetod för VFA tillämpats, som bygger på titrering (3).

Analyserad VFA-halt i dagliga stickprov (VFA är ej stabil i kylda dygnsprov) på försedimenterat vatten från två linjer med primärslamhydrolys samt från en referenslinje utan hydrolys, beräknade som 15-dygns medelvärden för att illustrera trender, visas i figur 4.

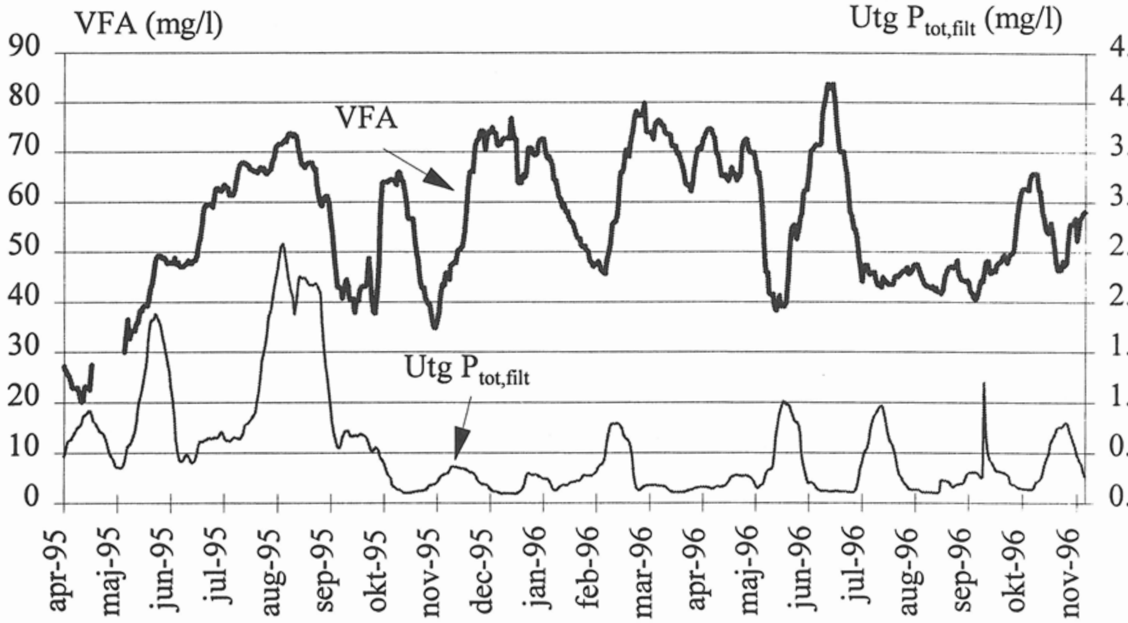


Figur 4. VFA-halten i försedimenterat vatten med primärslamhydrolys och utan hydrolys samt vattenflödet per linje.

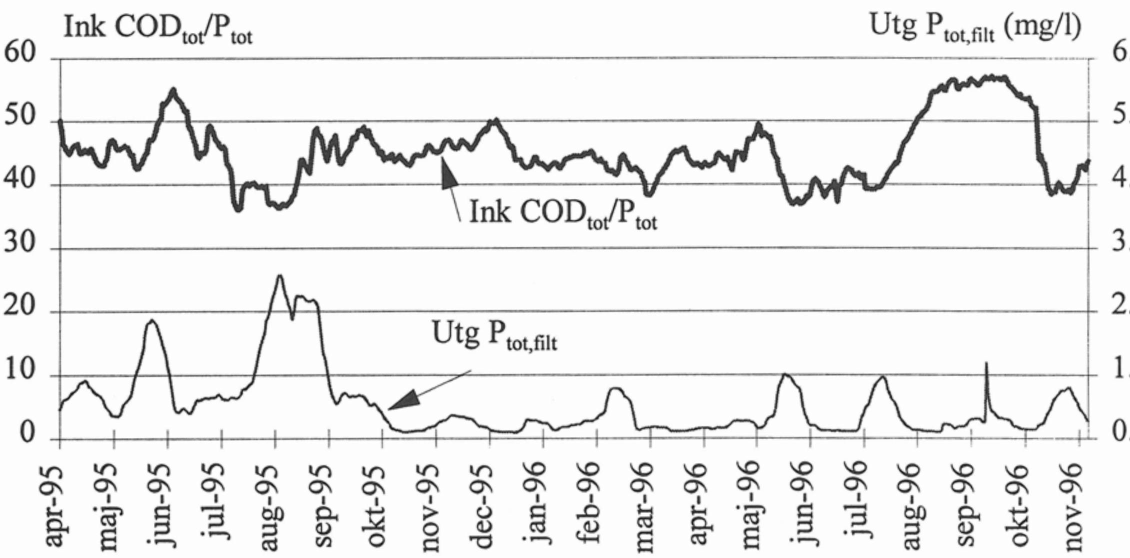
I figur 4 visas också flödet till respektive linje. Figur 4 indikerar att halten producerad VFA varierar i intervallet 10 - 60 mg/l och beror av flödet, sålunda att vid höga flöden minskar producerad VFA-halt. Detta är en effekt, förutom av utspädningen, av att vid höga flöden sker slamflykt från hydrolysbassängerna. Det krävs sedan en viss tid för att bygga upp en ny slamhydrolyskultur. Någon uppenbar effekt av temperaturen kan ej spåras.

Processtabilitet

I figurerna 5 och 6 visas utgående $P_{tot,filt}$ från slutsedimenteringen från de båda bio-P-linjerna och VFA respektive COD_{tot}/P_{tot}-kvoten i inkommande vatten till anaerobzonen, beräknade som 15-dygns medelvärden för att illustrera trender.



Figur 5. VFA i inkommande vatten till anaerobzonen och utgående $P_{tot,filt}$ från slutsedimenteringen i bio-P-linjerna.

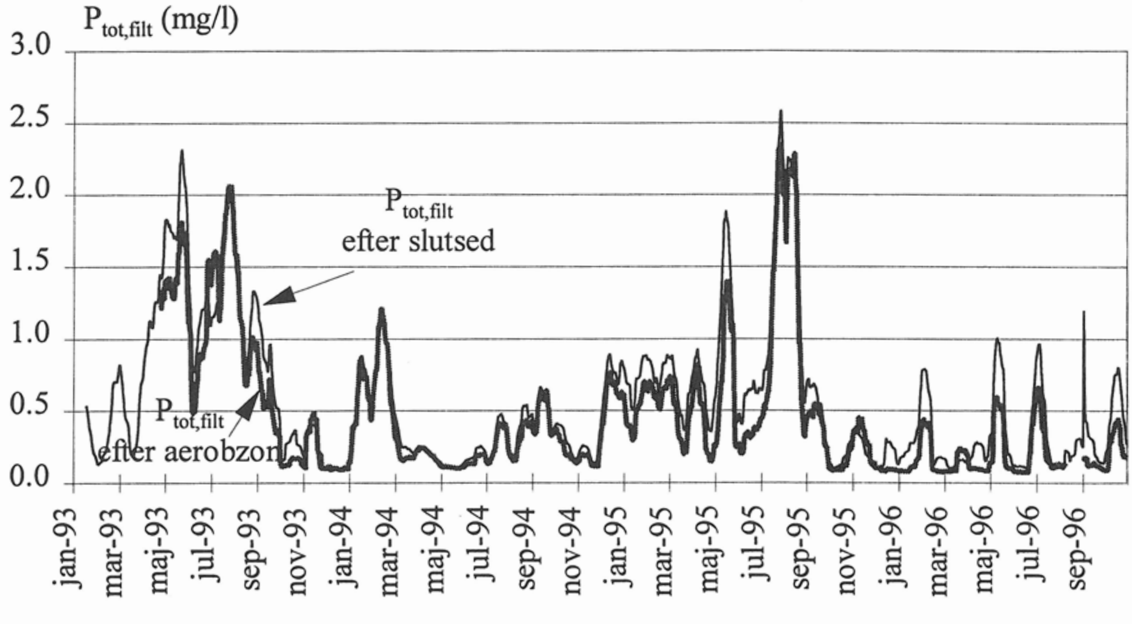


Figur 6. COD_{tot}/P_{tot}-kvot i inkommande vatten till anaerobzonen och utgående $P_{tot,filt}$ från slutsedimenteringen i bio-P-linjerna

Det framgår av figurerna 5 och 6 att en stabil låg utgående $P_{tot,filt}$ kräver både tillräcklig mängd VFA och en COD_{tot}/P_{tot}-kvot större än cirka 40.

Vid två tillfällen har en bio-P-linje tagits ur drift under 2 - 4 veckor. I samband med återstarten har slam från den i drift varande linjen ympats in motsvarande cirka 1/3 av slaminnehållet i den avställda linjen. Stöddosering med fällningskemikalie har måst tillgripas under första dagarna, för att ta hand om den fosfor som släppts av slammet i slutsedimenteringsbassängerna. Efter cirka en veckas drift var bio-P-funktionen återställd.

Kontroll av eventuellt fosforläckage från slammet i bassängerna i slutsedimenteringen sker via analyser av $P_{tot,\ filt}$ efter aerobzonen och efter slutsedimenteringen, se figur 7.

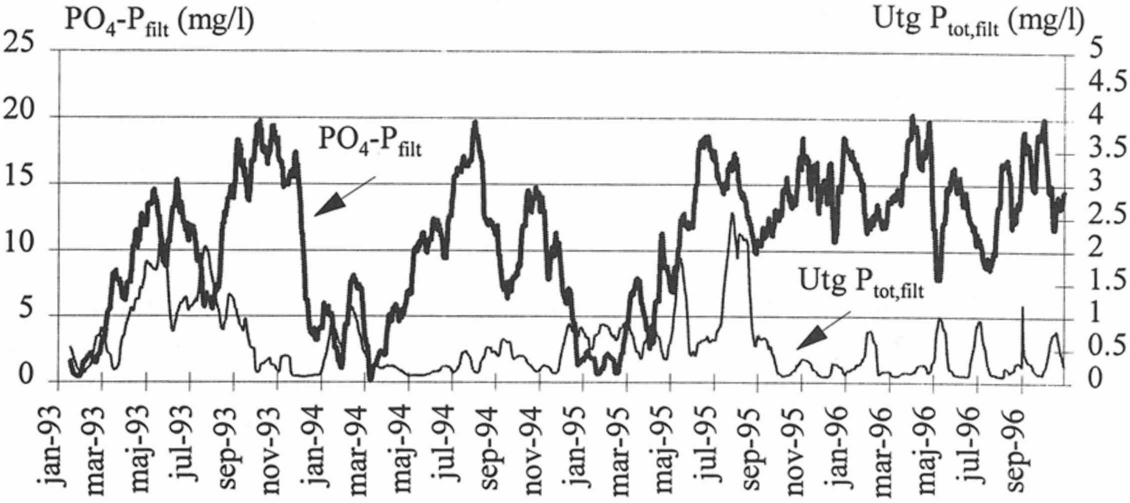


Figur 7. $P_{tot,\ filt}$ efter aerobzon och efter slutsedimentering i bio-P-linjerna

Av figur 7 framgår att det periodvis kan ske ett litet fosforläckage från slammet i slutsedimenteringsbassängerna. Analysen efter aerobzonen är från stickprov tagna vid middagstid, medan analysen efter slutsedimenteringen är från dygnsprov, dvs det kan inte uteslutas att figur 7 också illustrerar en något sämre bio-P-funktion nattetid.

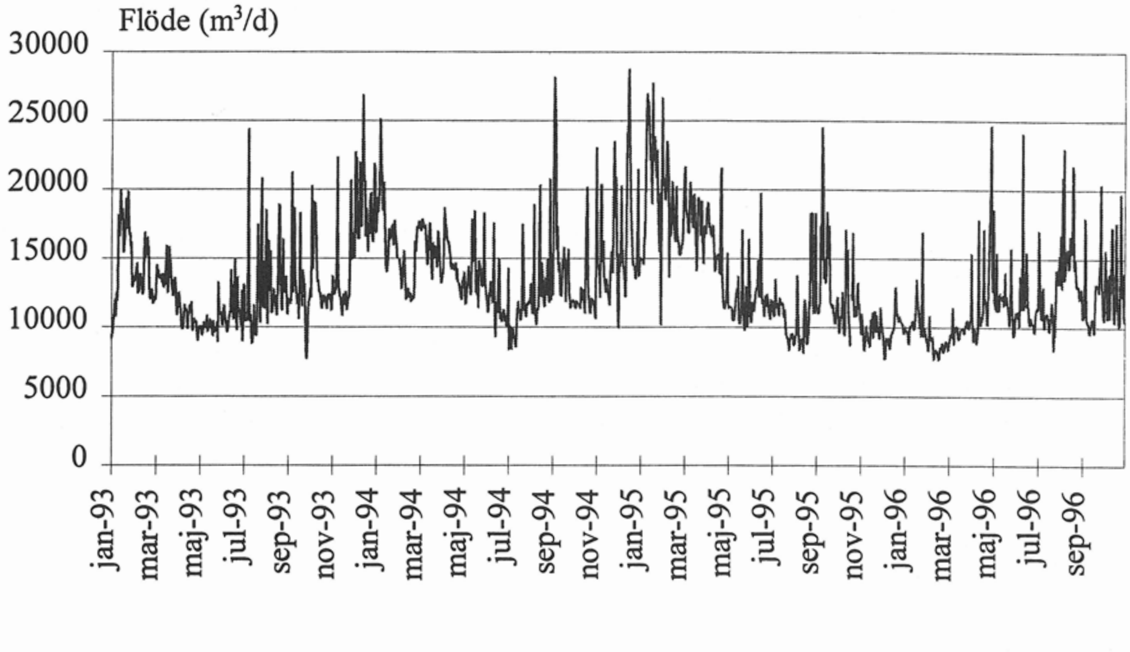
Fosforsläpp i anaerobzonen

Som ett mått på bio-P-funktionen har fosfatfosforhalten mätts på filtrerade prover från anaerobzonen. Detta motsvarar dock inte det verkliga fosforsläppet, eftersom ingen hänsyn tas till recirkulationsströmmar. I figur 8 visas PO_4-P_{filt} i anaerobzonen, beräknat som 15-dygns medelvärden för att illustrera trender.



Figur 8. PO_4-P_{filt} i anaerobzonen och utgående $P_{tot,filt}$ från slutsedimenteringen i bio-P-linjerna

Det finns i figur 8 en tydlig årstidsvariation i PO_4-P_{filt}, sålunda att halten minskar kraftigt under nederbördsrika vintrar (jämför figur 9). Dessutom minskar halten i anslutning till industrisemestrarna i juli-augusti.

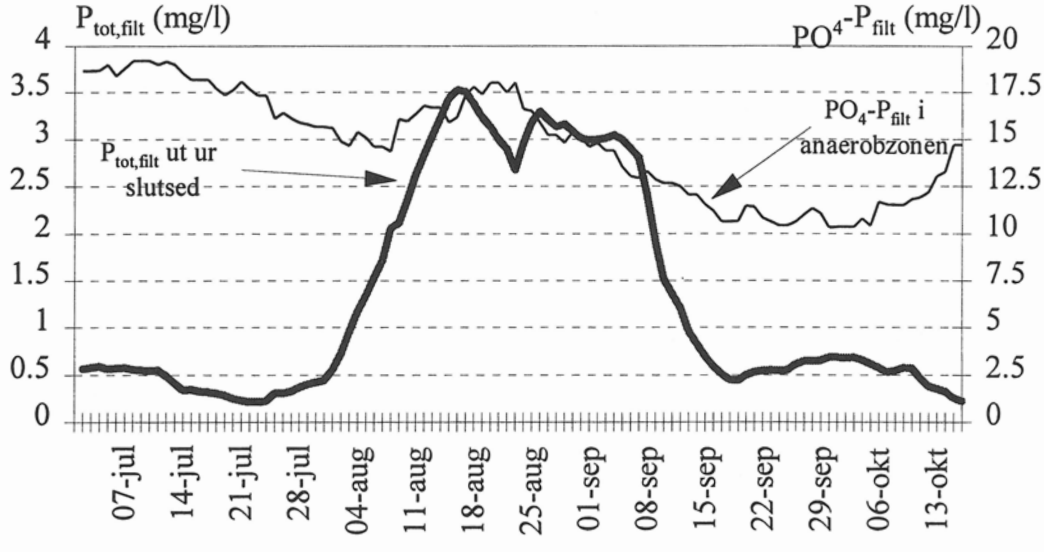


Figur 9. Flöde i bio-P-linjer

Vanligen medför en ökad PO_4-P_{filt}-halt i anaerobzonen en lägre utgående $P_{tot,filt}$ från slutsedimenteringen. Resultaten i samband med nederbördsrika vintrar och industrisemestrar är mera svårtolkade mot bakgrund av den gängse uppfattningen om mekanismerna bakom bio-P-funktionen. Fosfathalten i anaerobzonen bör inte användas som en direkt driftparameter, eftersom enstaka låga värden inte behöver påverka reningsresultatet. Däremot kan fosfathalten i anaerobzonen användas som en larmparameter. Längre perioder med lägre värden indikerar en försämrad bio-P-funktion.

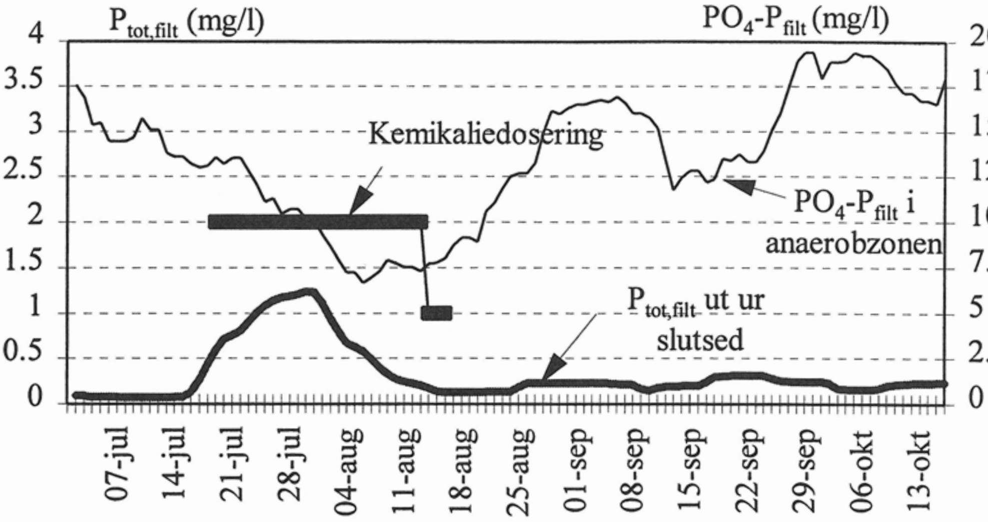
Kompletterande efterfällning

Vid enstaka tillfällen har bio-P-processen tappat funktionen. Det mest markanta tillfället av dessa inträffade under sommaren 1995, se figur 10. Troligen beror problemen på att under industrisemestern förändras kvoten COD_{tot}/P_{tot} i inkommande vatten.



Figur 10. PO_4-P_{filt} i anaerobzonen och utgående $P_{tot,filt}$ ut från slutsedimenteringen under sommaren 1995

För att inte få samma problem sommaren 1996 infördes dosering av järnklorid till inloppskanalen till slutsedimenteringen. Dosering startades den 18/7 i samband med att utgående fosforhalt började öka. Dosen sattes inledningsvis till 40 ml/m^3 motsvarande 7,8 g Fe/m^3. Den 13/8 sänktes dosen till 20 ml/m^3 för att den 16/8 stoppas helt. Resultaten från 1996 visas i figur 11.



Figur 11. PO_4-P_{filt} i anaerobzonen och utgående $P_{tot,filt}$ ut från slutsedimenteringen samt kemikaliedosering till slutsedimenteringen under sommaren 1996.

Som framgår av figur 11 kunde utgående halt filtrerad totalfosfor hållas nere under sommaren 1996. När dosering upphörde fungerade Bio-P-processen så att utgående fosforhalt var låg.

Diskussion och slutsatser

Bio-P-processen har visat sig relativt stabil. Funktionen kan tappas mera långvarigt under nederbördsrika vintrar samt i anslutning till industrisemestrar, möjligen beroende på kort anaerob kontakttid speciellt med hänsyn till att i en UCT-process är slamhalten i anaerobzonen låg. Vid sådana tillfällen har efterfällning med järnklorid tillämpats utan att bio-P-funktionen efter avslutad dosering har tappats.

Avgörande faktorer för funktionen är tillräcklig tillgång på VFA och en COD_{tot}/P_{tot}-kvot större än cirka 40 i inkommande vatten till anaerobzonen. Fosfathalten i anaerobzonen kan användas som en larmparameter för funktionen. Längre perioder med lägre värden indikerar försämrad funktion. Sambandet mellan fosforsläpp i anaerobzonen och utgående totalfosforhalt under nederbördsrika vintrar och industrisemestrar är periodvis svårtolkat mot bakgrund av den gängse uppfattningen om mekanismerna bakom bio-P-funktionen.Som kortsiktiga funktionsparametrar kan användas totalfosforhalten efter den luftade zonen samt totalfosfor efter slutsedimenteringen. Kortvarig funktionsförsämring har hanterats genom polering med järnklorid på filter.

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Start-up and running in of the two wastewater treatment plants of the Lynettefællesskabet in Copenhagen

by

Carsten Thirsing, Lynettefællesskabet I/S, Refshalevej 250, DK-1432 Copenhagen K, Denmark

Introduction

The Lynettefællesskabet I/S owns and operates two wastewater treatment plants, the Lynetten and Damhusåen WWTPs. The partners in the Lynettefællesskabet are 8 municipalities situated in the Greater Copenhagen Area. The catchment area of the Lynettefællesskabet stretches over 123 km^2 with a population in 1992/93 of 721,000.

In 1987, the Danish Parliament adopted the Danish Action Plan on the Aquatic Environment. According to this act, the annual average values of organic matter, nitrogen and phosphorus in the wastewater discharged from municipal wastewater treatment plants must not exceed the following limit values: BOD 15 mg/l, total nitrogen 8 mg/l and total phosphorus 1.5 mg/l.

In 1988, the preparation and planning of the extension of the wastewater treatment plants of the Lynettefællesskabet were initiated. In 1990, it was decided that both treatment plants were to be upgraded to nutrient removal.

The civil engineering works were commenced in 1992 after a period of preliminary investigation of 4 years. Pilot tests with different plant configurations were conducted at both the Lynetten and Damhusåen wastewater treatment plants, and simulation of the start-up of the full-scale plants was carried out. Furthermore, a number of design variables were determined.

Owing to the fact that the two plants were already existing, it was important in the planning of the extension that all the existing plant structures be reused if possible. In addition, both plants had to be operational and meet the existing effluent standards laid down by the authorities, during the extension period.

The upgrade of the wastewater treatment plants to nutrient removal will be completed in mid-1997. The budget for the extension/upgrade of the Damhusåen and Lynetten wastewater treatment plants amounts to DKK 1.8 bn.

Running in of the Damhusåen WWTP

As the running in of the Damhusåen WWTP is almost completed, it has been chosen to focus primarily on the running in of this plant in the present article.

The treatment process chosen for nutrient removal is biological nitrogen removal according to the alternating mode of operation combined with biological phosphorus removal (BIO-DENIPHO) supplemented with chemical phosphorus removal with iron salts (simultaneous precipitation).

Plant data

Table 1 below shows the key plant data for the Damhusåen WWTP.

Plant data	**Damhusåen**
Catchment area	47 km^2
Design basis PE	350,000
Qmax. plant	23,000 m^3/h
Qmax. biology	10,000 m^3/h
Biological phosphorus tanks	8,300 m^3
Aeration tanks	71,000 m^3
Final settling tanks	27,000 m^3
Digesters	7,600 m^3
Primary sludge production	15 t TS/d
Biological sludge production	12 t TS/d

Table 1: Selected plant data for the Damhusåen WWTP

Table 2 below indicates load data for the Damhusåen WWTP in the period from 10 May 1996 to 15 December 1996.

Load data for the Damhusåen WWTP				
Parameter	**Influx to plant**		**Influx to biology**	
Flow	55,000 m^3/d	–	55,000 m^3/d	–
SS	350 mg/l	19.3 t/d	150 mg/l	8.3 t/d
COD	700 mg/l	38,5 t/d	400 mg/l	22.0 t/d
BOD	225 mg/l	12.4 t/d	150 mg/l	8.3 t/d
NH_4-N	28 mg/l	1.6 t/d	27 mg/l	1.5 t/d
Total N	49 mg/l	2.7 t/d	40 mg/l	2.2 t/d
Total P	9.3 mg/l	0.5 t/d	7.6 mg/l	0.4 t/d
Ortho-P	–	–	6.3 mg/l	0.35 t/d
COD/N	–	–	10	–
COD/P	–	–	53	–

Table 2: Load data for the Damhusåen WWTP

In the two following sections, a brief introduction to the plant configuration is given.

Configuration of the water treatment part

The wastewater admitted is subjected to physical treatment before it is introduced into the new biological tanks. The physical treatment of the wastewater takes place in a conventional physical treatment plant consisting of a screen structure, an aerated grit and grease chamber and primary settling tanks.

The new biological part of the Damhusåen WWTP consists of four parallel lines corresponding to four parallel plants. Each line comprises separate biological phosphorus tanks, a set of aeration tanks and associated final settling tanks.

Upstream of the biological phosphorus tanks, an anoxic selector tank is installed in which approx. 10% of the wastewater is mixed with the return sludge from the final settling tanks. If the return sludge flow contains nitrate, this nitrate is denitrified in the tank. The presence of nitrate in the return sludge may upset the release of phosphorus in the biological phosphorus tanks and reduce the biological phosphorus removal capacity.

Atmospheric air is supplied to the aeration tanks by means of 4 surface aerators in each tank. When the aerators are not in operation the activated sludge is kept in suspension by means of propeller mixers. The return sludge from the final settling tank is returned to the biological phosphorus tanks on the line in question. As the biological sludge from the four lines is not mixed, there are good possibilities of carrying out optimisation and special tests on a line. Each line is designed for a capacity of 62,500 PE.

Configuration of the sludge treatment part

The primary sludge withdrawn is digested in digesters and the gas produced is used to produce power and heat. The digested primary sludge is dewatered by means of centrifuges while the biological sludge is first dewatered in predewatering units and then with the digested sludge in centrifuges.

The dewatered digested primary sludge and the biological sludge are transported to the Lynetten wastewater treatment plant where the sludges are dried and incinerated in a sludge incineration facility.

Both the water and sludge treatment installations are monitored and controlled by means of a modern SCADA system.

External environment

The Damhusåen WWTP is situated in a densely populated area. The closest neighbours are at a distance of approx. 300 m from the plant. Owing to the location of the plant, much has been done in connection with the extension of the plant to reduce and eliminate any odour sources. Investigations of potential sources of odour showed that the largest single point sources causing odour nuisances were the screen structure and the grit chamber. Therefore, the grit and grease chamber has been covered, and the exhaust air from the cover is treated in a bioscrubber together with the exhaust air from the screen structure. The treatment of the exhaust air is performed in an activated sludge unit followed by an activated carbon filter. The bioscrubber is designed for treatment of 6000 m^3/h. After the bioscrubber was put into service, no odour problems from the screen structure or the grit and grease chamber have been recorded.

Floc formation and sludge build-up

The plant was put into operation on 10 May 1996. During the start-up period, the plant was operated with constant aeration corresponding to 100% nitrification. After approx. two weeks of operation, there were appreciable sludge flocs in the aeration tank and the SS effluent concentration was below 15 mg/l. This means that sludge flocs could be retained in the plant without problems.

The SS content in the aeration tank increased by approx. 0.5 g SS/l* per week. To avoid foam problems, anti-foaming agents were dosed to the aeration tanks during the last 14 days of May 1996.

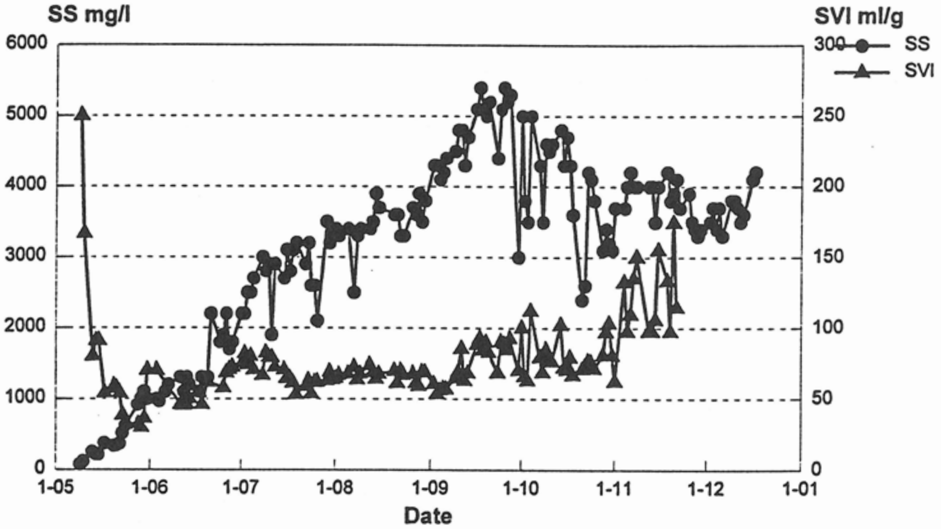

Figure 1: Suspended solids and sludge volume index in line B

In the running-in period, there have been no appreciable problems with light sludge, neither in the aeration tanks nor in the final settling tanks. After approx. 60 days of operation the SVI in the aeration tank was stable at a level of about 75 mg/l, which means that the settling properties of the biological sludge are very good. Once a week, the sludge from the four lines has been microscoped and the filament index has generally been between 1 and 2, and only few filamentous bacteria have been detected.

The alternating mode of operation

Figure 2 below shows the principle of the BIO-DENIPHO process based on the alternating mode of operation. The nitrogen removal is performed in two tanks in which alternately aerobic (N) and anoxic (DN) conditions exist.

In phase A the wastewater is admitted to the anoxic phase. Owing to the readily degradable organic matter in the wastewater, the nitrogen is denitrified and the nitrate is converted to free gaseous nitrogen. Simultaneously, ammonia from the wastewater admitted accumulates in the tank. Nitrification takes place in the tank with aerobic conditions, in which process ammonia is converted to nitrate which accumulates in the tank. The water is discharged from the aerobic reactor where the ammonia and nitrate concentrations are low. In phase B aerobic conditions exist in both tanks. In this intermediate phase, the ammonia content in the tank which was anoxic in phase A is reduced so as to allow discharge from this tank. Phases C and D are mirror images of phases A and B. Once the cycle A-D has been completed, a new cycle starts using the same sequence. Biological phosphorus removal is accomplished as follows: Phosphorus is released in the anaerobic tank (P) and simultaneously readily degradable organic matter is taken up by phosphorus-accumulating bacteria. The released phosphorus is incorporated into the biological sludge in the downstream aerobic/anoxic tanks and the sludge rich in phosphorus is removed as excess sludge from the secondary tanks. The biological phosphorus removal may be supplemented with chemical precipitation with iron salts in the aeration tank and/or inlet to the secondary tanks.

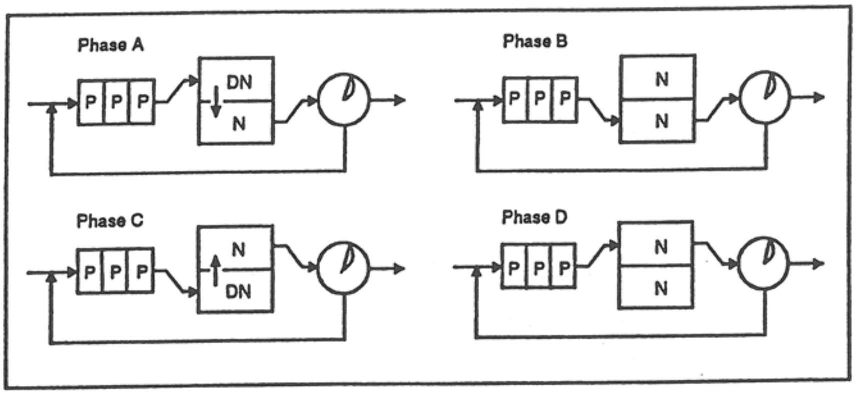

Figure 2: The BIO-DENIPHO process

The process in the aeration tanks is monitored by means of on-line ammonia-nitrogen, nitrate-nitrogen and orthophosphate meters. The mixture of wastewater and activated sludge is pumped to the measuring chamber where it is filtered through a cross-flow filter before being led to the on-line meters. As there are 2 sets of meters, it is possible to perform measurements in both tanks of a tank set or in one tank of two different tank sets. Intensive use has been made of the on-line meters during the running-in period in order to, among other things, optimise the duration of the nitrification and denitrification phases.

Nitrogen removal

After 60 days of operation (9 July 1996) the ammonia concentration in the effluent was below 1 mg/l at an SS concentration in the aeration tank of 2.5 g/l. This means that full nitrification has been established. This is in good agreement with the results obtained in a start-up test conducted at the pilot plant at the Damhusåen WWTP where full nitrification was obtained approx. 55 days after start-up. The oxygen set point in the nitrification phases has been 1.5 mg O_2/l during the entire running-in period.

A switch to phase operation with a 25% denitrification and 75% nitrification time was made after 73 days of operation (22 July 1996). The content of nitrate in the effluent dropped in the course of few days from 20 mg/l to a level of 10 mg/l.

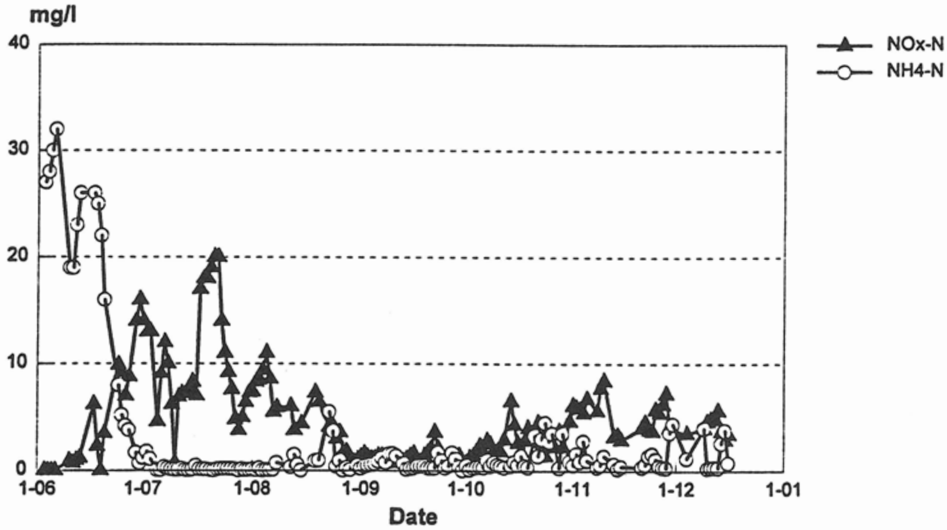

Figure 3: *Ammonium-N and nitrate-N in the effluent from the Damhusåen WWTP*

To reduce the nitrate concentration in the effluent further, the denitrification time was increased to 33% after 87 days (5 August 1996) and the nitrification time was reduced to 67%. Late in June 1996, excess sludge was withdrawn from the plant for the first time. The biological sludge production was 9 t TS/d.

After 159 days of operation (16 October 1996), a switch was made to 50% denitrification during the interval from midnight to 3 a.m. The setting of the plant control was changed in mid-November 1996 so that the denitrification time was increased during the periods with low ammonia loading on the plant and so that the duration of the phases on weekdays differed from that in weekends. At night on weekdays the plant was operated with 61% denitrification and in the daytime with 31% denitrification. During weekends, when the ammonia load is lower than on weekdays, the period during which the plant is operated with 61% denitrification time is extended from 9 to 15 hours a day.

Total nitrogen in the effluent from the plant has in the period from day 107 after start-up (25 August 1996) been stable at a level of about 4 mg/l. Only few effluent total nitrogen values above 8 mg/l have been recorded and they have been the result of sludge escape from the final settling tanks during heavy rain.

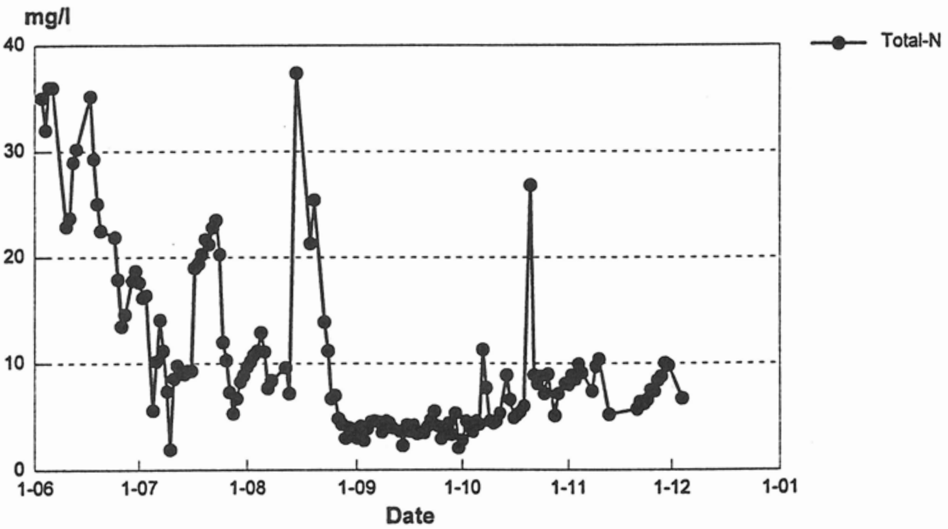

Figure 4: *Total N in the effluent from the Damhusåen WWTP*

Running-in of the biological phosphorus removal process

In the period from 1 September the biological phosphorus removal process has worked relatively efficiently, being the phosphorus content in the biological sludge during the period with biological phosphorus removal approx. 3% without chemical precipitation. The effluent concentration of total P has been stable at a level of approx. 2.2 mg/l.

As the start-up of the digesters took longer than anticipated, all the primary sludge was led to the aeration tanks from 26 August 1996 to 20 September 1996. Consequently, the load on the biological plant has for some periods of time been considerably higher than expected, especially with regard to organic matter and suspended solids. This has improved the C/N and C/P ratios and increased the efficiency of the biological phosphorus removal process during this period, with effluent concentrations for total P of approx. 1.5 mg/l, i.e. round about the limit value for total phosphorus.

Late in September it was recorded that the gas production in the digesters had started and that the operation of these was stable. From then, an increasing amount of primary sludge was pumped to the digester. From 10 October 1996 all the primary sludge was pumped to the digesters, and consequently no primary sludge was led to the aeration tanks.

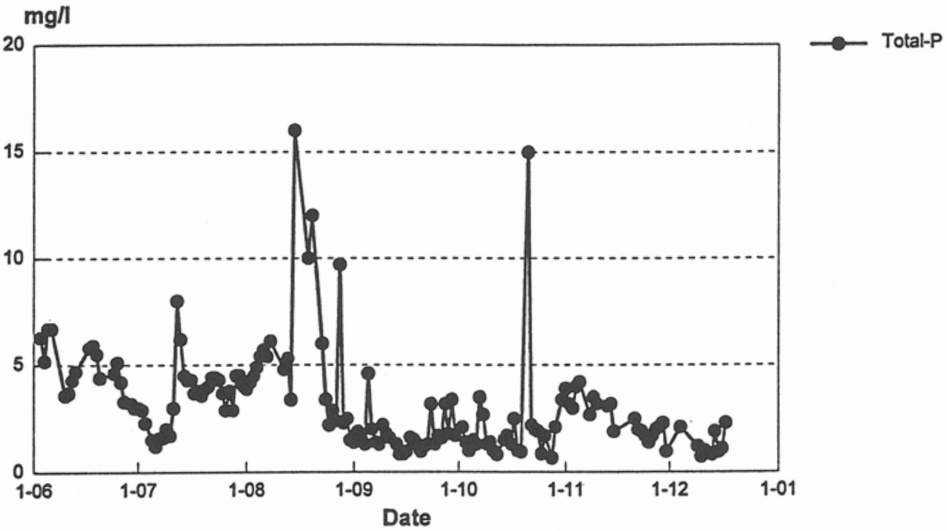

Figure 5: *Total P in the effluent from the Damhusåen WWTP*

Chemical precipitation

Chemical precipitation with iron salts was initiated on 4 December 1996 in three of the four lines while the last line acted as reference during the running-in period. Iron sulphate was dosed in a 20% solution proportionally to the flow corresponding to about 4 g of active iron per m³ of wastewater. This should lead to the precipitation of approx. 2 mg P/l assuming a molar ratio between Fe and P of 1.3. In the period with supplementary chemical precipitation, total P in the effluent was approx. 1.3 mg/l, which means that approx. 1 mg total P/l was precipitated chemically. At present, 70% of the iron sulphate is dosed in the inlet to the aeration tank and 30% in the inlet to the final settling tank.