5.4 NUTRIENT REMOVAL - DESIGN CASE

A Bardenpho system treats 15,000 m^3 of municipal waste water per day. In Table 5.7 the influent characteristics, the main process conditions and the estimated values of the kinetic- and stoichiometric parameters are listed. The excess sludge is thickened and sent to a central sludge treatment unit for digestion and final disposal. At present, effluent standards for nitrogen are < 10 mg.l^{-1} total nitrogen; < 5 mg.l^{-1} TKN and < 1 mg.l^{-1} NH_4-N. However, future legislation will be imposed in which an effluent total phosphorus concentration of < 2 mg P.l^{-1} is required. The following questions are to be evaluated:

(1) Determine whether the existing system can produce an effluent quality that meets the current nitrogen standards;
(2) To comply with the new effluent phosphorus standard, consider the following measures:
  a. Simultaneous precipitation (using $FeCl_3$);
  b. Installation of a primary settler and pre-precipitation (using $FeCl_3$);
  c. Biological phosphorus removal (UCT configuration), if required this can be supplemented with addition of $FeCl_3$.

Indicate for all options:

- The resulting system configuration for phosphorus removal;
- The expected daily $FeCl_3$ consumption;
- The effect on the effluent nitrogen quality.

Table 5.7 Waste water- and process characteristics used in Example 5.4

Par.	Value	Unit	Par.	Value	Unit
Q_i	15,000	m^3.d^{-1}	b_h	0.197	d^{-1}
V_r	17,500	m^3	K_2	0.082	mg N.mg^{-1} X_a.d^{-1}
S_{ti}	600	mg COD.l^{-1}	K_3	0.069	mg N.mg^{-1} X_a.d^{-1}
N_{ti}	65	mg N.l^{-1}	μ_m	0.224	d^{-1}
P_{ti}	15	mg P.l^{-1}	b_n/b_p	0.033	d^{-1}
f_{sb}	0.30	(-)	K_n	0.560	mg N.l^{-1}
f_{np}	0.15	(-)	f_n	0.1 / 0.06$^{(2)}$	mg N.mg^{-1} VSS
f_{ns}	0.08	(-)	f_p	0.025 / 0.015$^{(2)}$	mg P.mg^{-1} VSS
T	15	°C	f_{pp}	0.38	mg P.mg^{-1} VSS
f_v	0.7/0.8$^{(1)}$	mg VSS/mg TSS	f	0.2	mg VSS/mg VSS
f_{vp}	0.46	mg VSS/mg TSS	f_{ep}	0.25	mg VSSmg/ VSS
f_{x1}	0.225	(-)	f_{pd}	0.7	(-)
f_{x3}	0.200	(-)	f_{an}	0.1	(-)
R_s	24	d	K_c	0.06	litre.mg^{-1} VSS.d^{-1}
a	4	(-)	R_p	0.8$^{(3)}$	(-)
s	1	(-)	X_{te}	20	mg TSS.l^{-1}
r	1	(-)	N_{oes}	0.5	mg N.l^{-1}
N	2	(-)	P_{oes}	0.125	mg P.l^{-1}

Notes: (1) When pre-precipitation is employed.
(2) Fraction of N and P in the primary sludge volatile solids removed during pre-precipitation.
(3) Removal efficiency of particulate COD

In both cases $N_{av} > D_c$, indicating that the denitrification capacity is indeed limiting and that in both zones sufficient nitrate is available for maximum denitrification. Therefore N_{ne} can be calculated as above. The effluent nitrogen composition can now be evaluated. The total effluent nitrogen concentration N_{te} equals 9.6 mg $N.l^{-1}$ and is composed of 6.9 mg $N.l^{-1}$ of nitrate and 2.7 mg $N.l^{-1}$ of Kjeldahl nitrogen (N_{ae} = 0.8 mg $N.l^{-1}$ and N_{oe} = 2.0 mg $N.l^{-1}$). It can be concluded that the nitrogen effluent criteria are met. As concerns phosphorus removal (correcting P_l for the loss of particulate organic phosphorus with the effluent using Eq. 4.82):

$$\begin{aligned}P_{lex} &= P_l - P_{oep} = f_p \cdot ME_v/Q_i - f_p \cdot f_v \cdot X_{te}\\ &= 0.025 \cdot 1959 \cdot 1000/15{,}000 - 0.025 \cdot 0.75 \cdot 20\\ &= 3.3 - 0.4 = 2.9 \text{ mg P.l}^{-1}\end{aligned}$$

Thus approximately 20% of the influent phosphorus concentration is removed together with the excess sludge. The effluent phosphorus compositions can now be estimated as:

$$P_{oe} = P_{oes} + P_{oep} = 0.125 + 0.35 = 0.475 \text{ mg P.l}^{-1}$$

$$P_{pe} = P_{ti} - P_l - P_{oe} = 15.0 - 2.9 - 0.475 = 11.5 \text{ mg P.l}^{-1}$$

$$P_{te} = P_{pe} + P_{oe} = 11.5 + 0.5 = 12.0 \text{ mg P.l}^{-1}$$

$C_r = 0.45 \cdot 19.6/(1 + 0.197 \cdot 19.6) = 1.81$

$ME_v = ((1 - f_{np} - f_{ns}) \cdot (1 + f \cdot b_h \cdot R_s) \cdot C_r + f_{np} \cdot R_s/f_{cv}) \cdot Q_i \cdot S_{ti}/R_s$
$= ((1 - 0.15 - 0.08) \cdot (1 + 0.2 \cdot 0.197 \cdot 19.6) \cdot 1.81 + 0.15 \cdot 19.6/1.5) \cdot 15{,}000 \cdot 0.6/19.6$
$= 2037$ kg VSS.d^{-1}

$ME_t = 2037/0.7 = 2909$ kg TSS.d^{-1} (excluding the chemical sludge)

As the amount of phosphorus discharged with the excess sludge will increase slightly, the composition of the chemical sludge will marginally change: i.e. less $FePO_4$ and more $Fe(OH)_3$ is formed. However, as the $FeCl_3$ consumption will not change and the molar weights of the two components are comparable, this will have minimal impact on the total quantity of chemical sludge formed. In this example it can be calculated that the net decrease in chemical sludge production is only 2 kg. The total sludge mass (biological and chemical) in the system is calculated as $19.6 \cdot (2909 + 1220) = 80{,}875$ kg TSS or 4.62 kg TSS.m^{-3}, which is still somewhat above the specified value of 4.5 kg TSS.m^{-3}.

A second iteration is initiated with a sludge age of $78{,}750/(2909 + 1220) = 19.1$ days, returning a sludge age of 19.0 days. This change is a small enough value to end the iterative procedure. It is interesting to note that as a result of the chemical dosing the organic sludge fraction f_v has decreased from 0.70 to 0.50. Now finally the effects on nitrogen removal performance can be calculated:

$C_r = 0.45 \cdot 19.0/(1 + 0.197 \cdot 19.0) = 1.8$

$ME_v = 2048$ kg VSS.d^{-1}

$MN_{lex} = f_n \cdot ME_v - MN_{oep} = 0.1 \cdot 2048 - 21 = 184$ kg N.d^{-1}

$N_{lex} = MN_{lex}/Q_i = 12.3$ mg N.l^{-1}

$D_{C1} = (f_{sb} \cdot (1 - f_{cv} \cdot Y_h)/2.86 + K_2 \cdot C_r \cdot f_{x1}) \cdot S_{bi}$
$= (0.3 \cdot (1 - 1.5 \cdot 0.45)/2.86 + 0.082 \cdot 1.8 \cdot 0.225) \cdot 462 = 31.0$ mg N.l^{-1}

$D_{C3} = K_3 \cdot C_r \cdot f_{x3} \cdot S_{bi}$
$= 0.069 \cdot 1.8 \cdot 0.2 \cdot 462 = 11.5$ mg N.l^{-1}

$N_{ae} = K_n \cdot (b_n + 1/R_s)/((1 - f_m) \cdot \mu_{m,n} - b_n - 1/R_s)$
$= 0.56 \cdot (0.033 + 1/19.1)/((1 - 0.425) \cdot 0.224 - 0.033 - (1/19.1)) = 1.1$ mg N.l^{-1}

$N_{ne} = N_{ti} - N_{lex} - N_{oe} - N_{ae} - D_{C1} - D_{C3}$
$= 65 - 12.3 - 1.9 - 1.1 - 31.0 - 11.5 = 7.2$ mg N.l^{-1}

Both effluent nitrogen discharge limits are slightly exceeded: the total effluent nitrogen concentration is $1.1 + 7.2 + 1.9 = 10.2$ mg N.l^{-1}, while effluent Kjeldahl nitrogen is 3.0 mg N.l^{-1}, containing 1.1 mg N.l^{-1} of ammonium. Both demands could be met by increasing the sludge age (at the expense of a further increase of the sludge concentration). As an alternative the addition of an external carbon source may be considered: this will increase D_c and reduces N_{ne} and thus also N_{ti} but not N_{ae} or N_{oe}.

The value of R_s can be calculated as 106 days. Clearly this is an excessive sludge age and well outside the range of sludge ages for which the model has been validated (2 to 50 days). The main effect on the sludge composition will be a very low active fraction, while there may be problems with sludge settleability as small sludge flocs tend to escape with the effluent of the final settler. A secondary effect is that less phosphorus (and also nitrogen) is removed with the excess sludge than originally anticipated, and hence the chemical dosing has to be increased to remove more phosphorus in the primary settler.

To determine whether denitrification will be complete, the limiting ratio for complete denitrification in a Bardenpho configuration $(N_{ti}/S_{ti})_o$, must be compared to the ratio N'_{ti}/S'_{ti} in the pre-settled influent. S'_{ti} has been calculated already as 269 mg COD.l^{-1}. N'_{ti} can be calculated by subtracting the nitrogen removed in the primary settler from N_{ti} (remember that $f_n = 0.06$ as most of N_{ki} is present in the form of ammonium).

$N'_{ti}/S'_{ti} = [65 - 0.06 \cdot (600 - 269)/1.5]/269 = 51.7/269 = 0.192$ mg N.mg^{-1} COD

To calculate $(N_{ti}/S_{ti})_o$ the following procedure is followed:

$C_r = 0.45 \cdot 106/(1+0.197 \cdot 106) = 2.18$

$(N_c/S_{bi})_o = ((a+s+1) \cdot (f'_{sb} \cdot (1 - f_{cv} \cdot Y_h)/2.86 + K_2 \cdot C_r \cdot f_m)) / (a + (K_2/K_3) \cdot (s+1))$
$= ((4+1+1) \cdot (0.68 \cdot (1 - 1.5 \cdot 0.45)/2.86 + 0.082 \cdot 2.18 \cdot 0.425)) / (4+(0.082/0.069) \cdot (1+1)$
$= 0.144$ mg N.mg^{-1} COD

$MN_{lex} = f_n \cdot ME_v - MN_{oep} = 0.1 \cdot 0.8 \cdot 67{,}168 / 106 - 21$
$= 50.7 - 21 = 29.7$ kg N.d^{-1}

$N_{lex} = MN_{lex}/Q_i$
$= 29.7 \cdot 1000/15{,}000 = 2.0$ mg N.l^{-1}

$N_{ae} = K_n \cdot (b_n + 1/R_s)/((1 - f_m) \cdot \mu_m - b_n - 1/R_s)$
$= 0.56 \cdot (0.033 + 1/106)/((1 - 0.425) \cdot 0.224 - 0.033 - 1/105) = 0.3$ mg N.l^{-1}

$(N_{ti}/S_{ti})_o = (1 - f'_{ns} - f'_{np}) \cdot (N_c/S_{bi})_o + (N_{lex} + N_a + N_{oe})/S'_{ti}$
$= (1 - 0.18 - 0.07) \cdot 0.144 + (2.0 + 0.3 + 1.9)/269 = 0.124$ mg N.mg^{-1} COD

As expected, $N_{ti}/S_{ti} >> (N_{ti}/S_{ti})_o$ (0.192 >> 0.124) and complete denitrification is no longer possible. The effluent nitrogen concentration can be calculated as $N_{te} = N_{ne} + N_{ae} + N_{oe}$.

$S'_{bi} = (1 - f'_{ns} - f'_{np}) \cdot S'_{ti} = (1 - 0.18 - 0.07) \cdot 269 = 203$ mg COD.l^{-1}

$D_{C1} = (f'_{sb} \cdot (1 - f_{cv} \cdot Y_h)/2.86 + K_2 \cdot C_r \cdot f_{x1}) \cdot S'_{bi}$
$= (0.68 \cdot (1 - 1.5 \cdot 0.45)/2.86 + 0.082 \cdot 2.18 \cdot 0.225) \cdot 203 = 23.9$ mg N.l^{-1} and

$D_{C3} = K_3 \cdot C_r \cdot f_{x3} \cdot S'_{bi}$
$= 0.069 \cdot 2.18 \cdot 0.2 \cdot 203 = 6.1$ mg N.l^{-1}

$N_{ne} = N'_{ti} - N_{oe} - N_{lex} - N_{ae} - D_{C1} - D_{C3}$
$= 51.7 - 1.8 - 2.0 - 0.3 - 23.9 - 6.1 = 17.6$ mg N.l^{-1}

$N_{te} = 17.6 + 0.3 + 2.0 = 19.8$ mg N.l^{-1}

As the actual denitrification capacity is a little larger than the required denitrification capacity, the effluent nitrogen criteria are met. The effluent nitrogen composition will be: N_{oe} = 1.9 mg N.l^{-1}; N_{ae} = 0.3 mg N.l^{-1} and N_{ne} = 7.8 mg N.l^{-1}. Now it is finally possible to calculate the amount of chemical precipitation required to meet the effluent phosphorus limit.

MP_{lex} $= f_p \cdot ME_v - MP_{oep} = 0.025 \cdot 0.80 \cdot 3.0 \cdot 17{,}500/68 - 5.3 = 10.2$ kg P.d^{-1}

MP_{chem} $= MP_{ti} - MP_{lex} - MP_{te} = 225 - 10.2 - 30 = 184.8$ kg P.d^{-1} or $P_{chem} = 12.3$ mg P.l^{-1}

This amounts to 184.8/31 = 6.0 kmol P.d^{-1}. The fraction of phosphorus to be removed in the primary settler is 12.3/15 = 82%, corresponding to a molar dosing ratio Me/P_{ti} ratio of 2.1 as can be determined from Fig. 5.10. The daily $FeCl_3$ consumption is 12.5 kmol Fe^{3+}.d^{-1}, which amounts to 2031 kg $FeCl_3$.d^{-1} or 3.63 m^3 40% wt $FeCl_3$.d^{-1}. The production of chemical sludge can be calculated after correcting for the amount of phosphorus removed with the primary sludge:

ME_{v1} $= Q_i \cdot (S_{ti} - S'_{ti})/f_{cv} = 15{,}000 \cdot (0.6 - 0.27)/1.5 = 3307$ kg VSS.d^{-1}

MP_{l1} $= f_p \cdot ME_{v1} = 0.015 \cdot 3307 = 49.6$ kg P.d^{-1}

ME_{FePO4} $= (184.8-49.6)/31 \cdot mw_{fepo4} = 4.4 \cdot 151 = 658$ kg.d^{-1} and

$ME_{Fe(OH)3}$ $= (12.5 - 4.4) \cdot mw_{fe(oh)3} = 8.2 \cdot 107 = 871$ kg.d^{-1}

ME_t $= 3307/0.9 + 658 + 871 + 619/0.8 = 5977$ kg TSS.d^{-1}

If this option is pursued, a digester could be employed for sludge volume reduction and energy generation. However, as ammonium nitrogen is released during the sludge digestion process, the N_{ki} load to the activated sludge system will increase, resulting in higher methanol consumption for denitrification.

(2c) Biological excess phosphorus removal with supplementary chemical dosing

In this configuration, the existing Bardenpho system will be expanded with an anaerobic zone, changing it from a Bardenpho- into an UCT configuration. The main performance objective of this UCT system will be to ensure nitrogen effluent standards are complied too, while simultaneously maximising excess biological phosphorus removal. If the effluent phosphorus concentration cannot be reduced below the effluent limit, the difference will be removed by (supplementary) simultaneous precipitation. The calculation proceeds in an iterative manner. Based on a first estimate of the operational sludge age and of the amount of recirculation of nitrate to the anaerobic reactor, the proportion of COD available to PAO and to normal heterotrophic biomass is calculated. Using these values, the performance of the activated sludge system is evaluated with respect to nitrogen removal as a function of the sludge age.

Nitrification may become a critical process, as the aerobic sludge mass fraction will decrease when an anaerobic zone is included. If the selected sludge age and recycle nitrate concentration differ significantly from the first estimate, they are adapted and the proportion of COD available to PAO and heterotrophs is recalculated. The starting value for R_s is 25 days and that of the nitrate concentration in the “r” recycle (N_{n1}) is 0 N.l^{-1}. With Eq. 5.2 the initial estimate of the amount of easily biodegradable COD available to the PAO is calculated:

Table 5.8 Division of volume- and mass fraction over the different zones of the UCT system of Example 5.4

Reactor	Volume (m^3)	Mass fraction	Vol. fraction
Pre-D	$= 0.225 \cdot 17{,}500 = 3937$	$f_{x1} = 0.2025$	0.18
Post-D	$= 0.200 \cdot 17{,}500 = 3500$	$f_{aer} = 0.5175$	0.47
Aerobic	$= 0.575 \cdot 17{,}500 = 10{,}063$	$f_{x3} = 0.18$	0.16
Anaerobic	$= (3500/0.18 - 17{,}500) \cdot (1 + 1) = 3889$	$f_{an} = 0.1$	0.18
Total	21,389	1.00	1.00

The composition of the biomass is calculated as:

$MX_{vh} = [f_{bh} \cdot (1 - f_{ns} - f_{np}) \cdot (1 + f \cdot b_h \cdot R_s) \cdot C_{rh} + f_{np} \cdot R_s / f_{cv}] \cdot MS_{ti}$
$= [0.76 \cdot (1 - 0.08 - 0.15) \cdot (1 + 0.2 \cdot 0.197 \cdot 25) \cdot 1.90 + 0.15 \cdot 25/1.5] \cdot 9000 = 42{,}341$ kg VSS

$C_{rp} = 0.45 \cdot 25/(1 + 0.033 \cdot 25) = 6.17$

$MX_{ap} = f_{bp} \cdot (1 - f_{ns} - f_{np}) \cdot C_{rp} \cdot MS_{ti}$
$= 0.24 \cdot (1 - 0.08 - 0.15) \cdot 6.17 \cdot 9000 = 10{,}271$ kg VSS

$MX_{ep} = f_{ep} \cdot b_p \cdot R_s \cdot MX_{ap} = 0.25 \cdot 0.033 \cdot 25 \cdot 10{,}271 = 2111$ kg VSS

$MX_v = MX_{vh} + MX_{ap} + MX_{ep} = 42{,}341 + 10{,}271 + 2111 = 54{,}723$ kg VSS

$MX_t = MX_{ap}/f_{vp} + (MX_{vh} + MX_{ep})/f_v = 10{,}271/0.46 + (42{,}341 + 2111)/0.70 = 85{,}831$ kg TSS

$X_t = MX_t / [V_r - V_{an} + V_{an} \cdot r/(r + 1) \cdot V_r]$
$= 85{,}831/[(21{,}389 - 3889) + 3889 \cdot 1/(1+1)] = 4.41$ kg $TSS.m^{-3}$

Now the nitrogen removal in the system can be determined as:

$MN_{lex} = f_n \cdot mX_v / R_s - MN_{oep} = 0.1 \cdot 54{,}723/25 - 21 = 198$ kg $N.d^{-1}$

$N_{lex} = MN_{lex}/Q_{ti} = 13.2$ mg $N.l^{-1}$

$N_{ae} = K_n \cdot (b_n + 1/R_s) / ((1 - f_m) \cdot \mu_m - b_n - 1/R_s)$
$= 0.56 \cdot (0.033 + 1/25) / (0.5175 \cdot 0.224 - 0.033 - 1/25) = 0.95$ mg $N.l^{-1}$

$N_c = N_{ti} - N_{lex} - N_{oe} - N_{ae} = 65 - 13.2 - 1.9 - 0.95 = 49.0$ mg $N.l^{-1}$

$D_{C1} = [f_{dn} \cdot (f_{bsp} \cdot f_{pd} + f_{bsh}) \cdot f_{sb} + K_2 \cdot f_{x1} \cdot (C_{rh} \cdot f_{bh} + C_{rp} \cdot f_{bp} \cdot f_{pd})] \cdot S_{bi}$
$= [0.11 \cdot (0.80 \cdot 0.7 + 0.20) \cdot 0.3 + 0.082 \cdot 0.2025 \cdot (1.90 \cdot 0.76 + 6.17 \cdot 0.24 \cdot 0.7)] \cdot 462$
$= 30.9$ mg $N.l^{-1}$

$D_{C3} = K_3 \cdot f_{x3} \cdot (C_{rh} \cdot f_{bh} + C_{rp} \cdot f_{bp} \cdot f_{pd}) \cdot S_{bi}$
$= 0.068 \cdot 0.18 \cdot (1.90 \cdot 0.76 + 6.17 \cdot 0.24 \cdot 0.7) \cdot 462 = 14.2$ mg $N.l^{-1}$

$D_C = D_{c1} + D_{c3} = 30.9 + 14.2 = 45.1$ mg $N.l^{-1}$

Table 5.9 Comparison of effluent quality and sludge production of the configurations in Example 5.4

Parameter	UoM	BDP	Sim-P	Pre-P	UCT
Sludge concentration	kg TSS.m^{-3}	3.86	4.50	3.0	4.41
Sludge age	days	24	19	68	25
Effluent composition:					
- Total nitrogen	mg N.l^{-1}	9.6	10.2	10.0	6.7
- Nitrate	mg N.l^{-1}	6.9	7.2	7.8	3.8
- TKN	mg N.l^{-1}	2.7	3.0	2.2	2.9
- Total phosphorus	mg P.l^{-1}	12.0	2.0	2.0	2.0
- Ortho-phosphate	mg P.l^{-1}	11.5	1.5	1.5	1.5
Sludge production:					
- Primary	kg TSS.d^{-1}	---	---	3658	---
- Biological	kg TSS.d^{-1}	2798	2926	774	3419
- Chemical	kg TSS.d^{-1}	---	1212	1529	---
- Total	kg TSS.d^{-1}	2798	4138	5977	3419
Volatile sludge fraction	(-)	0.7	0.50	0.8	0.64
Chemical dosing:					
- $FeCl_3$	kg $FeCl_3$.d^{-1}	---	1531	2031	---
- Methanol	kg CH_3OH.d^{-1}	---	---	513	---
Additional units:					
- Primary clarifier	m^3	---	---	1250	---
- Anaerobic reactor	m^3	---	---	---	3889

However, the costs of constructing an anaerobic reactor are smaller than the construction costs of a primary clarifier, as this is fitted with an inclined bottom, a scraper mechanism and might also require air tight sealing of the surface area to prevent odour problems. Furthermore, the downstream biological nitrogen removal process is seriously affected. Methanol dosing is required to meet the nitrogen effluent standards, further adding to the costs and operational complexity.

Pre-precipitation is only an interesting option, if the existing activated sludge system is overloaded and a primary settler is already installed. In regions with a hot climate, the combination with primary sludge hydrolysis might be interesting, in order to increase the VFA content in the waste water, but requires an assessment of the potential VFA production for the waste water at hand.

The main disadvantages of simultaneous precipitation are the high consumption of chemicals and the reduction of biological treatment capacity. Meeting nitrogen effluent limits may be hard, as in the example.