Example 10.5

For the same conditions as in Example 10.2 to 10.4 (specified in Tables 10.6 and 10.7), determine the optimal Bardenpho configuration for complete removal of nitrate. The following additional data are given:

(1) Nitrification parameters:

- $\mu_{m20} = 0.3\ d^{-1}$
- $b_{n20} = 0.04\ d^{-1}$
- $K_{n20} = 1.0$ mg $N.l^{-1}$
- $f_{max} = 0.6$.
- $N_{ad} = 2$ mg $N.l^{-1}$
- $N_{oe} = 2$ mg $N.l^{-1}$

(2) Denitrification parameters: $K_{2,20}$ =0.1 mg $N.mg^{-1}\ X_a.d^{-1}$ and $K_{3,20}$ = 0.08 mg $N.mg^{-1}\ X_a.d^{-1}$;

(3) Easily biodegradable influent COD fraction: $f_{sb} = 0.24$.

Step 1: Determine the sludge age and the division into aerobic and anoxic zones

Using a spreadsheet to solve Eq. (4.72) for the specified conditions, a minimum sludge age of 10.5 days is calculated for efficient nitrification: N_{ad} = 2 mg $N.l^{-1}$, effluent organic nitrogen concentration N_{oe} = 2 mg $N.l^{-1}$ and complete nitrate removal. Using this value of the sludge age the system parameters can be calculated:

a) Nitrification capacity (Eq. 4.43):

$$C_r = Y \cdot R_s/(1 + b_h \cdot R_s) = 0.45 \cdot 10.5/(1 + 0.24 \cdot 10.5) = 1.34$$

$$\begin{aligned} N_c &= N_{ti} - N_l - N_{oe} - N_{ad} \\ &= N_{ti} - f_n \cdot [(1 - f_{ns} - f_{np}) \cdot (1 + f \cdot b_h \cdot R_s) \cdot C_r/R_s + f_{np}/f_{cv}] \cdot S_{ti} - N_{oe} - N_{ad} \\ &= 50 - 0.1 \cdot [(1 - 0.10 - 0.08) \cdot (1 + 0.2 \cdot 0.24 \cdot 10.5) \cdot 1.34/10.5 + 0.08/1.5] \cdot 650 - 2 - 2 \\ &= 32.3 \text{ mg N.l}^{-1} \end{aligned}$$

b) Biodegradable organic material in the influent (Eq. 3.3):

$$S_{bi} = S_{ti} \cdot (1 - f_{ns} - f_{np}) = 650 \cdot (1 - 0.10 - 0.08) = 533 \text{ mg COD.l}^{-1}$$

c) Anoxic sludge mass fractions f_{x1} and f_{x3} (Eqs. 4.69 and 4.70) with $f_{dn} = (1 - f_{cv} \cdot Y)/2.86 = 0.11$:

$$\begin{aligned} f_{x1} &= (N_c/S_{bi}) \cdot (a/(a + s + 1) - f_{dn} \cdot f_{bs})/(K_2 \cdot C_r) \\ &= (32.3/533) \cdot (4/6 - 0.11 \cdot 0.2)/(0.1 \cdot 1.21) = 0.13 \end{aligned}$$

$$\begin{aligned} f_{x3} &= (N_c/S_{bi}) \cdot (s + 1)/(a + s + 1)/(K_3 \cdot C_r) \\ &= (32.3/533) \cdot (2/6)/(0.08 \cdot 1.21) = 0.19 \end{aligned}$$

d) Calculate the aerated sludge mass fraction:

$$f_{ae} = 1 - f_{x1} - f_{x3} = 1 - 0.13 - 0.19 = 0.68$$

e) Verify if nitrate removal is complete (Eqs. 4.62 and 63):

$$\begin{aligned} D_{c1} &= (f_{dn} \cdot f_{sb} + K_2 \cdot C_r \cdot f_{x1}) \cdot S_{bi} \\ &= (0.11 \cdot 0.2 + 0.1 \cdot 1.34 \cdot 0.13) \cdot 533 = 21.5 \end{aligned}$$

D_{c3} $= K_3 \cdot C_r \cdot f_{x3} \cdot S_{bi}$
$= 0.08 \cdot 1.34 \cdot 0.19 \cdot 533 = 10.8$

Thus $D_c = D_{c1} + D_{c3} = 21.5 + 10.8 = 32.3$ mg N.l^{-1}, which is indeed equal to the value of the nitrification capacity.

f) Estimate the quantity of nitrogen liberated during the anaerobic sludge digestion:

For the conditions above, the excess volatile sludge mass before and after sludge digestion is calculated ($f_{av} = 0.50$)

ME_v = 1646 kg VSS.d^{-1}

ME_{ve} = 1128 kg VSS.d^{-1}

Therefore the maximum solubilisation of nitrogen in the digester is $f_n \cdot (ME_v - ME_{ve})$ = $0.1 \cdot (1646 - 1128)$ = 52 kg N.d^{-1} which amounts to an equivalent influent nitrogen concentration of 4.3 mg N.l^{-1}. Based on these preliminary results all calculations are repeated, based on an influent nitrogen concentration of $N_{ti}' = N_{ti} + 4.3 = 54.3$ mg N.l^{-1}. It is still possible to obtain complete nitrogen removal in this case, but it will be necessary to increase the design sludge age to 12 days:

C_r $= Y \cdot R_s/(1 + b_h \cdot R_s)$
$= 0.45 \cdot 12/(1 + 0.24 \cdot 12) = 1.39$

N_c $= N_{ti} - N_l - N_{oe} - N_{ad}$
$= 54.3 - 13.2 - 2 - 2 = 37.1$

f_{x1} $= (N_c/S_{bi}) \cdot (a/(a+s+1) - f_{dn} \cdot f_{bs})/(K_2 \cdot C_r)$
$= 36.8/533 \cdot (4/6 - 0.11 \cdot 0.2)/(0.1 \cdot 1.39)$
$= 0.17$

f_{x3} $= (N_c/S_{bi}) \cdot ((s+1)/(a+s+1))/(K_3 \cdot C_r)$
$= 36.8/533 \cdot (2/6)/(0.08 \cdot 1.39) = 0.21$

f_{ae} $= 1 - f_{x1} - f_{x3} = 1 - 0.17 - 0.21 = 0.62$

D_{c1} $= (f_{dn} \cdot f_{sb} + K_2 \cdot C_r \cdot f_{x1}) \cdot S_{bi}$
$= (0.11 \cdot 0.2 + 0.1 \cdot 1.39 \cdot 0.17) \cdot 533 = 24.7$

D_{c3} $= K_3 \cdot C_r \cdot f_{x3} \cdot S_{bi}$
$= 0.08 \cdot 1.39 \cdot 0.21 \cdot 533 = 12.4$

Thus $D_c = D_{c1} + D_{c3} = 24.5 + 12.3 = 37.1$ mg N.l^{-1}, which is equal to the nitrification capacity

ME_v = 1585 kg VSS.d^{-1}

ME_{ve} = 1102 kg VSS.d^{-1}

The maximum solubilisation of nitrogen in the digester is $f_n \cdot (ME_v - ME_{ve}) = 0.1 \cdot (1585 - 1102)$ = 48 kg N.d^{-1} which amounts to an equivalent influent nitrogen concentration of 4.0 mg N.l^{-1}. So it appears that the increase of the nitrogen influent concentration by 4.3 mg N.l^{-1} in this second iteration was a little too much and a third iteration could be executed, this time with an initial nitrogen concentration of $N_{ti}' = 50 + 4.0 = 54.0$ mg N.l^{-1}.

However, the difference in results between the second and a third iteration will be minimal and therefore it can be concluded that when a sludge age of R_s = 12 days is adopted, the system will be able to remove all nitrate generated in the nitrification process, not only from the nitrogen in the influent, but also from the nitrogen released in the digester.

The effluent nitrogen concentration N_{te} is equal to 4 mg $N.l^{-1}$, consisting of a residual organic fraction N_{oe} = 2 mg $N.l^{-1}$ and a residual ammonia concentration N_{ad} of 2 mg $N.l^{-1}$. The nitrogen present in the influent is divided into different fractions as follows:

(1) Nitrogen in the effluent: $N_{te} = N_{oe} + N_{ad} = 2 + 2 = 4$ mg $N.l^{-1}$

(2) Nitrogen in the stabilised excess sludge: $N_{le} = f_n{\cdot}ME_{ve}/Q_i = 0.1{\cdot}1.102/12 = 9.2$ mg $N.l^{-1}$

(3) Denitrified nitrogen: $N_d = N_{ti} - N_{le} - N_{te} = 50 - 9.2 - 4.0 = 36.8$ mg $N.l^{-1}$

Step 2 - 9: Optimise the system configuration C1

Once the required sludge age and the division of the reactor in anoxic and aerobic zones has been established, the calculations for optimisation of the system can be started, according to the procedure of Example 10.2. In Table 10.21 the annualised costs of configuration C1 are listed, while in Figs. (10.12 and 10.14) and Tables 10.23 to 10.29 the optimised solution is specified and compared to configuration C2.

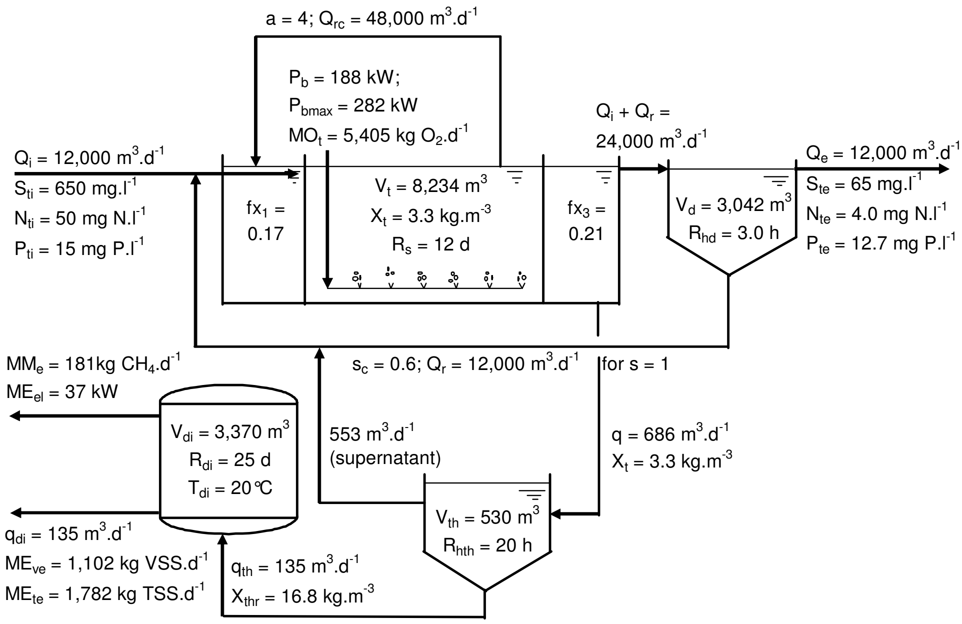

Figure 10.12 Schematic flow diagram of the optimised design of configuration C1

Table 10.21 Annualised investment and operational costs of system configuration C1

Cost item	Annual costs ($US\$.year^{-1}$)	Costs per m^3 (US$ cent)	Cost per PE (US$ cent)	Percentage (%)
Investment costs	890,000	20.3	8.9	47
Operational costs	1,020,000	23.3	10.2	53
- aeration	250,000	5.7	2.5	13
- sludge disposal	130,000	3.0	1.3	7
- personnel	310,000	7.1	3.1	16
- operation	100,000	2.2	1.0	5
- maintenance	200,000	4.6	2.0	10
- insurance	30,000	0.7	0.3	2
Total costs	1,910,000	43.6	19.1	100

The following remarks are made with respect to the calculations:

(1) Volumes of the anoxic and aerobic zones:

For the sludge age R_s = 12 days, the optimal volume of the biological reactor is determined as $V_r = 8234\ m^3$. As the anoxic sludge mass fractions were determined as f_{x1} = 0.17 and f_{x3} = 0.21, the volumes of the pre-D, post D and aerated zones can be calculated as:

$V_1 \quad = f_{x1} \cdot V_r = 0.17 \cdot 8234 = 1400\ m^3$

$V_3 \quad = f_{x3} \cdot V_r = 0.21 \cdot 8234 = 1715\ m^3$

$V_{ae} \quad = (1 - f_{x1} - f_{x3}) \cdot V_r = 0.62 \cdot 8234 = 5119\ m^3$

(2) Oxygen demand:

The mass of oxygen required for the process is given as the sum of the oxygen required for the oxidation of organic material and the oxygen required for nitrification. The mass of organic material oxidised by nitrate is subtracted from this amount (equivalent oxygen):

$MO_t \quad = MO_c + MO_n - MO_{eq}$

Where:

$MO_c \quad = (1 - f_{ns} - f_{np}) \cdot (1 - f_{cv} \cdot Y + f_{cv} \cdot (1 - f) \cdot b_h \cdot C_r) \cdot MS_{ti} = 4642\ kg\ O_2.d^{-1}$

$MO_n \quad = 4.57 \cdot MN_c = 4.57 \cdot 37.1 \cdot 12 = 2034\ kg\ O_2.d^{-1}$

As the removal of nitrate is complete the equivalent oxygen recovered in the denitrification process is:

$MO_{eq} \quad = {}^5/_8 \cdot MO_n = 0.625 \cdot MO_n = 1271\ kg\ O_2.d^{-1}$

Thus for the conditions specified in this example:

$MO_t \quad = 4642 + 2034 - 1271 = 5405\ kg\ O_2.d^{-1}$

The consumption of oxygen only takes place in the aerobic zone, so the OUR is given by:

$O_t \quad = MO_t/V_{ae} = 5405/5119 = 1.05\ kg\ O_2.m^{-3}.d^{-1}$ or $44\ mg\ O_2.l^{-1}.h^{-1}$