4.4.1 Nitrogen removal capacity

The concepts of nitrification and denitrification capacities are very convenient to describe nitrogen removal in the activated sludge process, as demonstrated in the following example. Consider the nitrogen removal in an activated sludge process characterised by the following parameters:

- N_{ti} = 50 mg N.l^{-1}
- S_{ti} = 500 mg COD.l^{-1}
- N_{ad} = 2 mg N.l^{-1}
- T = 20°C
- f_{ns} = 0.10
- f_{np} = 0.06
- f_{sb} = 0.25
- a = 4
- b_n = 0.04 d^{-1}
- K_n = 1 mg N.l^{-1}
- K_2 = 0.1 mg N.mg$^{-1}X_a$.d^{-1}
- s = 1

The nitrification and denitrification capacities can be calculated as functions of the sludge age using Eq. (4.44) for N_c and Eqs. (4.57 and 4.58) for D_{c1}, for two values of the maximum growth rate μ_m (0.3 and 0.6 d^{-1}). To calculate D_{c1}, it is necessary to first determine the maximum allowable anoxic sludge mass fraction f_m as a function of sludge age, using Eq. (4.40). In Fig. 4.18 the resulting curves of N_c, D_{c1} and f_m are shown.

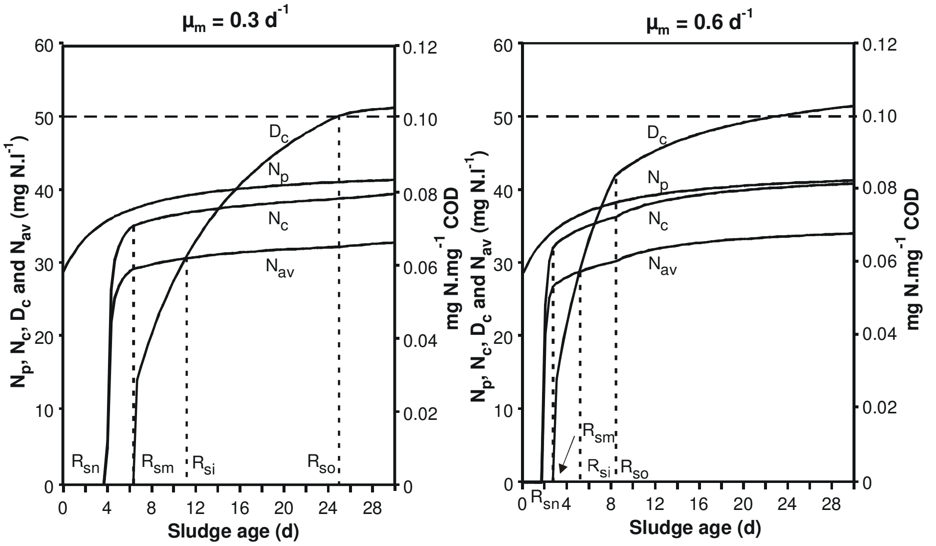

Figure 4.18 Nitrification- and denitrification capacity in a pre-D configuration as a function of the sludge age for the maximum anoxic mass fraction

It is convenient to introduce yet another parameter related to the nitrification capacity: the available nitrate in the anoxic reactor N_{av}. In a pre-D system, the available nitrate is the fraction of the nitrification capacity that is recirculated to the anoxic reactor. Having recirculation factors "a" from the aerobic reactors and "s" from the settler, the flow entering into the aerobic reactor is $(a+s+1)\cdot Q_i$ of which a fraction (a+s)/(a+s+l) is recirculated to the anoxic reactor. The remaining fraction 1/(a+s+l) is discharged from the system. Hence for a nitrate production of N_c in the aerobic reactor, a nitrate concentration of $(a+s)/(a+s+l)\cdot N_c$ is effectively available for denitrification in the pre-D anoxic reactor:

$$N_{av} = (a+s)/(a+s+1)\cdot N_c \qquad (4.64)$$

Where N_{av} = available nitrate in the pre-D reactor (mg N.l^{-1} influent)

The value of N_{av} is indicated in Fig. 4.18 as a function of the sludge age for recirculation factors a = 4 and s = l, i.e. for $N_{av} = (4+l)/(4+l+l)\cdot N_c = 0.833\cdot N_c$. The value of N_{av} represents the maximum nitrogen concentration that can be removed in a pre-D activated sludge process. Fig. 4.18 is a useful illustration that demonstrates the utility of the concept of nitrification- and denitrification capacity. With increasing sludge age the following situations can be observed (for $\mu_m = 0.3\ d^{-1}$):

(1) When $R_s < R_{sn}$, nitrification is impossible. The minimum sludge age for nitrification R_{sn} is given by Eq. (4.32):

$$R_{sn} = 1/(\mu_m - b_n) = 1/(0.3 - 0.04) = 3.85 \text{ days}$$

(2) For $R_s > R_{sn}$, nitrification is possible. However, it is not yet possible to comply with the condition that $N_{ae} \leq N_{ad}$, the specified effluent ammonium concentration. The reduction of N_{ae} to a value $\leq N_{ad}$ is possible when the applied sludge age is higher than R_{sm}. This sludge age R_{sm} can be calculated from the condition that $f_m = 0$ i.e.:

$$f_m = 0 = 1 - (1 + K_n/N_{ad})\cdot(1/R_{sm} + b_n)/\mu_m \text{ or}$$

$$R_{sm} = 1/[\mu_m/(1 + K_n/N_{ad}) - b_n] \tag{4.65}$$

For the data in this example:

$$R_{sm} = 1/[0.3/(1 + 1/2) - 0.04] = 6.25 \text{ days}$$

(3) For sludge ages longer than R_{sm}, it is possible to attain the specified residual ammonium concentration N_{ad} and to include an anoxic zone in the system as well. Using Eq. (4.40) to determine the anoxic sludge mass fraction, the denitrification capacity can be calculated from Eqs. (4.58 or 4.62). The nitrification capacity is calculated with the aid of Eq.(4.44):

$$f_m = 1 - (1+K_n/N_{ad})\cdot(b_n+1/R_s)/\mu_m \tag{4.40}$$

$$D_{c1} = (K_1 + K_2)\cdot C_r\cdot S_{bi}\cdot V_1/V_r = (K_1 + K_2)\cdot C_r\cdot f_{x1}\cdot S_{bi}\ (f_{x1}<f_{min}) \tag{4.58}$$

$$\begin{aligned} D_{c1} &= N_{ds} + N_{dp} \\ &= (f_{dn}\cdot f_{sb} + K_2\cdot C_r\cdot f_{x1})\cdot S_{bi}\ (f_{x1} > f_{min}) \end{aligned} \tag{4.62}$$

(4) For some particular sludge age R_{so}, the feasible anoxic sludge mass fraction f_x will be equal to the maximum value allowed f_{max}. For the given operating conditions and for f_{max} = 0.6 the value of R_{so} is calculated as:

$$f_m = f_{max} = 0.6 = 1 - (1 + K_n/N_{ad})\cdot(1/R_{so} + b_n)/\mu_m \text{ or}$$

$$R_{so} = 1/[\mu_m\cdot(1 - f_{max})/(1 + K_n/N_{ad}) - b_n] \tag{4.66}$$

For the example considered:

$$R_{so} = 1/[0.3\cdot(1 - 0.6)/(1 + 1/2) - 0.04] = 25 \text{ days}$$

(5) When the sludge age $R_s > R_{so}$, then both nitrification capacity and the denitrification capacity increase marginally with sludge age. D_{c1} will increase slightly more than N_c. Using the values of N_c and D_{c1}, the effluent nitrogen (ammonium and nitrate) concentration can be calculated as a function of the sludge age:

(a) $R_s < R_{sn}$

Below this sludge age nitrification is not possible. Hence, the ammonium concentration is equal to the nitrification potential and the nitrate concentration in the anoxic reactor is zero (it is assumed that no nitrate is present in the influent). No biological nitrogen removal will take place.

(b) $R_{sn} < R_s < R_{sm}$

In this range of sludge ages nitrification will develop. The effluent ammonium concentration is given by Eq. (4.30). The nitrate concentration will be equal to the nitrification capacity. Biological nitrogen removal will not take place.

(c) $R_s > R_{sm}$

Now it is possible to include an anoxic reactor. At increasing sludge age, the maximum allowed anoxic sludge mass fraction increases as well and so does the denitrification capacity. For a particular sludge age $R_s = R_{si}$, the value of D_{c1} will be equal to N_{av} so that:

$$D_{c1} = N_{av} \text{ or } (f_{dn} \cdot f_{sb} + K_2 \cdot C_r \cdot f_m) \cdot S_{bi} = N_c \cdot (a + s)/(a + s + 1) \tag{4.67}$$

The value of R_{si} can be graphically determined in Fig. 4.18 and is equal to 11 days (this value can also be calculated by trial and error using Eq. 4.67). In the range $R_{sm} < R_s < R_{si}$, the available nitrate in the pre-D zone N_{av} exceeds the denitrification capacity. It is concluded that the anoxic reactor is overloaded with nitrate. The nitrate load in excess of the denitrification capacity will be returned to the aerobic reactor. It is therefore possible to reduce the recirculation factors "a" and "s" and thus the value of N_{av} until N_{av} is equal to D_{c1}, without reducing the degree of nitrogen removal.

For example for $R_s = 10$ days and for the conditions specified in this example, one can calculate N_{av} as 37.2 mg $N.l^{-1}$ using Eq. (4.44) and D_{c1} as 28.9 mg $N.l^{-1}$ using Eq. (4.52). Hence for $D_{c1} = N_{av} = N_c \cdot (a+s)/(a+s+l)$, it is possible to apply a lower combined recirculation to the pre-D reactor: $a + s = 3.4$ will be sufficient, therefore $s = l$ and $a = 2.4$.

(d) $R_{sm} < R_s < R_{si}$

In this range of sludge ages, the ammonium effluent concentration is constant: $N_{ad} = 2$ mg $N.l^{-1}$ ($f_{x1} = f_{max}$). The nitrate concentration in the effluent will be equal to the difference between the nitrification capacity and the denitrification capacity: $N_{ne} = N_c - D_{c1}$.

(e) $R_{si} < R_s < R_{so}$

In this case, $D_{c1} > N_{av}$ and the anoxic reactor is underloaded, even when the maximum recirculation factors $(a+s) = 5$ are applied. All nitrate recirculated to the anoxic reactor will be removed. The effluent nitrate concentration will be equal to the fraction of the nitrification capacity that is discharged directly from the aerobic reactor to the effluent, without passing through the anoxic reactor: $N_{ne} = N_c/(a+s+l)$. It is assumed here that no denitrification will take place in the settler. The ammonium concentration will be constant at $N_{ad} = 2$ mg $N.l^{-1}$ (as f_{x1} will still be equal to f_{max}). In this range of sludge ages, the nitrogen removal efficiency could be increased by taking part of the pre-D reactor and using it to create a post-D reactor.

(f) $R_s > R_{so}$

Now the anoxic sludge mass fraction is limited by the condition that it may not exceed a maximum value: $f_x < f_{max}$ or $f_x < 0.6$. In this range of sludge ages, the residual ammonium concentration will be smaller than the specified value N_{ad}. The value of N_{ad} can be calculated with the aid of Eq. (4.39). As $D_{c1} > N_{av}$, the effluent nitrate concentration will still be given as $N_{ne} = N_c/(a+s+1)$.

In Fig. 4.19 the concentration of the different nitrogen fractions N_{ae}, N_{ne}, N_l and N_d is shown as function of the sludge age for the conditions specified in this example and in Fig. 4.18. For this particular example, it can be observed in Fig. 4.19 that for a sludge age of 11 days almost all of the influent nitrogen concentration (N_{ti}) of 50 mg $N.l^{-1}$ is removed. The effluent nitrogen concentration (N_{te}) is equal to $N_{ad} + N_{ne}$. The value of $N_{ne} = N_c/(a+s+1)$ is $38.0/6 = 6.3$ mg $N.l^{-1}$, so $N_{te} = 2.0 + 6.3 = 8.3$ mg $N.l^{-1}$. At the selected sludge age of 11 days the nitrogen concentration that is removed with the excess sludge N_l equals 10.0 mg $N.l^{-1}$. Hence, the denitrified nitrogen concentration N_d is equal to $N_{ki} - N_{ad} - N_{ne} = 50 - 2 - 6.3 - 10.0 = 31.7$ mg $N.l^{-1}$, which is equal to the denitrification capacity for $R_s = 11$ days.

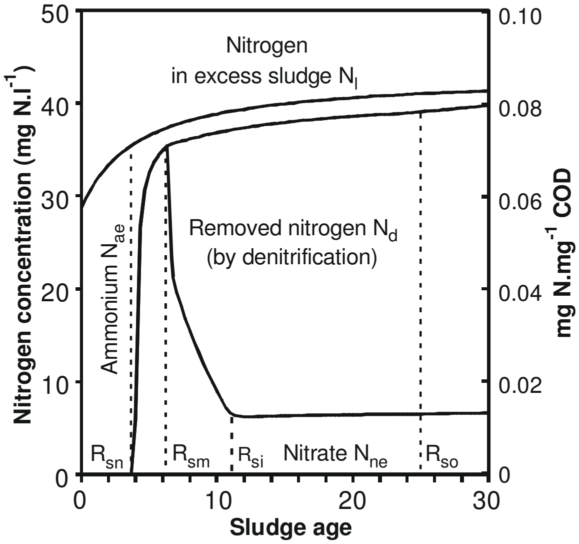

Figure 4.19 Division of the nitrogen in the influent over the different nitrogen fractions Calculated as a function of the sludge age (for $\mu_m = 0.3$ d^{-1})

If it is desired to reduce the effluent nitrogen concentration below the minimum value that can be obtained in the current pre-D configuration (in the example $N_{ne} = 8.3$ mg $N.l^{-1}$ for $R_s = R_{si} = 11$ days), it will be necessary to increase the sludge age and modify the reactor configuration of the process, transforming it from a pre-D system to a Bardenpho system. The optimisation of the Bardenpho system will be discussed in the next section.