Annex I

WSP process design examples

1. SURFACE WATER DISCHARGE

Design a WSP system to treat 10,000 m^3/day of a wastewater which has a BOD of 200 mg/l. The design temperature is 25°C and the net evaporation rate is 5 mm/day..

Solution

(a) With anaerobic ponds

Anaerobic pond

From Table 4.1 the design loading for 25°C is 300 g BOD/m^3 day.

Substitution of equation 4.2 into equation 4.3 gives the following alternative expression for the anaerobic pond retention time, θ_a:

$$\begin{aligned}\theta_a &= L_i/\lambda_v \\ &= 200/300 \\ &= 0.67 \text{ day}\end{aligned}$$

As θ_a <1 day, adopt θ_a = 1 day. Thus the anaerobic pond volume (V_a) is given by:

$$\begin{aligned}V_a &= Q/\theta_a \\ &= 10{,}000 \times 1 \\ &= 10{,}000 \text{ m}^3\end{aligned}$$

Assuming a depth of 4 m, the anaerobic pond area is 2,500 m^2.

At 25°C the BOD removal (Table 4.1) is 70%, so the BOD of the anaerobic pond effluent is (0.3 × 200), i.e. 60 mg/l.

Facultative Pond

From Table 4.3 the design loading for 25°C is 350 kg BOD/ha day. Thus the facultative pond area is given by equation 4.4 as:

$$\begin{aligned} A_f &= 10 L_i Q/\lambda_S \\ &= 10 \times 60 \times 10{,}000/350 \\ &= 17{,}143 \text{ m}^2 \end{aligned}$$

Calculate the retention time in the facultative pond from equation 4.12:

$$\theta_f = 2A_f D/(2Q_i - 0.001 A_f e)$$

Taking the depth as 1.5 m:

$$\begin{aligned} \theta_f &= 2 \times 17{,}143 \times 1.5/[(2 \times 10{,}000) - (0.001 \times 17{,}143 \times 5)] \\ &= 2.6 \text{ days} \end{aligned}$$

This is too low. Adopt for 25°C a minimum value of 4 days and calculate the area of the facultative pond from a rearrangement of equation 4.12 (i.e. use equation 4.18 with θ_f in place of θ_m):

$$\begin{aligned} A_f &= 2Q_i\theta_f/(2D + 0.001 e\theta_f) \\ &= 2 \times 10{,}000 \times 4/[(2 \times 1.5) + (0.001 \times 5 \times 4)] \\ &= 26{,}490 \text{ m}^2 \end{aligned}$$

The cumulative filtered BOD removal in the anaerobic and facultative ponds is 90% for $T > 20$°C, so the facultative pond effluent has a filtered BOD of (0.1 × 200), i.e. 20 mg/l, which is suitable for river discharge.

(b) Without anaerobic ponds

Facultative pond

$$A_f = 10\ L_i Q/\lambda_s$$
$$= 10 \times 200 \times 10{,}000/350$$
$$= 57{,}143\ \text{m}^2$$

Comparison of designs

The two designs, with and without anaerobic ponds, have the following mid-depth area requirements:

With anaerobic ponds:

Anaerobic pond:	2,500 m^2
Facultative pond:	26,490 m^2
Total:	28,990 m^2

Without anaerobic ponds:

Facultative pond: 57,143 m^2

Thus the use of anaerobic ponds results in a land saving of 49%. This confirms the observation of Professor Gerrit Marais (1970) that "**anaerobic pretreatment is so advantageous that the first consideration in the design of a series of ponds should always include anaerobic pretreatment**."

2. RESTRICTED IRRIGATION

Design a WSP system as in Design Example No. 1, but for restricted irrigation. Assume that the wastewater contains 750 intestinal nematode eggs per litre.

Solution

The anaerobic and facultative ponds are as calculated in Design Example No. 1. The retention times in the anaerobic and facultative ponds are 1 and 4 days, respectively. From Table 4.6 the percentage egg removals in the ponds are:

Anaerobic pond: 74.67
Facultative pond: 93.38

Thus the anaerobic pond effluent contains (0.2533 × 750), i.e. 190 eggs per litre, and the facultative pond effluent contains (0.066 × 190), i.e. 13 eggs per litre. A maturation pond is therefore required to reduce the number of eggs to 1 per litre for restricted irrigation (Table 10.1).

The required percentage egg removal in the maturation pond is:

$$100[(13 - 1)/13]$$

i.e. 92%. So, from Table 4.7, choose θ_m = 3.6 days. The maturation pond area is given by equation 4.18 as:

$$A_m = 2Q_i\theta_m/(2D + 0.0001e\theta_m)$$

Q_i is the effluent flow from the facultative pond, and is therefore given by:

$$\begin{aligned} Q_i &= 10{,}000 - 0.001\, A_f e \\ &= 10{,}000 - (0.001 \times 26{,}490 \times 5) \\ &= 9{,}867 \text{ m}^3\text{/day} \end{aligned}$$

Therefore, taking the depth as 1.5 m:

$$\begin{aligned} A_m &= 2 \times 9{,}867 \times 3.6/[\{2 \times 1.5\} \\ &\quad + (0.001 \times 5 \times 3.6)] \\ &= 23{,}540 \text{ m}^2 \end{aligned}$$

The final effluent flow for restricted irrigation is given by:

$$\begin{aligned} Q_e &= 9{,}867 - (0.001 \times 23{,}540 \times 5) \\ &= 9{,}749 \text{ m}^3\text{/day} \end{aligned}$$

Thus only 2.5% of the flow is lost due to evaporation.

Thus, for restricted irrigation, the mid-depth area requirements are:

Anaerobic pond: 2,500 m^2
Facultative pond: 26,490 m^2
Maturation pond: 23,540 m^2
Total: 52,530 m^2

3. UNRESTRICTED IRRIGATION

Design a WSP system as in Design Example No. 1, but for unrestricted irrigation. Assume that the wastewater contains 5×10^7 faecal coliforms per 100 ml.

Solution

The anaerobic and facultative ponds are as calculated in Design Example No. 1. The retention times in the anaerobic and facultative ponds are 1 and 4 days, respectively.

Maturation ponds

Use the following rearrangement of equation 4.14 to calculate θ_m:

$$\theta_m = \{[N_i/N_e(1 + k_T\theta_a)(1 - k_T\theta_f)]^{1/n} - 1\}/k_T$$

At 25°C k_T = 6.2 day^{-1} (Table 4.6). Therefore the above equation can be solved for the following values of *n* as follows, with N_e = 1000 for unrestricted irrigation (Table 10.1):

$$\begin{aligned} \theta_m &= \{[5 \times 10^7/1000\ (1 + 6.2 \times 1)(1 + 6.2 \times 4)]^{1/n} - 1\}/6.2 \\ &= 43.3 \text{ days for } n = 1 \\ &= 2.5 \text{ days for } n = 2 \end{aligned}$$

Choose 2 ponds each with a retention time of 3 days ($= \theta_m^{min}$). Check BOD loading on the first maturation pond from equation 4.17, assuming 80% cumulative removal in the anaerobic and facultative ponds and a depth of 1.5 m:

$$\begin{aligned} \lambda_{s(m1)} &= 10 \times (0.2 \times 200) \times 1.5/3 \\ &= 200 \text{ kg/ha day} \end{aligned}$$

This is satisfactory as it is less than 75% of the permissible design loading on facultative ponds at 25°C (350 kg/ha day; Table 4.3).

The area of the first maturation pond is given by equation 4.18 as:

$$\begin{aligned} A_{m1} &= 2Q_i\theta_m / (2D + 0.001e\theta_m) \\ &= 2 \times 9{,}867 \times 3/[(2 \times 1.5) + (0.001 \times 5 \times 3)] \\ &= 19{,}636 \text{ m}^2 \end{aligned}$$

The effluent flow is given by:

$$Q_e = Q_i - 0.001A_{m1}e$$
$$= 9{,}867 - (0.001 \times 19{,}636 \times 5)$$
$$= 9{,}769 \text{ m}^3\text{/day}$$

Similarly the area of the second maturation pond and its effluent flow are given by:

$$A_{m2} = 2 \times 9{,}769 \times 3/[(2 \times 1.5) + (0.002 \times 5 \times 3)]$$
$$= 19{,}441 \text{ m}^2$$

$$Q_e = 9{,}769 - (0.001 \times 19{,}441 \times 5)$$
$$= 9{,}672 \text{ m}^3\text{/day}$$

Thus only 3% of the flow is lost due to evaporation.

BOD removal

Assuming a 90% cumulative removal of filtered BOD in the anaerobic and facultative ponds, and 25% in each of the two maturation ponds, the final effluent will have a filtered (i.e. non-algal) BOD of:

$$200 \times 0.1 \times 0.75 \times 0.75 = 11 \text{ mg/l}$$

Summary

Thus, for unrestricted irrigation, the mid-depth area requirements are:

Anaerobic pond:	2,500 m^2
Facultative pond:	26,490 m^2
First maturation pond:	19,636 m^2
Second maturation pond:	19,441 m^2
Total:	68,067 m^2

This is 30% more than required for restricted irrigation (Design Example No. 2).

4. FISH CULTURE

Design a WSP system as in Design Example No. 1, but for fish culture. Assume that the total nitrogen and ammonia concentrations in the wastewater are 25 and 15 mg N/l, respectively.

Solution

The anaerobic and facultative ponds are as culated in Design Example No. 1. Assume that there is no total N removal in the anaerobic pond, and that there is an increase in the ammonia concentration in the anaerobic pond effluent to 20 mg N/l.

Calculate the total N and ammonia concentrations in the effluent of the facultative pond using equations 4.23 and 4.22, respectively, assuming the pH is 8:

$$C_e = C_i \exp\{-[0.0064(1.039)^{T-20}] [\theta + 60.6(\text{pH} - 6.6)]\}$$
$$= 25 \exp\{-[0.0064(1.039)^5] [4 + 60.6(8 - 6.6)]\}$$
$$= 12.6 \text{ mg total N/l}$$

$$C_e = C_i \{1 + [5.035 \times 10^{-3} (A_f/Q)] [\exp(1.504 \times (\text{pH} - 6.6)]\}$$
$$= 20/\{1 + [5.035 \times 10^{-3} (26{,}490/10{,}000)] [\exp(1.504 \text{ x}(8 - 6.6)]\}$$
$$= 18.0 \text{ mg } (NH_3 + NH_4^+) - \text{N/l}$$

Fishpond

Calculate the area of the fishpond on the basis of a surface loading of total nitrogen of 4 kg/ha day:

$$A_{fp} = 10C_iQ/\lambda_s$$
$$= 10 \times 12.6 \times 9{,}867/4$$
$$= 310{,}811 \text{ m}^2$$

The retention time in the fishpond is given by equation 4.12 as:

$$\theta_{fp} = 2A_{fp}D/(2Q_i - 0.001A_{fp}e)$$

Assuming the depth is 1 m:

$$\theta_{fp} = 2 \times 310{,}811 \times 1/[(2 \times 9{,}867) - (0.001 \times 310{,}811 \times 5)]$$
$$= 34 \text{ days}$$

Check the concentration of faecal coliform bacteria in the fishpond, using equation 4.14:

$$N_e = N_i/(1 + k_T\theta_a)(1 + k_T\theta_f)(1 + k_T\theta_{fp})$$
$$= 5 \times 10^7/(1 + 6.2 \times 1)(1 + 6.2 \times 4)(1 + 6.2 \times 34)$$
$$= 1271 \text{ per 100 ml}$$

This is just above 1000 per 100 ml, the WHO guideline for wastewater-fed aquaculture, but safe enough. The WHO guideline is really only refers to the order of magnitude, and 1271 is effectively 10^3 and, of course, $<<10^4$.

Check the ammonia concentration in the fishpond, using equation 4.22 and assuming the pH is 7.5:

$$C_e = 18/\{1 + [5.035 \times 10^{-3}(310{,}811/9{,}867)][\exp(1.504 \times (7.5 - 6.6))]\}$$
$$= 11 \text{ mg } (NH_3 + NH_4^+) - N/l$$

From Table 10.3 the percentage of free ammonia at pH 7.5 and 25°C is 1.77, so the concentration of free ammonia in the fishpond is (0.0177 × 11), i.e. 0.2 mg N/l, which is not toxic to fish.

Summary

Anaerobic pond:	2,500 m^2
Facultative pond:	26,490 m^2
Fishpond:	310,811 m^2
Total:	339,801 m^2

Thus only 8.5% of the total pond area is used for pretreatment prior to fish culture. Of course, the cost of the fishpond is not part of the cost of treatment and should be met by the fishfarmers, not the wastewater treatment authority.

5. WASTEWATER STORAGE AND TREATMENT RESERVOIRS

Design a wastewater storage and treatment reservoir system for the wastewater given in Design Example No. 1. Assume the irrigation season is 6 months.

Solutions

(a) Restricted irrigation

Pretreat the wastewater in an anaerobic pond, i.e. as calculated in Design Example No. 1.

The WSTR must be full at the start of the irrigation season and empty at the end of it, so its volume is equal to 6 months wastewater flow:

$$\begin{aligned} V &= (365/2) \times 10{,}000 \\ &= 1{,}825{,}000 \text{ m}^3 \end{aligned}$$

Assuming a depth of 10 m, the WSTR area is 18.25 ha.

(b) Restricted and unrestricted irrigation

Assume that the local farmers wish to use half the treated wastewater for restricted irrigation and half for unrestricted irrigation.

Use the hybrid WSP-WSTR system shown in Figure 9.1, i.e. use the anaerobic, facultative and maturation ponds calculated in Design Example No. 2, and calculate the WSTR volume for 6 months storage of the facultative pond effluent:

$$\begin{aligned} V &= (365/2) \times 9{,}749 \\ &= 1{,}779{,}193 \text{ m}^3 \end{aligned}$$

i.e. an area of 17.8 ha, assuming a depth of 10 m.