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 250 mg/l. The design temperature is 10°C. Ignore evaporation.

Solution

(a) With anaerobic ponds

Anaerobic pond

From Table 6.1 the design volumetric loading for 10°C is 100 g BOD/m^3 day. The anaerobic pond volume (V_a) is given by equation 6.2:

$$
\begin{aligned}
V_a &= L_i Q \lambda_v \\
&= 250 \times 10{,}000/100 \\
&= 25{,}000 \text{ m}^3
\end{aligned}
$$

The retention time (θ_a, days) is given by equation 6.3:

$$
\begin{aligned}
\theta_a &= V_a/Q \\
&= 25{,}000/10{,}000 \\
&= 2.5 \text{ days}
\end{aligned}
$$

Assuming a depth of 4 m, the anaerobic pond (mid-depth) area is 6,250 m^2.

At 10°C the BOD removal is 40% (Table 6.1), so the BOD of the anaerobic pond effluent is (0.6 × 250), i.e. 150 mg/l.

Facultative pond

From Table 6.3 the design surface loading for 10°C is 100 kg BOD/ha day. Thus the facultative pond area (A_f, m^2) is given by equation 6.4 as:

$$
\begin{aligned}
A_f &= 10\, L_i\, Q/\lambda_s \\
&= 10 \times 150 \times 10{,}000/100 \\
&= 150{,}000 \text{ m}^2
\end{aligned}
$$

Calculate the retention time (θ_f, days) from:

$$\theta_f = A_f D/Q$$

Taking the depth as 1.75:

$$\theta_f = 150{,}000 \times 1.75 / 10{,}000 = 26 \text{ days}$$

The cumulative filtered BOD removal in the anaerobic and facultative ponds is 80% (Section 6.5.3), so the facultative pond effluent has a filtered BOD of (0.2 × 250), i.e. 50 mg/l. This is too high for surface water discharge and maturation ponds are therefore required.

Maturation ponds

Try two maturation ponds as each reduces the filtered BOD by 30% (Section 6.5.3). Thus the effluent of the second maturation pond has a filtered BOD of (50 × 0.7 × 0.7), i.e. 25 mg/l, which is suitable for surface water discharge (Section 6.1).

Determine the BOD loading on the first maturation pond, assuming a depth of 1.5 m and a retention time of 13 days (= half that in the facultative pond) from equation 6.15.

$$\lambda_{s\,(m1)} = 10\,(0.3\,L_i)\,D/\theta_{m1} = 10 \times 0.3 \times 250 \times 1.5 / 13 = 87 \text{ kg/ha day}$$

This is satisfactory as it is less than the loading on the facultative pond (it need not be 75% of the latter as recommended in Section 6.5.1 as the purpose here is not faecal coliform removal).

Thus adopt two maturation ponds, each with a retention time of 13 days and each with a mid-depth area given by:

$$A_m = Q\theta_m/D = 10{,}000 \times 13 / 1.5 = 86{,}700 \text{ m}^2$$

(b) Without anaerobic ponds

Facultative pond

$$A_f = 10\,L_i Q/\lambda_s = 250{,}000 \times 10{,}000/100 = 250{,}000 \text{ m}^2$$

$$\theta_f = A_f D/Q = 250{,}000 \times 1.75/10{,}000 = 44 \text{ days}$$

Maturation ponds

Adopt two, each with a retention time of 22 days and a mid-depth area given by:

$$A_m = Q\,\theta_m/D = 10{,}000 \times 22/1.5 = 146{,}700 \text{ m}^2$$

Comparison of designs

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

With anaerobic ponds:

Anaerobic pond:	6,250 m^2
Facultative pond:	150,000 m^2
Maturation pond 1:	86,700 m^2
Maturation pond 2:	86,700 m^2
Total:	329,650 m^2

Without anaerobic ponds:

Facultative pond:	250,000 m^2
Maturation pond 1:	146,700 m^2
Maturation pond 2:	146,700 m^2
Total:	543,400 m^2

Thus the use of anaerobic ponds results in a land saving of 39%. 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 250 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 2.5 and 26 days, respectively. From equation 6.18 the percentage egg removals in the ponds are:

Anaerobic pond: 87.78
Facultative pond: 99.96

Thus the anaerobic pond effluent contains (0.1222 × 250), i.e. 31 eggs per litre, and the facultative pond effluent contains (0.004 × 31), i.e. << 1 egg per litre. Thus the facultative pond effluent can be safely used for restricted irrigation (Table 12.1).

3. UNRESTRICTED IRRIGATION

Design a WSP system as in Design Example 1, but for unrestricted irrigation. Assume that the wastewater contains 5×10^7 faecal coliforms per 100 ml and that the mean temperature and net evaporation rate in the coolest month of the irrigation season are 20ºC and 5 mm/day, respectively.

Solution

The anaerobic and facultative ponds are calculated for winter conditions as in Design Example No. 1. The retention times in the anaerobic pond is 2.5 days and that in the facultative pond is calculated from equation 6.10:

$$\theta_f = 2A_fD / (2Q - 0.001eA_f)$$
$$= 2 \times 150{,}000 \times 1.75/[(2 \times 10{,}000) - (0.001 \times 5 \times 150{,}000)]$$
$$= 27 \text{ days}$$

The effluent flow from the facultative pond in summer is given by:

$$Q_e = Q_i - 0.001eA_f$$
$$= 10{,}000 - (0.001 \times 5 \times 150{,}000)$$
$$= 9{,}250 \text{ m}^3\text{/day}$$

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 20ºC k_T = 2.6 day^{-1} (Table 6.4). Therefore the above equation can be solved for the following values of n as follows, with N_e = 1,000 for unrestricted irrigation (Table 12.1):

$$\theta_m = \{[5 \times 10^7/1000\ (1 + 2.6 \times 2.5)\ (1 + 2.6 \times 26]^{1/n} - 1\}/2.6$$
$$= 37 \text{ days for } n = 1$$
$$= 3.4 \text{ days for } n = 2$$

Thus choose two maturation ponds each with a retention time of 3.4 days.

Check BOD loading on the first maturation pond from equation 6.15, assuming 80% cumulative removal in the anaerobic and facultative ponds at 20ºC and a depth of 1.5 m:

$$\lambda_{s(m1)} = 10 \times (0.2 \times 250) \times 1.5/3.4$$
$$= 220 \text{ kg/ha day}$$

This is not satisfactory as it is more than 75% of the permissible design loading on facultative ponds at 20ºC (253 kg/ha day; Table 6.3). Calculate the required retention time from equation 6.15 rearranged and with $\lambda_{s(m1)}$ = (0.75 × 253), i.e. 190 kg/ha day:

$$\theta_{m1} = 10 \times (0.3 \times 250) \times 1.5/190$$
$$= 5.9 \text{ days}$$

Calculate the retention time in the second maturation pond from:

$$\theta_{m2} = \{[5 \times 10^7/1000\ (1 + 2.6 \times 2.5)\ (1 + 2.6 \times 26)\ (1 + 2.6 \times 5.9)] - 1\}/2.6$$
$$= 1.9 \text{ days}$$

Adopt θ_{m2} = 3 days (= θ_m^{min}).

The area of the first maturation pond is given by 6.16 as:

$$A_{m1} = 2Q_{im} / (2D + 0.001e\theta_m)$$

$$= 2 \times 9250 \times 5.9 / [(2 \times 1.5) + (0.001 \times 5 \times 5.9)]$$

$$= 36{,}100 \text{ m}^2$$

Its effluent flow is:

$$Q_e = 9250 - (0.001 \times 5 \times 36{,}100)$$

$$= 9070 \text{ m}^3/\text{day}$$

The area of the second maturation pond is given by:

$$A_{m2} = 2 \times 9070 \times 3 / [(2 \times 1.5) + (0.001 \times 5 \times 3)]$$

$$= 18{,}000 \text{ m}^2$$

The final effluent flow is:

$$Q_e = 9070 - (0.001 \times 5 \times 18{,}000)$$

$$= 8980 \text{ m}^3/\text{day}$$

Thus 10% of the flow is lost due to evaporation.

BOD removal

Assuming 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:

$$250 \times 0.1 \times 0.75 \times 0.75 = 14 \text{ mg/l}$$

This is satisfactory for irrigation.

Summary

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

Anaerobic pond:	6,250 m^2
Facultative pond:	150,000 m^2
Maturation pond 1:	36,100 m^2
Maturation pond 2:	18,000 m^2
Total:	210,350 m^2

This is 26% more than required for restricted irrigation (Design Example No. 2).

4. 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 (Figure 11.1a) 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:

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

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

(b) Unrestricted irrigation

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

Adopt three sequential batch-fed WSTR in parallel as shown in Figure 11.1b. The volume of each WSTR is equal to four months wastewater flow (Table 11.1):

$$V = (365/3) \times 10{,}000 = 1{,}216{,}700 \text{ m}^3$$

Assuming a depth of 10 m, the mid-depth area of each WSTR is 12.17 ha, i.e. a total mid-depth area – including that of the anaerobic pond – of 37 ha. (This is just under twice the area calculated in Design Example No. 3, but this system permits twice the quantity of crops to be grown.)

(c) 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 11.1c, i.e. use the anaerobic and facultative ponds calculated in Design Example No. 1, and the WSTR calculated in (a) above.

The total mid-depth area is 34 ha.

5. 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 calculated 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 concentration in the effluent of the facultative pond using equation 6.21, assuming the pH is 7.5.

$$\begin{aligned} C_e &= C_i \exp \{-[0.0064(1.039^{T-20}] [\theta + 60.6 (\text{pH} - 6.6)]\} \\ &= 25 \exp \{ - [0.0064 (1.039)^{-10}] [26 + 60.6 (7.5 - 6.6)]\} \\ &= 18 \text{ mg total N/l} \end{aligned}$$

Fishpond

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

$$\begin{aligned} A_{fp} &= 10 C_i Q/\lambda_s \\ &= 10 \times 18 \times 10{,}000/4 \\ &= 450{,}000 \text{ m}^2 \end{aligned}$$

The retention time in the fishpond is given by:

$$\theta_{fp} = A_{fp} D/Q$$

Assuming the depth is 1 m:

$$\begin{aligned} \theta_{fp} &= 450{,}000 \times 1/10{,}000 \\ &= 45 \text{ days} \end{aligned}$$

Check the concentration of faecal coliform bacteria in the fishpond, using the following version of equation 6.12 with $k_T = 0.46$ for 10°C:

$$\begin{aligned} N_e &= N_i/(1 + k_T\theta_a)(1 + k_T\theta_f)(1 + k_T\theta_{fp}) \\ &= 5 \times 10^7/(1 + 0.46 \times 2.5)(1 + 0.46 \times 26)(1 + 0.46 \times 45) \\ &= 83{,}000 \text{ per 100 ml} \end{aligned}$$

This is too high. Repeat the calculations for N_e at higher temperatures, i.e. higher values of k_T, until $N_e < 1000$ per 100 ml. Trial and error shows that 20°C, i.e. $k_T = 2.6$, is satisfactory:

$$\begin{aligned} N_e &= 5 \times 10^7/(1 + 2.6 \times 2.5)(1 + 2.6 \times 26)(1 + 2.6 \times 45) \\ &= 820 \text{ per 100 ml} \end{aligned}$$

This indicates that fish should not be harvested until the end of the first month of the year when the fishpond has reached a mean mid-depth temperature of 20°C.

Ammonia toxicity. First calculate the total ammonia concentration at 10°C in the effluent of the facultative pond, then in the fishpond, using equation 6.19 and assuming the pH in both is 7.5:

$$C_e = C_i/\{1 + [(A/Q)(0.0038 + 0.000134\, T) \exp((1.041 + 0.044\, T)(\text{pH} - 6.6))]\}$$

$$C_{e(f)} = 20/\{1 + [(150{,}000/10{,}000)(0.0038 + 0.000134 \times 10) \exp((1.041 + 0.044 \times 10)(7.5 - 6.6))]\}$$
$$= 15.5 \text{ mg/l}$$

$$C_{e(fp)} = 15.5/\{1 + [(450{,}000/10{,}000)(0.0038 + 0.000134 \times 10) \exp\{\{1.041 + 0.044 \times 10)(7.5 - 6.6))]\}$$
$$= 8.3 \text{ mg/l}$$

From Table 12.2 the percentage of free ammonia at pH 7.5 and 10ºC is 0.586, so the concentration of free ammonia in the fishpond at 10ºC is (0.00586 × 8.3) i.e. 0.05 mg N/l, which is not toxic to fish.

Summary

Anaerobic pond:	6,250 m^2
Facultative pond:	150,000 m^2
Fishpond:	450,000 m^2
Total:	606,250 m^2

Thus 26% of the total area is used for pretreatment prior to fish culture.