doi: 10.2166/9781789062304_0397

12

Final settling

Ferenc Házi and Eveline I.P. Volcke

12.1 INTRODUCTION

The abbreviations and nomenclature used in this chapter are identical to those in Chapter 12 in the textbook *Biological Wastewater Treatment: Principles, Modelling and Design* (Chen *et al.,* 2020), hereafter referred to as 'the textbook'. Chapter 12 of the textbook introduces the principles and mechanisms of the final settling process as well as the key factors that affect it. It gives an overview of the practical implementation of (gravitational) final settlers and provides the basics of the different design and operation methods for final settler design. These methods lead from understanding the basic measures and the flux theory to represent the observed settling behaviour to the comparison of different standards developed for the design of final settlers. The current chapter focuses on examples and exercises for the design and operational evaluation of final settlers. In particular, the examples help to generate state point analysis and Ekama D&O charts for operational support.

12.2 LEARNING OBJECTIVES

After the successful completion of this chapter, the reader will be able to:

- Describe the principles and objectives of final settling (clarification, thickening, and sludge storage).
- Describe and apply the basic measures of sludge settleability, and understand and choose between the different settling tank configurations.
- Apply flux theory and state point diagrams for the design and operation of secondary settling tanks.
- Apply and compare different methods (empirical, DWA, STOWA, etc) for the design of secondary settling tanks.

12.3 EXAMPLES

Evaluation of sludge settling properties

Example 12.3.1

Determine the Vesilind relationship between settling velocity and the test MLSS concentrations.

System under study – available data

A Stirred Zone Settling Velocity (SZSV) test has been performed with mixed liquor from a biological nutrient removal (BNR) activated sludge wastewater treatment plant (WWTP) at different solids concentrations ranging from 1,000 to 12,000 mg/l. The SZSV test results are summarized in Table 12.1.

Table 12.1 Experimental data from a Stirred Zone Settling Velocity (SZSV) test.

Time (min)	Time (h)	Sludge blanket height (cm) after settling starts in a 2 m-high column for different MLSS concentrations (mg/l)					
		1,000	2,000	4,000	6,000	8,000	12,000
0	0.000	200.0	200.0	200.0	200.0	200.0	200.0
10	0.167	82.9	109.5	158.8	182.9	195.1	197.0
20	0.333	11.0	32.9	115.9	165.9	189.9	193.9
30	0.500	7.9	17.1	72.3	149.1	185.1	190.9
40	0.667	7.0	11.9	43.9	132.0	179.9	188.1
50	0.833	7.0	11.0	33.8	114.9	174.1	186.0
60	1.000	6.1	10.1	28.0	97.9	168.9	184.1

Solution[1]

The SZSV test results from Table 12.1 are represented in Figure 12.1.

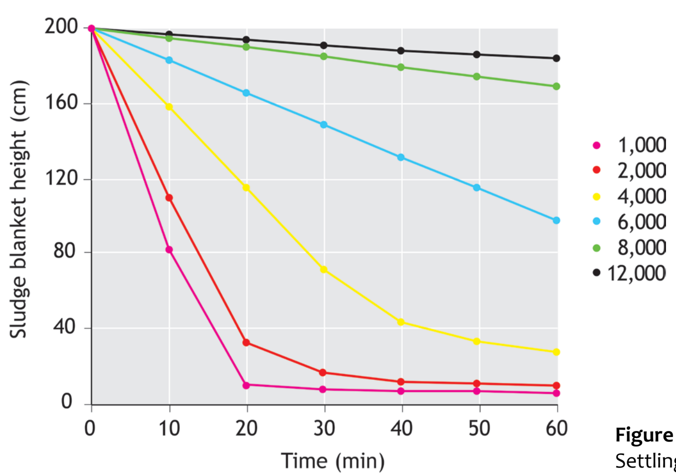


Figure 12.1 Graphical representation of the Stirred Zone Settling Velocity (SZSV) test results from Table 12.1.

[1] The solution is described below and made available as supplementary information for this chapter in the spreadsheet Chapter 12 Design example 1.xlsx, in the tabs 'ZSV data' and 'ZSV results'.

The settling velocity v_s for each MLSS concentration is determined as the slope of the linear section on the corresponding settling curve. However, the identification of the linear section of the settling curve is somewhat subjective and prone to uncertainty. The obtained data points are plotted in Figure 12.2 (markers) and show a decreasing exponential behaviour, described by the Vesilind function $v_s = v_0 \cdot e^{-p_{hin} \cdot X}$ (Eq. 12.1 in the textbook).

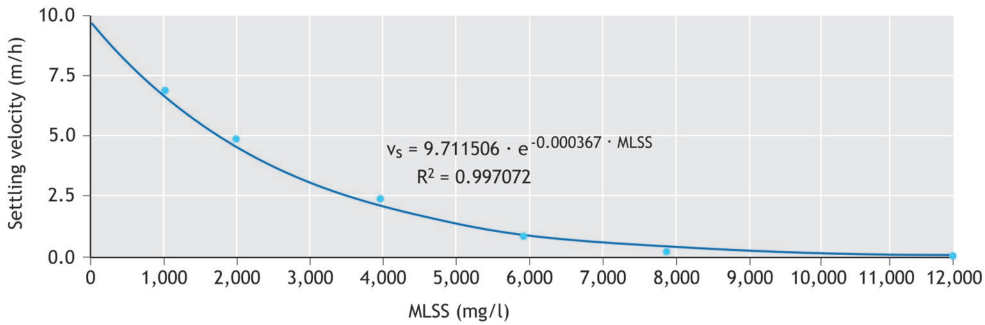


Figure 12.2 Vesilind relationship (solid line) based on ZSV measurements (markers).

By fitting an exponential curve to the data points, the parameter values are determined as v_0 = 9.4 m/h (initial settling velocity) and p_{hin} = 0.36 L/g [or m^3/kg] (hindered settling parameter).

Final settling design

Example 12.3.2[2]

System under study – design question

Design a secondary settler for an activated sludge plant where the MLSS is 4.5 kg/m^3 and the average dry weather flow rate is 1,000 m^3/h. Use the Vesilind function parameters obtained in Example 12.3.1. The additional required data are given in Table 12.2.

The goal of the design is to calculate the settler area and provide information on the underflow pump to handle peak flows. To this end, perform steady-state design according to the different methods from the textbook, based on flux theory, empirical design rules, STOWA, WRC, and ATV standards.

[2] This example and its solution are made available as supplementary information in the spreadsheet Chapter 12 Design example 1.xlsx, allowing the reader to check the calculations in detail. The figures provided in this chapter to illustrate the design process are also generated by this spreadsheet.

Table 12.2 Data summary for final settler design – Example 12.3.2.

Description	Symbol	Value	Unit
Plant design parameters			
MLSS	X_F	4.5	kg/m^3
Average dry weather flow (ADWF) rate	Q_{ADWF}	1,000	m^3/h
Diurnal peaking factor	P_{FDW}	1.5	-
Storm peak factor	P_{FWW}	2.5	-
Peak dry weather flow (PDWF)	Q_{PDWF}	1,500	m^3/h
Peak wet weather flow (PWWF)	Q_{PWWF}	3,000	m^3/h
Parameters for the flux theory based on Equation 12.1 and Figure 12.17			
Initial settling velocity	v_0	9.7[a)]	m/h
Hindered settling parameter	p_{hin}	0.367[a)]	m^3/kg
Safety factor on area	F_{corr}	1.25	-
Empirical design parameters			
Recycle ratio at PDWF	R_{PDWF}	1.0	-
Recycle ratio at PWWF	R_{PWWF}	0.5	-
Maximum dry weather surface overflow rate	SOR_{ADWF}	1	m/h
Maximum wet weather surface overflow rate	SOR_{PWWF}	2.5	m/h
Maximum dry weather solids loading rate	SLR_{ADWF}	6	kg/m^2.h
Maximum wet weather solids loading rate	SLR_{PWWF}	10	kg/m^2.h
WRC design parameters			
Stirred Sludge Volume Index (SSVI) at 3.5 g/l MLSS	$SSVI_{3.5}$	60	mg/l
Safety factor on area	F_{corr}	1.25	-
ATV and STOWA design parameters			
Diluted Sludge Volume Index (DSVI)	DSVI	100	mg/l
Maximum overflow rate	$q_{O,max}$	1.6	m/h
Minimum sludge volume loading	$q_{sv,min}$	300	l/m^2.h
Maximum sludge volume loading	$q_{sv,max}$	400	l/m^2.h
Maximum reduction due to sludge transferred at PWWF	f_{red}	0.7	-

[a)] Vesilind function parameters obtained in Section 12.3.1.

The data is summarized in the data sheet of the spreadsheet ‘Chapter 12 Design example 1.xlsx’ (Figure 12.3).

Input data for all methods				
Mixed liquour suspeneded solids	MLSS	4.5	kg/m^3	
Average dry weather flow	Q_{ADWF}	1,000	m^3/h	Enter or change red numbers only
Dry weather flow peak factor	PF_{DW}	1.5	-	
Peak dry weather flow	Q_{PDWF}	1,500	m^3/h	Use to check for DWF operation
Wet weather peak factor	PF_{WW}	3	-	
Wet weather peak flow	Q_{PWWF}	3,000	m^3/h	Design is based on this flow

Data specific to method

Empirical
No settleability input

Flux theory			
Initial settling velocity	v_o	9.7	m/h
Hindered settling parameter	p_{hin}	0.367	m^3/kg
Design safety factor	F_{corr}	1.25	-

Direct information from flux theory input data		
X at inflection	5.45	kg/m^3
X at maximum flux	2.72	kg/m^3
Slope at inflection ($q_{R,crit}$)	1.31	m/h

WRC			
Stirred Sludge Volume Index at 3.5 g/L	$SSVI_{3.5}$	60	ml/g
Design safety factor	F_{corr}	1.25	-

ATV and STOWA			
Diluted Sludge Volume Index	DSVI	100	ml/g
Settled volume of sludge at MLSS	DSV_{30}	450	ml/l

Figure 12.3 Data sheet for Example 12.3.2.

Solution

Design using flux theory

- Design assumptions

To carry out the design using flux theory, assume the following:

a) Steady-state design conditions.
b) The effluent solids flux is zero.
c) Solids Handling Criteria SHC I and SHC II are satisfied for the peak dry weather flow conditions.
d) SHC I and SHC II are critical for the peak wet weather flow conditions.
e) There is a 25 % safety factor (F_{corr}) in terms of surface area.

- Design procedure

Designing a settler according to the design using flux theory comes down to determining the following information, for both average dry weather flow (ADWF) and peak wet weather flow (PWWF) conditions:

1. Define gravity (J_S, $kg/m^2/h$) and bulk (J_B, $kg/m^2/h$) flux curves based on the Vesilind curve.
2. Calculate settling velocity (v_s, m/h) at the design MLSS concentration.
3. Calculate the minimum settler surface area based on PWWF (A, m^2) to meet SHC II.
4. Calculate the overflow line and state point for the state point diagram:
   a. Overflow line parameter: applied overflow rate (hydraulic loading, q_I, m/h).
   b. Overflow flux at feed concentration ($J_{I,F}$, $kg/m^2.h$), corresponding to the state point.

5. Determine the minimum recycle ratio required to meet the SHC I critical conditions on the state point diagram by aligning the underflow line for both PWWF and PDWF. Start with an initial recycle ratio (R_{init}) of 0.5:
   a. Calculate the underflow line parameters:
      i. Underflow flux (J_R, kg/m^2/h).
      ii. Total applied flux (J_{AP}, kg/m^2/h) or sludge loading rate (SLR).
   b. Repeat while changing the recycle ratio until the underflow line tangents the gravity flux curve:
      - If the underflow line is under the gravity flux curve above the design MLSS, decrease the recycle ratio.
      - If the underflow line intersects with the gravity flux curve above the design MLSS concentrations, increase the recycle ratio.
6. Calculate the corresponding recycle flow rates, underflow fluxes, total applied fluxes and recycle concentrations (X_R, kg/m^3) for both PDWF and PWWF.
7. As an alternative to using the state point diagram (Step 5), the minimum recycle flow can be determined using the Ekama Design & Operation (D&O) chart, as follows.
   a. Draw the SHC II line as the settling velocity at feed concentration ($v_{s,MLSS}$, m/h) (see Step 2).
   b. Determine the SCH I line or overflow rate (Q/A, m/h).
   c. To complete the Ekama D&O chart, the criterion boundary line is drawn.
8. Recalculate the settler surface area and the recycle pump capacity, taking into account the safety factor.

The calculations required to design a settler according to the flux theory, complying with SHC I and SHC II, are detailed below step by step.

1. Define gravity, bulk, and total flux curves for the Vesilind settling velocity function
The gravity flux (J_S, in kg/m^2.h) is obtained from:

$$J_S = v_s \cdot X \qquad \text{(Eq. 12.2 in the textbook)}$$

v_s represents the settling velocity at the design MLSS concentration X and is obtained from the Vesilind settling velocity function (Eq. 12.1 in the textbook) with the parameters determined in Example 12.3.1. Plotting the gravity flux as a function of the solids concentration X results in the gravity flux curve in Figure 12.4.

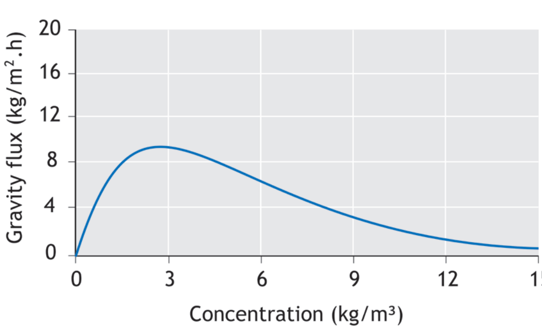


Figure 12.4 Gravity flux curve.

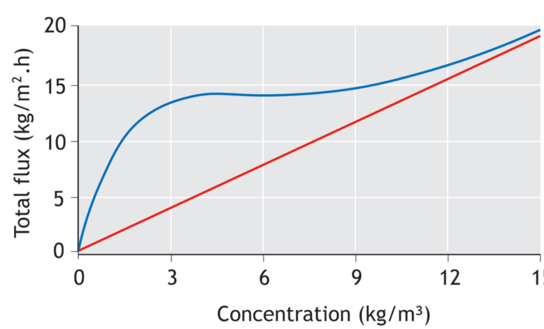


Figure 12.5 Bulk flux (red) and total flux curve (blue) at PWWF.

The bulk flux (J_B, in kg/m^2.h) represents the downward motion of solids in the settling tank, generated by the recycle flow (Q_R, in m^3.h). It is calculated from Eq. 12.1:

$$J_B = \frac{Q_R}{A} \cdot X \qquad (12.1)$$

in which Q_R represents the recycle flow rate (m^3/h) and A the settler surface area (m^2). The total flux transporting solids to the bottom of the clarifier is the sum of the gravity and bulk fluxes. Figure 12.5 displays the bulk flux and the total flux in PWWF conditions. The calculation of the bulk flux and total flux at PDWF is performed completely analogously.

2. *Calculate settling velocity at the design MLSS*

The settling velocity at the design MLSS concentration, *i.e.*, the solids concentration fed to the clarifier, is calculated from the Vesilind function (Eq. 12.1 in the textbook) as:

$$v_{s,MLSS} = 9.7 \cdot e^{-0.367 \cdot 4.5} = 1.86 \quad \text{m/h} \qquad (12.2)$$

3. *Calculate settler minimum surface (SHC II)*

SHC II requires that the overflow rate during PWWF must not exceed the settling velocity at feed concentrations:

$$q_{I,PWWF} = \frac{Q_{PWWF}}{A} \leq v_{s,MLSS} \qquad \text{(Eq. 12.5 in the textbook)}$$

The minimum surface of the settler is calculated from SHC II, by setting the maximum overflow rate equal to the settling velocity for peak wet weather conditions:

$$A = \frac{Q_{PWWF}}{v_{s,MLSS}} = \frac{3{,}000}{1.86} = 1.611 \quad \text{m}^2 \qquad (12.3)$$

4. *Calculate overflow for the state point diagram*

The overflow line in the state point diagram represents the overflow flux J_I in terms of the solids concentration X (see Eq. 12.6 in the main textbook):

$$J_I = \frac{Q_I}{A} \cdot X = q_I \cdot X \quad \text{kg/m}^2\text{.h} \qquad (12.4)$$

The slope of the overflow line, *i.e.*, the applied overflow rate or hydraulic loading, is calculated for PDWF as:

$$q_{I,PDWF} = \frac{Q_{PDWF}}{A} = \frac{1{,}500}{1{,}611} = 0.93 \quad \text{m/h} \qquad (12.5)$$

For PWWF conditions, the overflow rate equals the design settling velocity, as prescribed by SHC II (see Eq. 12.3):

$$q_{I,PWWF} = v_{s,MLSS} = 1.86 \quad h \qquad (12.6)$$

The overflow flux at the design MLSS (*i.e.*, the feed concentration) corresponds to the flux at the state point and is calculated as follows for PDWF and PWWF, respectively:

$$J_{I,PDWF,F} = \frac{Q_{PDWF}}{A} \cdot X_F = q_{I,PDWF} \cdot X_F = 0.93 \cdot 4.5 = 4.19 \quad kg/m^2.h \qquad (12.7)$$

$$J_{I,PWWF,F} = \frac{Q_{PWWF}}{A} \cdot X_F = q_{I,PWWF} \cdot X_F = 1.86 \cdot 4.5 = 8.38 \quad kg/m^2.h \qquad (12.8)$$

In the state point diagram, SHC II is fulfilled if the state point lies below the gravity flux curve, which is ensured by the calculation of the settler surface area by Eq. 12.3.

5. Determination of minimum recycle ratio using a state point diagram (SHC I)

SHC I requires the applied flux to the clarifier (*i.e.*, the mass of solids applied per unit settler area) to be lower than the minimum total flux. In the state point diagram, SHC I is evaluated by the position of the underflow line, which should be below the descending limb of the gravity curve.

The underflow line is determined by the underflow flux J_R (see Eq. 12.6 in the main textbook):

$$J_R = \frac{Q_R}{A} \cdot X = q_R \cdot X \quad kg/m^2.h \qquad (12.9)$$

which is plotted with a negative slope q_R (termed the hydraulic underflow rate) and shifted upwards such that the underflow line intersects the vertical axis at the total applied flux, which is the sum of the overflow flux and the underflow flux at the feed concentration (Eq. 12.8 in the textbook):

$$J_{AP} = \frac{Q_I + Q_R}{A} \cdot X_F = \frac{Q_I}{A} \cdot (1 + R) \cdot X_F = J_{I,F} + J_{R,F} \quad kg/m^2.h \qquad (12.10)$$

As a result, the underflow line is defined by:

$$\frac{Q_I + Q_R}{A} \cdot X_F - \frac{Q_R}{A} \cdot X = 0 \quad kg/m^2.h \qquad (12.11)$$

From Eq. 12.11, it is clear that the position of the underflow line and thus SHC I is influenced by both the settler surface area (A) and the recycle flow rate (Q_R). A being determined by SHC II (see Step 3.), SHC I will now be applied to determine the minimum recycle ratio $R = Q_I / Q_R$.

More specifically, the minimum recycle ratio is determined as the recycle ratio for which the underflow line is tangential to the descending limb of the gravity flux curve. This is done following an iterative procedure, applying different values of R, each time recalculating the position of the underflow line (Eq. 12.11) using updated values for the underflow flux (Eq. 12.9) and the total applied flux (Eq. 12.10).

Applying an initial value for the recycle ratio of R = 0.5 results in the state point diagrams of Figure 12.6 (PWWF) and 12.7 (PDWF). For PWWF conditions, the underflow line intersects with the gravity flux curve above the feed concentration, which means that the recycle ratio is too low and should be increased. A recycle ratio R = 1 is found too high because the corresponding underflow line is under the gravity flux curve above the feed concentration (Figure 12.8). After some trial and error the minimum recycle flow at PWWF conditions is found as $R_{min,PWWF} = 0.69$, resulting in an underflow line that is tangential to the descending limb of the gravity flux curve (Figure 12.10). For PDWF, a recycle ratio of R = 0.5 was found to be too high (the underflow line is under the gravity flux curve above the feed concentration, Figure 12.7), R = 0.3 was found to be too low (the underflow line intersects with the gravity flux curve above the feed concentration) and $R_{min,PDWF} = 0.4$ was found to be the minimum recycle flow at PDWF conditions (Figure 12.11).

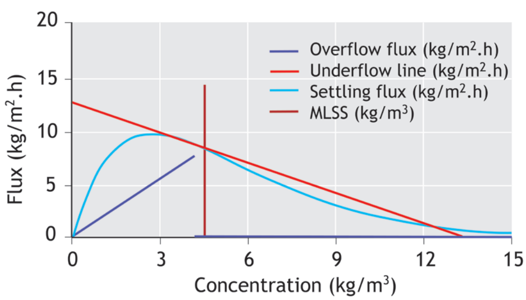


Figure 12.6 SPD at PWWF at R = 0.5.

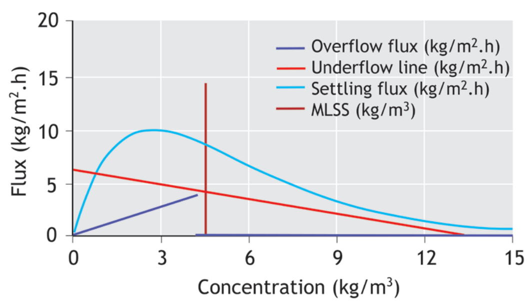


Figure 12.7 SPD at PDWF at R = 0.5.

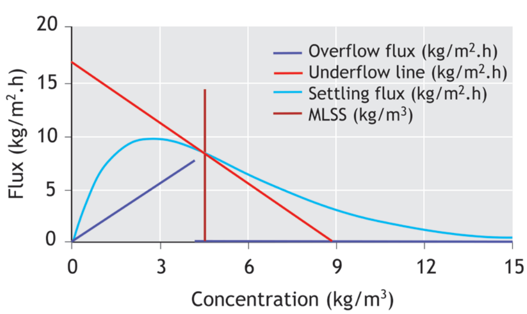


Figure 12.8 SPD at PWWF at R = 1.

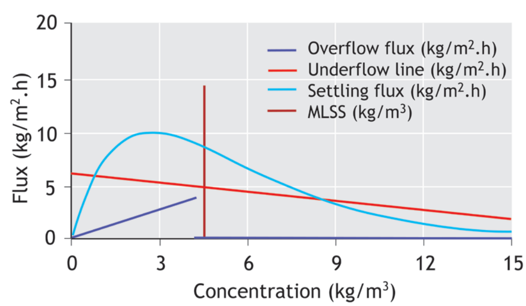


Figure 12.9 SPD at PDWF at R = 0.3.

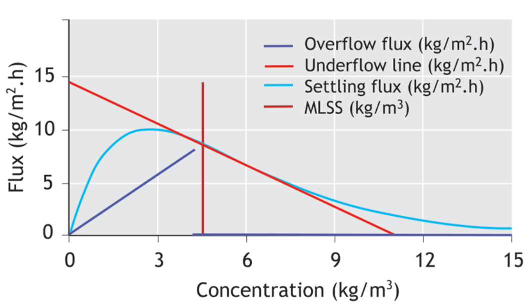


Figure 12.10 SPD at PWWF at $R_{min,PWWF} = 0.69$.

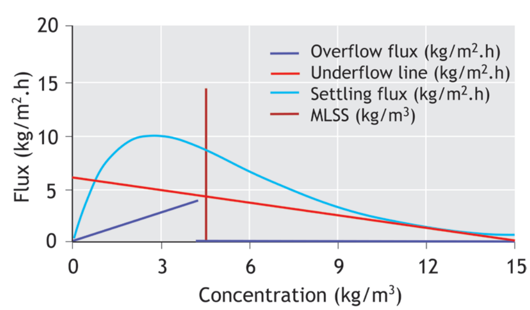


Figure 12.11 SPD at PDWF at $R_{min,PDWF} = 0.4$.

6. Calculate recycle flow rates and recycle concentrations

Taking into account $R_{min,PWWF}$ = 0.69 and $R_{min,PDWF}$ = 0.40, the minimum recycle flow rates required to fulfil SHC I for PDWF and PWWF are calculated as:

$$Q_{R,PDWF} = Q_{PDWF} \cdot R_{min,PDWF} = 1{,}500 \cdot 0.40 = 600 \qquad m^3/h \qquad (12.12)$$

$$Q_{R,PWWF} = Q_{PWWF} \cdot R_{min,FWWF} = 3{,}000 \cdot 0.69 = 2{,}073 \qquad m^3/h \qquad (12.13)$$

The corresponding hydraulic underflow rates under PDWF and PWWF conditions are obtained (see Eq. 12.9) as:

$$q_{R,PDWF} = \frac{Q_{R,PDWF}}{A} = \frac{1{,}500 \cdot 0.40}{1{,}611} = 0.37 \qquad m/h \qquad (12.14)$$

$$q_{R,PWWF} = \frac{Q_{R,PWWF}}{A} = \frac{3{,}000 \cdot 0.69}{1{,}611} = 1.29 \qquad m/h \qquad (12.15)$$

and the underflow fluxes at design MLSS (*i.e.*, the feed concentration) are calculated from Eq. 12.9 as:

$$J_{R,PDWF,F} = 0.37 \cdot 4.5 = 1.68 \qquad kg/m^2.h \qquad (12.16)$$

$$J_{R,PWWF,F} = 1.29 \cdot 4.5 = 5.79 \qquad kg/m^2.h \qquad (12.17)$$

The total applied flux at design MLSS under PDWF and PWWF conditions follow from eqs. 12.10, 12.7, 12.8, 12.16 and 12.17 as:

$$J_{AP,PDWF} = J_{I,PDWF,F} + J_{R,PDWF,F} = 4.19 + 1.68 = 5.87 \qquad kg/m^2.h \qquad (12.18)$$

$$J_{AP,PWWF} = J_{I,PWWF,F} + J_{R,PWWF,F} = 8.38 + 5.79 = 14.16 \qquad kg/m^2.h \qquad (12.19)$$

Assuming no solids in the clarifier effluent, the applied flux equals the flux leaving the settler with the underflow (recycle stream):

$$J_{AP} = \frac{Q_R}{A} \cdot X_R \qquad (12.20)$$

The sludge concentration in the recycle stream can be calculated from rearranging Eq. 12.20:

$$X_R = \frac{J_{AP} \cdot A}{Q_R} \qquad (12.21)$$

which, applied to PDWF and PWWF conditions, results in:

$$X_{R,PDWF} = \frac{J_{AP,PDWF} \cdot A}{Q_{R,ADWF}} = \frac{5.87 \cdot 1{,}611}{1{,}500} = 15.75 \quad \text{kg/m}^3 \quad (12.22)$$

$$X_{R,PWWF} = \frac{J_{AP,PWWF} \cdot A}{Q_{R,PWWF}} = \frac{14.16 \cdot 1{,}611}{3{,}000} = 11.02 \quad \text{kg/m}^3 \quad (12.23)$$

7. Iterate R_{min} values to calculate variables for the Ekama D&O chart

As an alternative to using the state point diagram, the minimum recycle ratio can be determined from the Ekama Design & Operation (D&O) chart.

Three lines are drawn to make up the Ekama D&O chart: the SHC II line, the SHC I line and the criterion boundary line. The SHC II line is easily drawn as a straight horizontal line representing the settling velocity at the design MLSS (= feed) concentration, $v_{s,MLSS} = 1.86$ (from Step 2., Eq 12.2). The latter value corresponds to the overflow rate at PWWF conditions: $v_{s,MLSS} = Q_{PWWF} / A$, see Eq. 12.3).

The SHC I line is determined by equations 12.9 and 12.10 in the textbook, for the given Vesilind parameters and the given feed concentration:

$$\frac{Q_I}{A} = \frac{v_0}{R} \cdot \frac{1+\alpha}{1-\alpha} e^{\frac{-p_{hin}(1+R) \cdot X_F \cdot (1+\alpha)}{2R}} = \frac{9.7}{R} \cdot \frac{1+\alpha}{1-\alpha} e^{\frac{-0.367(1+R) \cdot 4.5 \cdot (1+\alpha)}{2R}} \quad \text{m/h} \quad (12.24)$$

in which:

$$\alpha = \sqrt{1 - \frac{4R}{0.367 \cdot (1+R) \cdot 4.5}} \quad (12.25)$$

The value of Eq. 12.24 and Eq. 12.25 are calculated for a range of increasing recycle ratio values R, until the SHC I line intersects with the SHC II line, *i.e.*, until $Q_I / A = v_{s,MLSS}$, Figure 12.12). The minimum recycle ratio for peak wet weather conditions is thus found as $R_{min,PWWF} = 0.69$. In Excel, this is done by using the built-in ‘goal seek’ function (see the spreadsheet ‘Chapter 12 Design example 1.xlsx’).

The safe operating zone in the Ekama D&O chart is the zone below SHC II and to the right of SHC I (the green zone in Figure 12.12). For the clarifier not to be overloaded, the overflow rate Q_I / A should be below the SHC I line in the case $R < R_{min,PWWF}$; the overflow rate Q_I / A should be lower than $v_{s,MLSS}$ in the case $R > R_{min,PWWF}$. From the SHC I line, the minimum recycle rate for PDWF conditions (*i.e.,* corresponding with $Q_{PDWF} / A = 1{,}500 / 1{,}611 = 0.93$ is found as $R_{min,PDWF} = 0.4$. The values for the minimum recycle ratios at PWWF and PDWF conditions found in the Ekama D&O chart correspond with the values found in the state point diagram (Figure 12.10 and Figure 12.11, respectively).

To complete the Ekama D&O chart, the criterion boundary line is drawn based on Equation 12.11 in the textbook:

$$\frac{Q_I}{A} = \frac{v_0}{e^2 \cdot R} = \frac{9.7}{e^2 \cdot R}$$

The criterion boundary line is the boundary between lower recycle ratios where a critical flux can be found (SHC I applies) and higher recycle ratios where a critical flux cannot be found (only SHC II applies).

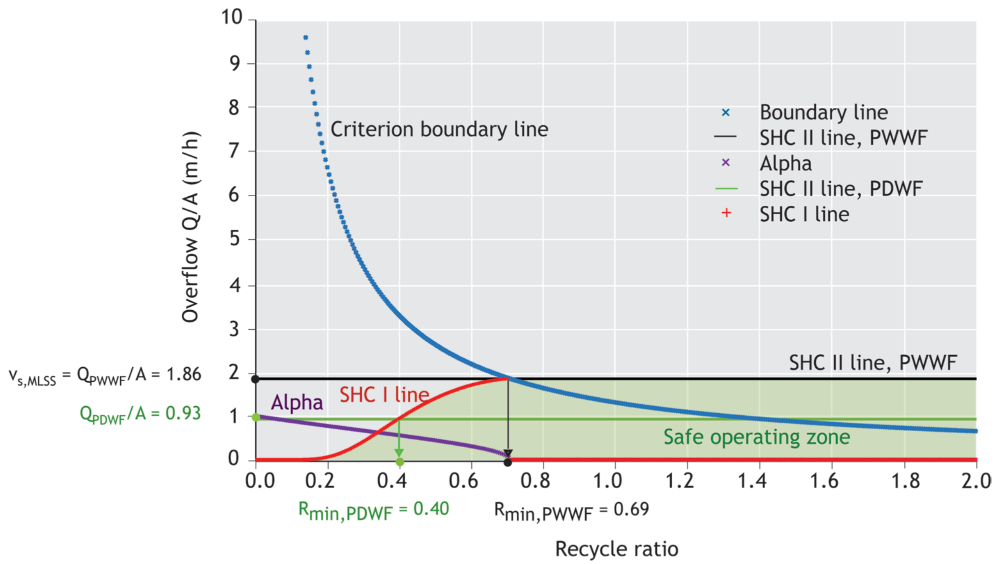


Figure 12.12 Ekama D&O chart for this example. The zone in green indicates the safe operating zone.

8. *Calculate the surface area and recycle pump capacity with a safety threshold*
Taking into account the safety factor F_{corr}, Table 12.2), the settler surface area (Eq. 12.3) is recalculated as:

$$A_{design,flux} = A \cdot F_{corr} = 1{,}611 \cdot 1.25 = 2{,}014 \qquad m^2 \qquad (12.26)$$

Due to practical considerations (standard design), the actual area chosen could be somewhat larger than the area theoretically required (Eq. 12.26), for instance:

$$A_{design,flux} \approx 2{,}020 \qquad m^2 \qquad (12.27)$$

The PWWF overflow rate becomes:

$$\frac{Q_{PWWF}}{A} = \frac{3{,}000}{2{,}020} = 1{,}5 \qquad h \qquad (12.28)$$

Given that the settler area increases by including a safety factor, the settler design will be in the safe operating zone. This can be verified by redrawing the state point diagram: revising the overflow line (Eq. 12.4), the state point (eqs. 12.7 and 12.8) and the underflow line (Eq. 12.11) (results not shown). In the Ekama D&O chart, it is immediately clear that the operating point corresponding with Q_{PWWF} / A = 1.5, Eq. 12.28) and that $R_{min,PWWF}$ = 0.69 is in the safe operating zone.

The recycle pump capacity is calculated according to the minimum recycle flow rates required at PDWF (and PWWF) conditions. Given that $Q_{R,PDWF}$ = 600 m^3/h (Eq. 12.12) and $Q_{R,PWWF}$ = 2,073 m^3/h (Eq. 12.13), say $Q_{R,PWWF}$ = 2,100 m^3/h, a total recycle pump capacity of 2,100 m^3/h needs to be provided. To optimize the pump operating time at maximum operating conditions (corresponding with maximum efficiency), a logical choice is to provide two pumps: one pump with a capacity of 600 m^3/h for dry weather conditions, and an additional pump with a capacity of 1,500 m^3/h to work in parallel with the first one in rain weather conditions. Taking into account the settler area including the safety factor (Eq. 12.27), some of the settler specifications need to be recalculated. A summary of the final settler design specifications is given in Table 12.3.

Empirical design

The settler surface area and the recycle pump capacity can also be calculated based on empirical methods. The recycle ratio serves as an empirical design parameter. Recycle ratios between 0.5 and 1.0 are usually satisfactory. In this example, the recycle ratio at PDWF is set at R_{PDWF} =1.0 and the recycle ratio at PWWF is set at R_{PWWF} = 0.5 (from Table 12.2). The recycle pump capacities at PDWF and PWWF are thus calculated as:

$$Q_{R,PDWF} = R_{PDWF} \cdot Q_{PDWF} = 1.0 \cdot 1{,}500 = 1{,}500 \qquad \mathrm{m^3/h} \qquad (12.29)$$

$$Q_{R,PWWF} = R_{PWWF} \cdot Q_{PWWF} = 0.5 \cdot 3{,}000 = 1{,}500 \qquad \mathrm{m^3/h} \qquad (12.30)$$

The corresponding recycle pump capacity amounts to:

$$Q_{R,Design} = \mathrm{Max}(Q_{R,PDWF}; Q_{R,PWWF}) = 1{,}500 \qquad \mathrm{m^3/h} \qquad (12.31)$$

The selection of the required settler surface area can be based on the maximum hydraulic loading specification and/or maximum solids loading specification (as presented in this example) or other criteria. In this case, the maximum surface overflow rates (hydraulic loading) for average dry weather flow and peak wet weather flow conditions are envisaged as SOR_{ADWF} = 1 m/h and SOR_{PWWF} = 2.5 m/h, respectively. In addition, the clarifier should not be loaded higher than 6 kg/m^2/h during average dry weather and 10 kg/m^2.h during wet weather conditions (*i.e.*, maximum solids loading specification). Each of the above four specifications will lead to a different required clarifier area, the largest of which will be selected, which in this case is 2,025 m^2 (Eq. 12.36). The calculations are provided in the design sheet in the spreadsheet 'Chapter 12 Design example 1.xlsx' (Figure 12.13).

The settler surface area based on maximum overflow rates at ADWF and PWWF are calculated as:

$$A_{design,SOR,ADWF} = \frac{Q_{ADWF}}{SOR_{ADWF}} = \frac{1{,}000}{1} = 1{,}000 \qquad \mathrm{m^2} \qquad (12.32)$$

$$A_{design,SOR,PWWF} = \frac{Q_{PWWF}}{SOR_{PWWF}} = \frac{3{,}000}{2.5} = 1{,}200 \qquad \mathrm{m^2} \qquad (12.33)$$

while the settler surface area based on the maximum solids loading at ADWF and PWWF is found as:

$$A_{design,SLR,ADWF} = X_F \cdot \frac{Q_{ADWF} + Q_{R,PDWF}}{SLR_{ADWF}} = 4.5 \cdot \frac{1{,}000 + 1{,}500}{6} = 1{,}875 \quad m^2 \qquad (12.34)$$

$$A_{design,SLR,PWWF} = X_F \cdot \frac{Q_{PWWF} + Q_{R,PWWF}}{SLR_{PWWF}} = 4.5 \cdot \frac{3{,}000 + 1{,}500}{10} = 2{,}025 \quad m^2 \qquad (12.35)$$

The settler surface area based on empirical design thus becomes:

$$A_{design,emp} = Max\left(A_{design,SOR,ADWF}, A_{design,SOR,PWWF}, A_{design,SLR,ADWF}, A_{design,SLR,PWWF}\right) = 2{,}025\ m^3 \qquad (12.36)$$

Empirical principles

Recycle ratio at PDWF	R_{PDWF}	1.0	-	Recycle pump (m^3/h)	Recycle pump: 1,500 m^3/h
Recycle ratio at PWWF	R_{PWWF}	0.5	-	Recycle pump (m^3/h)	1,500 m^3/h
	Design criteria			Area required (m^2)	
Maximum overflow rate at ADWF	SOR_{ADWF}	1.0	m/h	1,000	
Maximum overflow rate at PWWF	SOR_{PWWF}	2.5	m/h	1,200	Choose largest area
Maximum solids loading rate at ADWF	SLR_{ADWF}	6.0	$kg/m^2.h$	1,875	2,025 m^2
Maximum solids loading rate at PWWF	SLR_{PWWF}	10.0	$kg/m^2.h$	2,025	

Figure 12.13 Empirical clarifier design. Screenshot from the design sheet in the spreadsheet 'Chapter 12 Design example 1.xlsx'.

A number of additional settler specifications can be calculated and are summarized in Table 12.3.

WRC design

The WRC design method with the extension by Ekama *et al*. (1997) calculates the critical hydraulic underflow rate and the required settler surface area based on an empirical relationship with the $SSVI_{3.5}$ (Eq. 12.12 in the textbook). The Stirred Sludge Volume Index at 3.5 g/l MLSS for the given example is $SSVI_{3.5}$.= 60 mg/l (Table 12.2).

The resulting critical hydraulic underflow rate is calculated as:

$$q_{R,crit} = 1.612 - 0.00793 \cdot SSVI3.5 - 0.0015 \cdot \left(MAX\left(0, SSVI3.5 - 125\right)\right)^{1.115} =$$
$$1.612 - 0.00793 \cdot 60 - 0.0015 \cdot \left(MAX\left(0, 60 - 125\right)\right)^{1.115} = 1.14 \quad h \qquad (12.37)$$

and the required surface area is obtained from:

$$A_{design,PWWF} = X_F \cdot \frac{Q_{PWWF}}{306.86 \cdot SSVI3.5^{-0.77} \cdot q_{R,crit}^{0.68} - X_F \cdot Q_{R,crit}} =$$
$$4.5 \cdot \frac{3000}{306.86 \cdot 60^{-0.77} \cdot 1.14^{0.68} - 4.5 \cdot 1.14} = 1{,}469 \quad m^2 \qquad (12.38)$$

which is larger than the area required which would be obtained when applying the same relation for PDWF conditions.

Taking into account a safety factor of 25 % (F_{corr} = 1.25), the surface area becomes:

$$A_{design,WRC} = A_{design,PWWF} \cdot F_{corr} = 1{,}469 \cdot 1.25 = 1{,}836 \qquad m^2 \qquad (12.39)$$

The PWWF overflow rate is then:

$$q_{PWWF} = \frac{Q_{PWWF}}{A_{design,WRC}} = \frac{3{,}000}{1{,}836} = 1.63 \qquad m/h \qquad (12.40)$$

The recycle pump capacity corresponding with the obtained values for the critical hydraulic underflow rate and the settler surface area is then calculated and, for practical purposes, rounded off as:

$$Q_R = A_{design,WRC} \cdot q_{R,crit} = 1{,}469 \cdot 1.14 = 2{,}086 \approx 2{,}100\ 2{,}086 \approx 2{,}100 \qquad m^3/h \qquad (12.41)$$

The calculations are provided in the design sheet in the spreadsheet ‘Chapter 12 Design example 1.xlsx’ (Figure 12.14). Additional settler specifications are summarized in Table 12.3.

WRC principles

Calculate Critical Recycle Rate	$q_{R,crit}$	1.14	m/h
Calculate Area based on $SSVI_{3.5}$ for PWWF		1,469	m^2
Calculate Area based on $SSVI_{3.5}$ for PDWF		734	m^2

→

Choose larger area	1,469	m^2
Area with safety	**1,836**	m^2
PWWF recycle flow	2,086	m^3/h
Choose Pump	**2,100**	m^3/h
PWWF overflow rate	1.6	m/h

Figure 12.14 WRC principle-based clarifier design. Screenshot from the design sheet in the spreadsheet ‘Chapter 12 Design example 1.xlsx’.

<u>ATV design</u>

The ATV design method is based on the Diluted Sludge Volume Index (DSVI) test. In addition, it considers the settled volume of the MLSS under test conditions (DSV_{30}, Eq. 12.13 in the textbook), which is calculated for this example as:

$$DSV_{30} = X_{F,DWF} \cdot DSVI = 4.5 \cdot 100 = 450 \qquad ml/l \qquad (12.42)$$

The design steps are as follows:

1) The permissible overflow rate, q_O, is calculated as Eq. 12.15 in the textbook:

$$q_O = 2{,}400 \cdot DSV_{30}^{-1.34} = 2{,}400 \cdot 450^{-1.34} = 0.67 \qquad m/h \qquad (12.43)$$

2) q_O must be smaller than $q_{O,max}$ = 6 m/h, which is the case.
3) The settler surface area follows from the permissible overflow rate and the influent PWWF flow rate:

$$A_{design,ATV} = \frac{Q_{PWWF}}{\mathrm{Min}\left(q_O, q_{O,max}\right)} = \frac{3{,}000}{0.67} = 4{,}490 \qquad m^2 \qquad (12.44)$$

4) For practical considerations, the value obtained is rounded off as:

$$A_{design,ATV} \approx 4{,}500 \qquad m^2 \qquad (12.45)$$

5) The maximum recycle solids concentration that can be reached under ADWF and PWWF conditions is calculated according to Eq. 12.16 and Eq. 12.17 in the textbook, respectively:

$$X_{R,ADWF} = \frac{1{,}200}{DSVI} = \frac{1{,}200}{100} = 12 \qquad g/l \qquad (12.46)$$

$$X_{R,PWWF} = X_{RAS,ADWF} + 2 = 12 + 2 = 14 \qquad g/l \qquad (12.47)$$

6) The necessary recycle flow is calculated from the solids mass balance over the settler (Eq. 12.18 in the main textbook), both for ADWF and PWWF, as:

$$Q_{R,ADWF} = \frac{X_F}{X_{RAS,ADWF} - X_F} \cdot Q_{ADWF} = \frac{4.5}{12 - 4.5} \cdot 1{,}000 = 600 \qquad m^3/h \qquad (12.48)$$

$$Q_{R,PWWF} = \frac{X_F}{X_{RAS,PWWF} - X_F} \cdot Q_{PWWF} = \frac{4.5}{14 - 4.5} \cdot 3{,}000 = 1{,}421 \qquad m^3/h \qquad (12.49)$$

The recycle pump capacity is rounded up, to a practical value of:

$$Q_R = 1{,}500 \qquad m^3/h \qquad (12.50)$$

for all weather conditions.

The calculations are provided in the design sheet of the spreadsheet 'Chapter 12 Design example 1.xlsx' (Figure 12.15). Additional settler specifications are summarized in Table 12.3.

ATV principles

Permissible overflow rate (depends on DSV30)	q_O	0.67	m/h
Maximum q_O	$q_{O,max}$	1.60	m/h
area based on smaller of the two above rates	A	4,490	m^2
Maximum RAS, ADWF	$X_{RAS,ADW}$	12	g/l
Maximum RAS, PWWF	$X_{RAS,PWW}$	14	g/l

→

Choose area	**4,500**	m^2
ADWF recycle flow	600	m^3/h
PWWF recycle flow	1,421	m^3/h
Choose pump	**1,500**	m^3/h

Figure 12.15 ATV principle-based clarifier design for this example; screenshot from the design sheet in the spreadsheet 'Chapter 12 Design example 1.xlsx'.

STOWA design

The STOWA design method is closely related to the ATV design procedure and is performed according to the following steps:

1) The permissible overflow rate is calculated based on the DSV_{30} (Eq. 12.19 in the textbook), as follows:

$$q_O = \frac{1}{3} + \frac{200}{DSV30} = \frac{1}{3} + \frac{200}{450} = 0.78 \quad \text{m/h} \quad (12.51)$$

2) The sludge volume loading rate is calculated according to Eq. 12.52, taking into account Eq. 12.42 and 12.51.

$$q_{sv} = q_O \cdot DSV30 = 0.78 \cdot 450 = 350 \quad \text{m}^2\text{/h} \quad (12.52)$$

3) The sludge volume loading rate must be between 300 and 400 $l/m^2.h$ – this condition is fulfilled. As a result, the permissible overflow rate remains q_O =78 m/h (Eq. 12.51).

4) The settler surface area follows from the permissible overflow rate and the influent ADWF flow rate according to Eq. 12.53:

$$A_{design,ADWF} = \frac{Q_{ADWF}}{q_O} = \frac{1{,}000}{0.78} = 1{,}286 \quad \text{m}^2 \quad (12.53)$$

5) The settler surface area based on PWWF conditions, taking into account a maximum reduction on the MLSS concentration of 30 % (corresponding with a reduction factor f_{red} = 0.7), results from Eq. 12.54:

$$A_{design,PWWF} = f_{red} \cdot \frac{Q_{PWWF}}{q_O} = 0.7 \cdot \frac{3{,}000}{0.78} = 2{,}700 \quad \text{m}^2 \quad (12.54)$$

6) The settler surface area is taken as the maximum of Eq. 12.53 and Eq. 12.54, and rounded up:

$$A_{design,STOWA} = \text{above}\,\text{Max}(A_{design,ADW}, A_{design,PWWF}) = 2{,}700\ \text{m}^2$$

7) The recycle pump design is identical to the ATV method; the selected recycle pump has 1,500 m^3/h capacity.

The calculations are provided in the design sheet in the spreadsheet ‘Chapter 12 Design example 1.xlsx’ (Figure 12.16). Additional settler specifications are summarized in Table 12.3.

Table 12.3 A summary of the final settler design specifications. The variables in bold have been explicitly prescribed or calculated in the example; the remaining ones can be calculated additionally from the given relations. The calculations are provided in the summary sheet in the spreadsheet 'Chapter 12 Design example 1.xlsx'.

Parameter	Unit	Flux theory	Empirical	WRC	ATV	STOWA
Area, A	m^2	**2,020**	**2,025**	**1,836**	**4,500**	**2,700**
At ADWF						
Overflow rate, Q_{ADWF}	m^3/h			**1,000**		
Surface overflow rate, SOR_{ADWF}	m/h	0.50	0.49	0.54	0.22	0.37
Recycle flow rate, $Q_{R,ADWF}$	m^3/h	600	1,500	**2,100**	**1,500**	**1,500**
Hydraulic underflow rate, $q_{R,ADWF}$		0.30	0.74	**1.14**	0.33	0.56
Recycle ratio, R	-	0.60	1.50	2.10	1.50	1.50
RAS concentration, $X_{R,ADWF}$[1)]	kg/m^3	12.00	7.50	6.64	7.50	7.50
Solids loading rate, SLR_{ADWF}[2)]	$kg/m^2.h$	3.56	5.56	7.60	2.50	4.17
At PDWF						
Overflow rate, Q_{PDWF}	m^3/h			**1,500**		
Surface overflow rate, SOR_{PDWF}	m/h	0.74	0.74	0.82	0.33	0.56
Recycle flow rate, $Q_{R,PDWF}$	m3/h	**600**	**1,500**	**2,100**	**1,500**	**1,500**
Hydraulic underflow rate, $q_{R,PDWF}$	m/h	0.30	0.74	**1.14**	0.33	0.56
Recycle ratio, $R_{min,PDWF}$	-	**0.4**	**1.0**	1.4	1.0	1.0
RAS concentration, $X_{R,PDWF}$[1)]	kg/m^3	15.75	9.00	7.71	9.00	9.00
Solids loading rate, SLR_{PDWF}[2)]	$kg/m^2.h$	4.68	6.67	8.82	3.00	5.00
At PWWF						
Overflow rate, Q_{PWWF}	m^3/h			**3,000**		
Surface overflow rate, SOR_{PWWF}	m/h	1.49	1.48	**1.63**	0.67	1.11
Recycle flow rate, $Q_{R,PWWF}$	m^3/h	**2,100**	1,500	**2,100**	**1,500**	**1,500**
Hydraulic underflow rate, $q_{R,PWWF}$	m/h	1.04	0.74	**1.14**	0.33	0.56
Recycle ratio, $R_{min,PWWF}$	-	**0.69**	**0.5**	0.7	0.5	0.5
RAS concentration, $X_{R,PWWF}$[1)]	kg/m^3	10.93	13.50	10.93	13.5	13.50
Solids loading rate, SLR_{PWWF}[2)]	$kg/m^2.h$	11.36	**10**	12.50	4.50	7.50

[1)] The sludge concentration in the recycle stream (*i.e.*, the RAS concentration) can be calculated from:

$$\frac{(Q+Q_R)}{Q_R}\cdot X_F \tag{12.55}$$

[2)] The solids loading rate is calculated as:

$$SLR = \frac{Q+Q_R}{A}\cdot X_F \tag{12.56}$$

STOWA principles

Permissible overflow rate	q_O	0.78	m/h
Sludge volume loading	q_{sv}	350	l/m².h
minimum sludge volume loading	$q_{sv,min}$	300	l/m².h
maximum sludge volume loading	$q_{sv,max}$	400	l/m².h
Sludge volume loading used	$q_{sv,design}$	350	l/m².h
Overflow rate used	q_O	0.78	m/h
Maximum reduction due to sludge transferred at PWWF	f_{red}	0.7	-
Maximum RAS, ADWF	$X_{RAS, ADW}$	12	g/l
Maximum RAS, PWWF	$X_{RAS, PWW}$	14	g/l

Maximum area, ADWF	1,286	m²
Maximum area, PWWF	2,700	m²
Choose area	**2,700**	m²
ADWF recycle flow	600	m³/h
PWWF recycle flow	1,421	m³/h
Choose pump	**1,500**	m³/h

Figure 12.16 STOWA principle-based clarifier design for this example; a screenshot from the design sheet in the spreadsheet 'Chapter 12 Design example 2.xlsx'.

Summary and discussion

An overview of the design specifications obtained with the different methods is given in Table 12.3. The design input indicates a sludge with not particularly good settling properties because DSVI is 100 ml/g. Besides, the settler is loaded with a high MLSS concentration (4.5 kg/m³) and the peak wet weather flow is high (Q_{PWWF} = 3,000 m³/h). The combination of these factors results in a high settler area, which is more or less pronounced according to the extent to which they are taken into account in a given design procedure. The empirical design does not consider the settling properties of the sludge at all but does take into account the high MLSS and PWWF flow rates.

Final settling design

Example 12.3.3[3]

System under study - design question

Design a secondary settler for an activated sludge plant where the MLSS is 3.5 kg/m³ and the average dry weather flow rate is 625 m³/h. Additional required data is given in Table 12.4, including values for the Vesilind function parameters.

The goal of the design is to calculate the settler area and provide information on the underflow pump to handle peak flows. To this end, perform steady-state design according to the different methods from the textbook, based on flux theory, empirical design rules, STOWA, WRC and ATV standards.

[3] This example and its solution are available as supplementary information in the spreadsheet 'Chapter 12 Design example 2.xlsx', allowing the reader to check the calculations in detail. Note that this example is completely the same as Example 1, but with different design parameters (Table 12.2 versus Table 12.4).

Table 12.4 Data summary for final settler design – Example 12.3.3.

Description	Symbol	Value	Units
Plant design parameters			
MLSS	X_F	3.5	kg/m^3
Average dry weather flow rate (ADWF)	Q_{ADWF}	625	m^3/h
Diurnal peaking factor	P_{FDW}	1.5	-
Storm peak factor	P_{FWW}	2.5	-
Peak dry weather flow (PDWF)	Q_{PDWF}	938	m^3/h
Peak wet weather flow (PWWF)	Q_{PWWF}	1,563	m^3/h
Parameters for the flux theory based on Equation 12.1 and Figure 12.17			
Initial settling velocity	v_0	16.8	m/h
Hindered settling parameter	p_{hin}	0.36	m^3/kg
Safety factor on area	F_{corr}	1.25	-
Empirical design parameters			
Recycle ratio at PDWF	R_{PDWF}	0.6	-
Recycle ratio at PWWF	R_{PWWF}	0.4	-
Maximum dry weather surface overflow rate	SOR_{ADWF}	1	m/h
Maximum wet weather surface overflow rate	SOR_{PWWF}	2.5	m/h
Maximum dry weather solids loading rate	SLR_{ADWF}	6	$kg/m^2.h$
Maximum wet weather solids loading rate	SLR_{PWWF}	15	$kg/m^2.h$
WRC design parameters			
Stirred Sludge Volume Index at 3.5 g/l MLSS	$SSVI_{3.5}$	48	mg/l
Safety factor on area	F_{corr}	1.25	-
ATV and STOWA design parameters			
Diluted Sludge Volume Index	DSVI	60	mg/l
Maximum overflow rate	$q_{O,max}$	1.6	m/h
Minimum sludge volume loading	$q_{sv,min}$	300	$l/m^2.h$
Maximum sludge volume loading	$q_{sv,max}$	400	$l/m^2.h$
Maximum reduction due to sludge transferred at PWWF	f_{red}	0.7	-

The data is summarized in the data sheet of the spreadsheet 'Chapter 12 Design example 2.xlsx' (Figure 12.17).

Input data for all methods

Mixed liquour suspeneded solids	MLSS	**3.5**	kg/m^3	
Average dry weather flow	Q_{ADWF}	**625**	m^3/h	**Enter or change red numbers only**
Dry weather flow peak factor	PF_{DW}	**1.5**	-	
Peak dry weather flow	Q_{PDWF}	938	m^3/h	Use to check for DWF operation
Wet weather peak factor	PF_{WW}	**2.5**	-	
Wet weather peak flow	Q_{PWWF}	1562.5	m^3/h	Design is based on this flow

Data specific to method

Empirical
No settleability input

Flux theory			
Initial settling velocity	v_o	**16.8**	m/h
Hindered settling parameter	p_{hin}	**0.36**	m^3/kg
Design safety factor	F_{corr}	1.25	-

Direct information from flux theory input data		
X at inflection	5.56	kg/m^3
X at maximum flux	2.78	kg/m^3
Slope at inflection ($q_{R,crit}$)	2.27	m/h

WRC			
Stirred Sludge Volume Index at 3.5 g/L	$SSVI_{3.5}$	**48**	ml/g
Design safety factor	F_{corr}	1.25	-

ATV and STOWA			
Diluted Sludge Volume Index	DSVI	**60**	ml/g
Settled volume of sludge at MLSS	DSV_{30}	210	ml/l

Figure 12.17 Data sheet for Example 12.3.3.

Design assumptions and design procedure

The design assumptions and the design procedure are completely the same as Example 12.3.2.

Solution

Design using flux theory

1. Define gravity, bulk, and total flux curves for the Vesilind settling velocity function

The gravity flux is obtained from Eq. 12.2 in the main textbook using the Vesilind settling velocity function with parameters v_o and p_{hin} from Table 12.4. The gravity flux curve is plotted in Figure 12.18. The bulk flux (J_B, in $kg/m^2.h$) is calculated from Eq. 12.1. Figure 12.19 displays the bulk flux and the total flux at PWWF conditions.

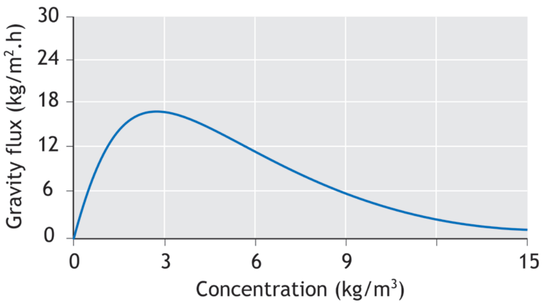


Figure 12.18 Gravity flux curve.

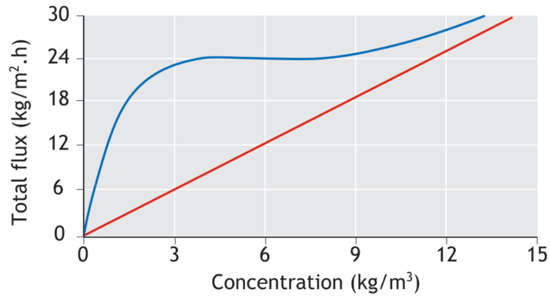


Figure 12.19 Bulk flux (red) and total flux curve (blue) at PWWF.

2. Calculate the settling velocity at the design MLSS

The settling velocity at the design MLSS concentration, *i.e.*, the solids concentration fed to the clarifier, is calculated from the Vesilind function (Eq. 12.1 in the main textbook) as:

$$v_{s,MLSS} = 16.8 \cdot e^{-0.36 \cdot 3.5} = 4.77 \qquad \text{m/h} \qquad (12.57)$$

3. Calculate the settler minimum surface (SHC II)

The minimum surface of the settler is calculated from SHC II, by setting the maximum overflow rate equal to the settling velocity for peak wet weather conditions:

$$A = \frac{Q_{PWWF}}{v_{s,MLSS}} = \frac{1{,}563}{4.77} = 328 \qquad \text{m}^2 \qquad (12.58)$$

4. Calculate the overflow for the state point diagram

The slope of the overflow line, *i.e.* the applied overflow rate or hydraulic loading, is calculated for PDWF as:

$$q_{I,PDWF} = \frac{Q_{PDWF}}{A} = \frac{938}{328} = 2.86 \qquad \text{m/h} \qquad (12.59)$$

For PWWF conditions, the overflow rate equals the design settling velocity, as prescribed by SHC II (see Eq. 12.58):

$$q_{I,PWWF} = v_{s,MLSS} = 4.77 \qquad \text{m/h} \qquad (12.60)$$

The overflow flux at the design MLSS (*i.e.*, the feed concentration) corresponds to the flux at the state point and is calculated as follows, for PDWF and PWWF, respectively:

$$J_{I,PDWF,F} = \frac{Q_{PDWF}}{A} \cdot X_F = q_{I,PDWF} \cdot X_F = 2.86 \cdot 3.5 = 10.0 \qquad \text{kg/m}^2\text{.h} \qquad (12.61)$$

$$J_{I,PWWF,F} = \frac{Q_{PWWF}}{A} \cdot X_F = q_{I,PWWF} \cdot X_F = 4.76 \cdot 3.5 = 16.7 \qquad \text{kg/m}^2\text{.h} \qquad (12.62)$$

In the state point diagram, SHC II is fulfilled if the state point lies below the gravity flux curve, which is ensured by the calculation of the settler surface area by Eq. 12.58.

5. Determination of minimum recycle ratio using the state point diagrams (SHC I)

The minimum recycle ratio is determined as the recycle ratio for which the underflow line is tangential to the descending limb of the gravity flux curve. This is done following an iterative procedure, applying different values of R, each time recalculating the position of the underflow line (Eq. 12.11) using updated values for the underflow flux (Eq. 12.9) and the total applied flux (Eq. 12.10).

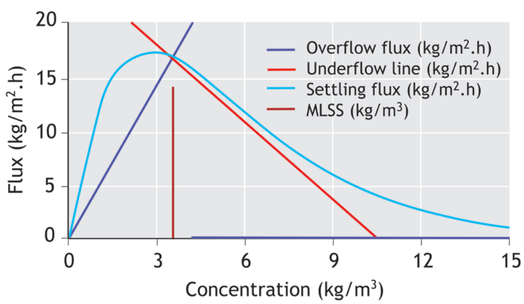


Figure 12.20 SPD at PWWF at R = 0.5.

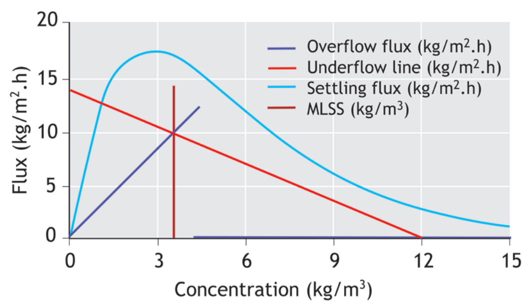


Figure 12.21 SPD at PDWF at R = 0.4.

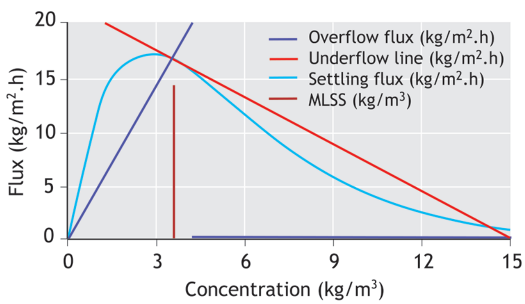


Figure 12.22 SPD at PWWF at R = 0.3.

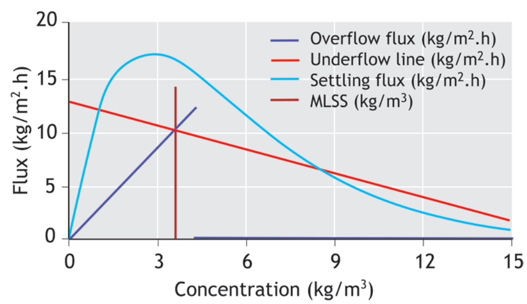


Figure 12.23 SPD at PDWF at R = 0.25.

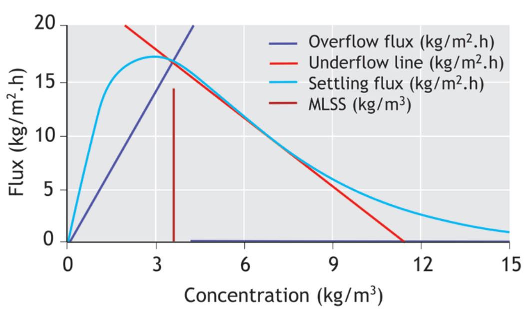


Figure 12.24 SPD at PWWF at $R_{min,PWWF}$ = 0.44.

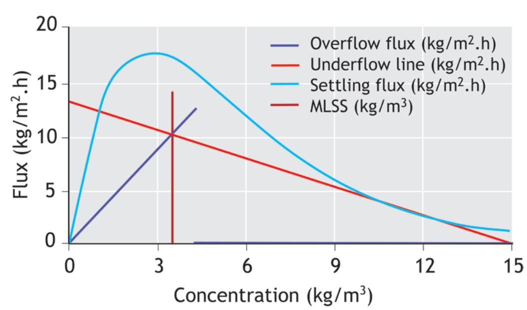


Figure 12.25 SPD at PDWF at $R_{min,PDWF}$ = 0.30.

Applying an initial value for the recycle ratio of R = 0.5 for PWWF conditions and R = 0.4 for PDWF conditions results in the state point diagrams of Figure 12.20 and Figure 12.21, respectively. In both cases, the underflow line is under the gravity flux curve above the feed concentration, which means that the recycle ratio is too high. Applying a recycle ratio of R = 0.3 for PWWF conditions and R = 0.25 for PDWF conditions, the underflow lines intersect with the gravity flux curve above the feed concentration, which means that the recycle ratio is too low (the state point diagrams in Figure 12.22 and Figure 12.23). After some trial and error, the minimum recycle flow at PWWF and PDWF conditions is found as $R_{min,PWWF}$ = 0.44 (Figure 12.24) and $R_{min,PDWF}$ = 0.30 (Figure 12.25), respectively.

6. Calculate recycle flow rates and recycle concentrations

Taking into account $R_{min,PWWF}$ = 0.44 and $R_{min,PDWF}$ = 0.30, the minimum recycle flow rates required to fulfil SHC I for PDWF and PWWF are calculated as:

$$Q_{R,PDWF} = Q_{PDWF} \cdot R_{min,PDWF} = 938 \cdot 0.30 = 281 \quad m^3/h \quad (12.63)$$

$$Q_{R,PWWF} = Q_{PWWF} \cdot R_{min,FWWF} = 1{,}563 \cdot 0.435 = 688 \quad m^3/h \quad (12.64)$$

The corresponding hydraulic underflow rates under PDWF and PWWF conditions are obtained (see Eq. 12.9) as:

$$q_{R,PDWF} = \frac{Q_{R,PDWF}}{A} = \frac{281}{328} = 0.86 \quad m/h \quad (12.65)$$

$$q_{R,PWWF} = \frac{Q_{R,PWWF}}{A} = \frac{688}{328} = 2.10 \quad m/h \quad (12.66)$$

and the underflow fluxes at design MLSS (*i.e.*, the feed concentration) are calculated from Eq. 12.9 as:

$$J_{R,PDWF,F} = 0.87 \cdot 3.5 = 3.05 \quad kg/m^2.h \quad (12.67)$$

$$J_{R,PWWF,F} = 2.07 \cdot 3.5 = 7.25 \quad kg/m^2.h \quad (12.68)$$

The total applied flux at design MLSS under PDWF and PWWF conditions follow from eqs. 12.10, 12.61, 12.62, 12.67 and 12.68 as:

$$J_{AP,PDWF} = J_{I,PDWF,F} + J_{R,PDWF,F} = 10.0 + 3.05 = 13.05 \quad kg/m^2.h \quad (12.69)$$

$$J_{AP,PWWF} = J_{I,PWWF,F} + J_{R,PWWF,F} = 16.7 + 7.25 = 23.95 \quad kg/m^2.h \quad (12.70)$$

Assuming no solids in the clarifier effluent, the sludge concentration in the recycle stream can be calculated from Eq. 12.21 which, applied to the given PDWF and PWW conditions, results in:

$$X_{R,PDWF} = \frac{J_{AP,PDWF} \cdot A}{Q_{R,ADWF}} = \frac{13.0 \cdot 328}{938} = 15.0 \quad kg/m^3 \quad (12.71)$$

$$X_{R,PWWF} = \frac{J_{AP,PWWF} \cdot A}{Q_{R,PWWF}} = \frac{23.9 \cdot 328}{1{,}563} = 11.6 \qquad \text{kg/m}^3 \qquad (12.72)$$

7. Iterate R_{min} values to calculate variables for the Ekama D&O chart

As an alternative to using the state point diagram, the minimum recycle ratio can be determined from the Ekama Design & Operation (D&O) chart.

The SHC II line is easily drawn as a straight horizontal line representing the settling velocity at the design MLSS (= feed) concentration, $v_{s,MLSS}$ = 4.77 (from Step 2., Eq 12.57). The latter value corresponds to the overflow rate at PWWF conditions: $v_{s,MLSS} = Q_{PWWF}$ / A, see Eq. 12.58).

The SHC I line is determined by equations 12.9 and 12.10 in the main textbook for the given Vesilind parameters and the given feed concentration, respectively:

$$\frac{Q_I}{A} = \frac{v_0}{R} \cdot \frac{1+\alpha}{1-\alpha} e^{\frac{-p_{hin}(1+R) \cdot X_F \cdot (1+\alpha)}{2R}} = \frac{16.8}{R} \cdot \frac{1+\alpha}{1-\alpha} e^{\frac{-0.36(1+R) \cdot 3.5 \cdot (1+\alpha)}{2R}} \qquad \text{m/h} \qquad (12.73)$$

in which:

$$\alpha = \sqrt{1 - \frac{4R}{0.36 \cdot (1+R) \cdot 3.5}} \qquad (12.74)$$

The value of Eq. 12.73 and Eq. 12.74 are calculated for a range of increasing recycle ratio values R, until the SHC I line intersects with the SHC II line, *i.e.*, until Q_I / A = $v_{s,MLSS}$ (Figure 12.26). The minimum recycle ratio for peak wet weather conditions is thus found as $R_{min,PWWF}$ = 0.44. In Excel, this is done by using the built-in 'goal seek' function (see the spreadsheet 'Chapter 12 Design example 2.xlsx').

The safe operating zone in the Ekama D&O chart is the zone below SHC II and to the right of SHC I (the green zone in Figure 12.24). For the clarifier not to be overloaded, the overflow rate Q_I / A should be below the SHC I line in the case R < $R_{min,PWWF}$; the overflow rate Q_I/A should be lower than $v_{s,MLSS}$ in the case R > $R_{min,PWWF}$. From the SHC I line, the minimum recycle rate for PDWF conditions (*i.e.*, corresponding with Q_{PDWF} / A = 938 / 328 = 2.86) is found as $R_{min,PDWF}$ = 0.3. The values for the minimum recycle ratios at PWWF and PDWF conditions found in the Ekama D&O chart correspond with the values found in the state point diagram (Figure 12.22 and Figure 12.23, respectively).

To complete the Ekama D&O chart, the criterion boundary line is drawn based on Equation 12.11 in the textbook:

$$\frac{Q_I}{A} = \frac{v_0}{e^2 \cdot R} = \frac{16.8}{e^2 \cdot R} \qquad (12.75)$$

The criterion boundary line gives the boundary between the lower recycle ratios where a critical flux can be found (SHC I applies) and higher recycle ratios where a critical flux cannot be found (only SHC II applies).

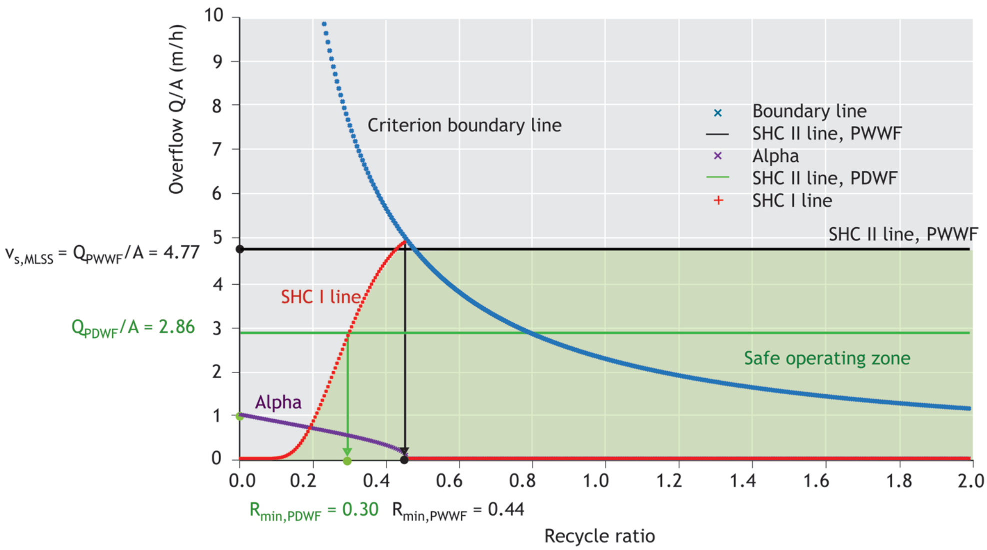


Figure 12.26 Ekama D&O chart. The green zone indicates the safe operating zone.

8. *Calculate surface area and recycle pump capacity with safety threshold*

Taking into account the safety factor F_{corr} (Table 12.4), the settler surface area (Eq. 12.58) is recalculated as:

$$A_{design,flux} = A \cdot F_{corr} = 328 \cdot 1.25 = 410 \qquad m^2 \qquad (12.76)$$

Due to practical considerations (standard design), the actual area chosen could be somewhat larger than the theoretically required (Eq. 12.26), for instance:

$$A_{design,flux} = 450 \qquad m^2 \qquad (12.77)$$

The recycle pump capacity is calculated according to the minimum recycle flow rates required at PDWF (and PWWF) conditions. Given that $Q_{R,PDWF}$ = 281 m^3/h (Eq. 12.63) and $Q_{R,PWWF}$ = 688 m^3/h (Eq. 12.64), say $Q_{R,PWWF}$ = 700 m^3/h, the decision is made to install two pumps of 350 m^3/h each. During dry weather conditions, only one pump will be operational, while during rainy weather conditions both pumps will be in use.

Taking into account the settler area including the safety factor (Eq. 12.77), some of the settler specifications need to be recalculated. A summary of the final settler design specifications is given in Table 12.5.

Empirical design

In this example, the recycle ratio for empirical design is set at R_{PDWF} = 0.6 for PDWF conditions and at R_{PWWF} = 0.4 during PWWF conditions (from Table 12.4).

The recycle pump capacities at PDWF and PWWF are thus calculated as:

$$Q_{R,PDWF} = R_{PDWF} \cdot Q_{PDWF} = 0.6 \cdot 938 = 563 \qquad m^3/h \qquad (12.78)$$

$$Q_{R,PWWF} = R_{PWWF} \cdot Q_{PWWF} = 0.4 \cdot 1{,}563 = 625 \qquad m^3/h \qquad (12.79)$$

The corresponding recycle pump capacity amounts to:

$$Q_{R,Design} = Max(Q_{R,PDWF}; Q_{R,PWWF}) = 625 \qquad m^3/h \qquad (12.80)$$

The selection of the required settler surface area is based on the envisaged maximum surface overflow rates (hydraulic loading) for average dry weather flow and peak wet weather flow conditions, which are envisaged as SOR_{ADWF}.= 1 m/h and SOR_{PWWF} = 2.5 m/h, respectively. In addition, the clarifier should not be loaded higher than 6 kg/m^2/h during average dry weather and 15 kg/m^2/h during wet weather conditions (*i.e.*, maximum solids loading specification). Each of the above four specifications will lead to a different required clarifier area, the largest of which will be selected, in this case 693 m^2 (Eq. 12.36). The calculations are provided in the design sheet in the spreadsheet 'Chapter 12 Design example 2.xlsx' (Figure 12.27). A number of additional settler specifications can be calculated and are summarized in Table 12.5.

The settler surface area based on maximum overflow rates at ADWF and PWWF are calculated as:

$$A_{design,SOR,ADWF} = \frac{Q_{ADWF}}{SOR_{ADWF}} = \frac{625}{1} = 625 \qquad m^2 \qquad (12.81)$$

$$A_{design,SOR,PWWF} = \frac{Q_{PWWF}}{SOR_{PWWF}} = \frac{1{,}563}{2.5} = 625 \qquad m^2 \qquad (12.82)$$

while the settler surface area based on the maximum solids loading at ADWF and PWWF is found as:

$$A_{design,SLR,ADWF} = X_F \cdot \frac{Q_{ADWF} + Q_{R,PDWF}}{SLR_{ADWF}} = 3.5 \cdot \frac{625 + 563}{6} = 693 \qquad m^2 \qquad (12.83)$$

$$A_{design,SLR,PWWF} = X_F \cdot \frac{Q_{PWWF} + Q_{R,PWWF}}{SLR_{PWWF}} = 3.5 \cdot \frac{1{,}563 + 625}{15} = 510 \qquad m^2 \qquad (12.84)$$

The settler surface area based on empirical design, and thus becomes:

$$A_{design,emp} = Max\left(A_{design,SOR,ADWF}, A_{design,SOR,PWWF}, A_{design,SLR,ADWF}, A_{design,SLR,PWWF}\right) = 693\ m^2 \qquad (12.85)$$

Empirical principles

Recycle ratio at PDWF	R_{PDWF}	0.6	-
Recycle ratio at PWWF	R_{PWWF}	0.4	-
		Design criteria	
Maximum overflow rate at ADWF	SOR_{ADWF}	1.0	m/h
Maximum overflow rate at PWWF	SOR_{PWWF}	2.5	m/h
Maximum solids loading rate at ADWF	SLR_{ADWF}	6.0	kg/m^2.h
Maximum solids loading rate at PWWF	SLR_{PWWF}	15.0	kg/m^2.h

Recycle pump (m^3/h)	
Recycle pump (m^3/h)	
Area required (m^2)	
	625
	625
	693
	510

Recycle pump	
563	m^3/h
625	m^3/h

Choose largest area	
693	m^2

Figure 12.27 Empirical clarifier design results from the design sheet of the 'Final Settling Design Spreadsheet'.

<u>WRC design</u>

The critical hydraulic underflow rate corresponding with the given $SSVI_{3.5}$.= 48 mg/l (Table 12.4) is calculated according to Eq. 12.12 in the main textbook, as:

$$q_{R,crit} = 1.612 - 0.00793 \cdot SSVI_{3.5} - 0.0015 \cdot \left(MAX\left(0, SSVI_{3.5} - 125\right)\right)^{1.115}$$
$$= 1.612 - 0.00793 \cdot 48 - 0.0015 \cdot \left(MAX\left(0, 48 - 125\right)\right)^{1.115} = 1.23 \qquad \text{m/h} \qquad (12.86)$$

and the required surface area is obtained from:

$$A_{design,PWWF} = X_F \cdot \frac{Q_{PWWF}}{306.86 \cdot SSVI_{3.5}^{-0.77} \cdot q_{R,crit}^{0.68} - X_F \cdot Q_{R,crit}}$$
$$= 3.5 \cdot \frac{1{,}563}{306.86 \cdot 60^{-0.77} \cdot 1.23^{0.68} - 3.5 \cdot 1.23} = 401 \qquad \text{m}^2 \qquad (12.87)$$

Taking into account a safety factor of 25 % (F_{corr} = 1.25), the surface area becomes:

$$A_{design,WRC} = A_{design,PWWF} \cdot F_{corr} = 401 \cdot 1.25 = 501 \qquad \text{m}^2 \qquad (12.88)$$

The PWWF overflow rate is then:

$$q_{PWWF} = \frac{Q_{PWWF}}{A_{design,WRC}} = \frac{1{,}563}{501} = 3.1 \qquad \text{m/h} \qquad (12.89)$$

The recycle pump capacity corresponding with the obtained values for the critical hydraulic underflow rate and the settler surface area is then calculated and, for practical purposes, rounded off as 650 m^3/h:

$$Q_R = A_{design,WRC} \cdot q_{R,crit} = 501 \cdot 1.23 = 618\ (650) \qquad \text{m}^3\text{/h} \qquad (12.90)$$

The calculations are provided in the design sheet of the spreadsheet 'Chapter 12 Design example 2.xlsx' (Figure 12.28). Additional settler specifications are summarized in Table 12.5.

WRC principles

Calculate Critical Recycle Rate	$q_{R,crit}$	1.23	m/h
Calculate Area based on $SSVI_{3.5}$ for PWWF		401	m^2
Calculate Area based on $SSVI_{3.5}$ for PDWF		241	m^2

→

Choose larger area	401	m^2
Area with safety	**501**	m^2
PWWF recycle flow	618	m^3/h
Choose Pump	650	m^3/h
PWWF overflow rate	3.1	m/h

Figure 12.28 WRC principle-based clarifier design in this example; a screenshot of the design sheet of the spreadsheet 'Chapter 12 Design example 2.xlsx'.

ATV design

The settled volume of the MLSS under the test conditions (DSV_{30}), Eq. 12.13 in the main textbook, which is calculated for this example as:

$$DSV_{30} = X_{F,DWF} \cdot DSVI = 3.5 \cdot 60 = 210 \quad ml/l \qquad (12.91)$$

The design steps below are followed:

1) The permissible overflow rate, q_O, is calculated as Eq. 12.15 in the textbook:

$$q_O = 2{,}400 \cdot DSV_{30}^{-1.34} = 2{,}400 \cdot 210^{-1.34} = 1.86 \quad m/h \qquad (12.92)$$

2) q_O must be smaller than $q_{O,max}$ = 1.6 m/h, which is not the case, so in what follows the latter value is used.

3) The settler surface area follows from the permissible overflow rate and the influent PWWF flow rate:

$$A_{design,ATV} = \frac{Q_{PWWF}}{Min\left(q_O, q_{O,max}\right)} = \frac{1{,}563}{1.6} = 977 \quad m^2 \qquad (12.93)$$

4) For practical considerations, the latter value is rounded off as:

$$A_{design,ATV} = 1{,}000 \quad m^2 \qquad (12.94)$$

5) The maximum recycle solids concentration that can be reached under ADWF and PWWF conditions is calculated according to Eq. 12.16 and Eq. 12.17 in the main textbook, respectively:

$$X_{R,ADWF} = \frac{1{,}200}{DSVI} = \frac{1{,}200}{60} = 20 \quad g/l \qquad (12.95)$$

$$X_{R,PWWF} = X_{RAS,ADWF} + 2 = 20 + 2 = 22 \quad g/l \qquad (12.96)$$

6) The necessary recycle flow is calculated from the solids mass balance over the settler (Eq. 12.18 in the main textbook), both for ADWF and PWWF, as:

$$Q_{R,ADWF} = \frac{X_F}{X_{RAS,ADWF} - X_F} \cdot Q_{ADWF} = \frac{3.5}{20 - 3.5} \cdot 625 = 133 \qquad m^3/h \qquad (12.97)$$

$$Q_{R,PWWF} = \frac{X_F}{X_{RAS,PWWF} - X_F} \cdot Q_{PWWF} = \frac{3.5}{22 - 3.5} \cdot 1{,}563 = 296 \qquad m^3/h \qquad (12.98)$$

The recycle pump capacity is rounded up, to a practical value of:

$$Q_R = 300 \qquad m^3/h \qquad (12.99)$$

for all weather conditions.

The calculations are provided in the design sheet of the spreadsheet 'Chapter 12 Design example 2.xlsx' (Figure 12.29). Additional settler specifications are summarized in Table 12.5.

ATV principles

Permissible overflow rate (depends on DSV30)	q_O	1.86	m/h
Maximum q_O	$q_{O,max}$	1.60	m/h
area based on smaller of the two above rates	A	977	m^2
Maximum RAS, ADWF	$X_{RAS,ADW}$	20	g/l
Maximum RAS, PWWF	$X_{RAS,PWW}$	22	g/l

→

Choose area	1,000	m^2
ADWF recycle flow	133	m^3/h
PWWF recycle flow	296	m^3/h
Choose pump	300	m^3/h

Figure 12.29 ATV principle-based clarifier design for this example; a screenshot from the design sheet of the spreadsheet 'Chapter 12 Design example 2.xlsx'.

STOWA design

1) The permissible overflow rate is calculated based on the DSV_{30} (Eq. 12.19 in the main textbook), as follows:

$$q_O = \frac{1}{3} + \frac{200}{DSV_{30}} = \frac{1}{3} + \frac{200}{210} = 1.86 \qquad m/h \qquad (12.100)$$

2) The sludge volume loading rate is calculated according to Eq. 12.101, taking into account eqs. 12.91 and 12.100:

$$q_{sv} = q_O \cdot DSV_{30} = 1.86 \cdot 210 = 270 \qquad l/m^2.h \qquad (12.101)$$

3) The sludge volume loading rate q_{sv} must be between 300 and 400 $l/m^2.h$, which is not the case (Eq. 12.101). As a result, its value is set to $q_{sv} = 300\ l/m^2.h$. The permissible overflow rate is recalculated by rearranging Eq. 12.101, as follows:

$$q_O = \frac{q_{sv}}{DSV_{30}} = \frac{300}{210} = 1.43 \quad \text{m/h} \quad (12.102)$$

4) The settler surface area follows from the permissible overflow rate and the influent ADWF flow rate according to Eq. 12.103:

$$A_{design,ADWF} = \frac{Q_{ADWF}}{q_O} = \frac{625}{1.43} = 438 \quad \text{m}^2 \quad (12.103)$$

5) The settler surface area based on PWWF conditions, taking into account a maximum reduction on the MLSS concentration of 30 % (corresponding with a reduction factor $f_{red} = 0.7$), results from Eq. 12.104:

$$A_{design,PWWF} = f_{red} \cdot \frac{Q_{PWWF}}{q_O} = 0.7 \cdot \frac{1,563}{1.43} = 766 \quad \text{m}^2 \quad (12.104)$$

6) The settler surface area is taken as the maximum of Eq. 12.103 and Eq. 12.104, and rounded up:

$$A_{design,STOWA} = \text{above}\,\text{Max}(A_{design,ADW}, A_{design,PWWF}) = 800\ \text{m}^2.$$

7) The recycle pump design is identical to the ATV method; the selected recycle pump has a capacity of 300 m^3/h.

The calculations are provided in the design sheet of the spreadsheet 'Chapter 12 Design example 2.xlsx' (Figure 12.30). Additional settler specifications are summarized in Table 12.5.

STOWA principles

Permissible overflow rate	q_O	1.29	m/h
Sludge volume loading	q_{sv}	270	$l/m^2.h$
minimum sludge volume loading	$q_{sv,min}$	300	$l/m^2.h$
maximum sludge volume loading	$q_{sv,max}$	400	$l/m^2.h$
Sludge volume loading used	$q_{sv,design}$	300	$l/m^2.h$
Overflow rate used	q_O	1.43	m/h
Maximum reduction due to sludge transferred at PWWF	f_{red}	0.7	-
Maximum RAS, ADWF	$X_{RAS, ADW}$	20	g/l
Maximum RAS, PWWF	$X_{RAS, PWW}$	22	g/l

Maximum area, ADWF	438	m^2
Maximum area, PWWF	766	m^2
Choose area	**800**	m^2
ADWF recycle flow	133	m^3/h
PWWF recycle flow	296	m^3/h
Choose pump	**300**	m^3/h

Figure 12.30 STOWA principle-based clarifier design; a screenshot from the design sheet of the spreadsheet 'Chapter 12 Design example 2.xlsx'.

Summary and discussion

An overview of the design specifications obtained with the different methods is given in Table 12.5. The design input indicates a sludge with good settling properties as DSVI is 60 ml/g. In addition, the settler load is in the middle range (MLSS is 3.5 kg/m^3) and the wet weather peak is not extreme. The combination of these factors results in a relatively small settler area which is indicated in the design procedures. The ATV design stands out with the conservative approach for the maximum overflow rate of 1.6 m/h which results in a higher settler area.

Table 12.5 Summary of the final settler design detailed calculations. The calculations are provided in the summary sheet of the spreadsheet 'Chapter 12 Design example 2.xlsx'.

Parameter	Unit	Flux theory	Empirical	WRC	ATV	STOWA
Area, A	m^2	**450**	**693**	**501**	**1,000**	**800**
At ADWF						
Overflow rate, Q_{ADWF}	m^3/h			**625**		
Surface overflow rate, SOR_{ADWF}	m/h	1.39	0.90	1.25	0.63	0.78
Recycle flow rate, $Q_{R,ADWF}$	m^3/h	350	563	**650**	**300**	**300**
Hydraulic underflow rate, $q_{R,ADWF}$		0.78	0.81	**1.23**	0.30	0.38
Recycle ratio, R	-	0.56	0.90	1.04	0.48	0.48
RAS concentration, $X_{R,ADWF}$ [1)]	kg/m^3	9.75	7.39	6.87	10.79	10.79
Solids loading rate, SLR_{ADWF} [2)]	$kg/m^2.h$	7.58	**6**	8.90	3.24	4.05
At PDWF						
Overflow rate, Q_{PDWF}	m^3/h			**938**		
Surface overflow rate, SOR_{PDWF}	m/h	2.08	1.35	1.87	0.94	1.17
Recycle flow rate, $Q_{R,PDWF}$	m3/h	**350**	**563**	**650**	**300**	**300**
Hydraulic underflow rate, $q_{R,PDWF}$	m/h	0.78	0.81	**1.23**	0.30	0.38
Recycle ratio, $R_{min,PDWF}$	-	**0.30**	**0.6**	0.69	0.32	0.32
RAS concentration, $X_{R,PDWF}$ [1)]	kg/m^3	12.88	9.33	8.55	14.44	14.44
Solids loading rate, SLR_{PDWF} [2)]	$kg/m^2.h$	10.01	7.58	11.08	4.33	5.41
At PWWF						
Overflow rate, Q_{PWWF}	m^3/h			**1,563**		
Surface overflow rate, SOR_{PWWF}	m/h	3.47	2.26	**3.1**	1.56	1.95
Recycle flow rate, $Q_{R,PWWF}$	m^3/h	**700**	**625**	**650**	**300**	**300**
Hydraulic underflow rate, $q_{R,PWWF}$	m/h	1.56	0.90	**1.23**	0.30	0.38
Recycle ratio, $R_{min,PWWF}$	-	**0.44**	**0.4**	0.42	0.19	0.19
RAS concentration, $X_{R,PWWF}$ [1)]	kg/m^3	11.31	12.25	11.91	21.73	21.73
Solids loading rate, SLR_{PWWF} [2)]	$kg/m^2.h$	17.60	11.05	15.44	6.52	8.15

1) See Eq. 12.55
2) See Eq. 12.56

12.4 EXERCISES

Final clarifier design principles (exercises 12.4.1-12.4.4)

Exercise 12.4.1

List the functions of a secondary settler tank.

Exercise 12.4.2

List the three main types of (gravitational) final settlers. What are the typical add-ons to improve their performance?

Exercise 12.4.3

Which considerations determine the settler type selection?

Exercise 12.4.4

What kind of operational problems can occur with inadequate settler implementation (design and/or operation)?

Sludge settleability and design measurements (exercises 12.4.5-12.4.8)

Exercise 12.4.5

What is the purpose of SVI tests? What are typical values? What are the main advantage and the main drawback of this method? How can the latter be overcome?

Exercise 12.4.6

What is the Zone Settling Velocity (ZSV)? Draw three ZSV test charts for an ideal settling sludge for low, medium, and high sludge concentrations.

Exercise 12.4.7

Identify the phases and the resulting zones of the ZSV test.

Exercise 12.4.8

Describe the Vesilind function.

Flux theory (exercises 12.4.9-12.4.10)

Exercise 12.4.9

Draw a typical total flux curve and discuss its constituents. Show the trend of bulk flux and gravity flux as well.

Exercise 12.4.10

Explain what the critical recycle flow rate and the lowest limiting concentration are.

State point analysis (exercises 12.4.11-12.4.13)

Exercise 12.4.11

What is state point analysis (SPA) and what are the associated considerations? List the variables used to draw the state point diagram, which forms the basis for SPA.

Exercise 12.4.12

Define Solids Handling Criterion (SHC) I and II types and their 3 conditions.

Exercise 12.4.13
What is the design principle for final settlers in terms of SHC I and II?

Ekama D&O chart (exercises 12.4.14-12.4.16)
Exercise 12.4.14
What is the Ekama D&O chart and how does it evaluate the Sludge Handling Criteria SHC I and SHC II?

Exercise 12.4.15
Explain the meaning of the criterion boundary line.

Exercise 12.4.16
How is the minimum recycle ratio determined based on the Ekama D&O chart?

Extreme manifestation of sludge bulking in a secondary settler (photo: D. Brdjanovic).

ANNEX 1: SOLUTIONS TO EXCERSISES

Final clarifier design principles (solutions 12.4.1-12.4.4)

Solution 12.4.1

Secondary settling tanks have three distinct functions:

- clarification, providing a clear effluent with suspended solids removal up to 99.9 %,
- thickening of sludge, in the blanket, to provide a concentrated recycle stream and thus lower the RAS flow,
- sludge storage, usually on a temporary basis, to cope with overload events.

Solution 12.4.2

The three main different types of (gravitational) final settlers are:

- circular clarifiers with a radial flow pattern,
- rectangular clarifier with a horizontal flow pattern,
- deep clarifiers with a vertical flow pattern.

Their operation can be improved by:

- a flocculation well, reducing the effluent solids concentration by promoting flocculation,
- scum baffles or other scum removal mechanisms,
- baffles for flow diversion and energy dissipation,
- lamellae, *i.e.*, slanted tubular or plate structures, to reduce the settling time.

Solution 12.4.3

The settler type selection is determined by the available space, cost limitation, plant loading, and performance.

Solution 12.4.4

The following are typical operational problems with final settlers:

- Shallow tanks (less than 2.5-3 m side water depth) are susceptible to solids overload, leading to scouring (loss of solids) from the sludge blanket or gross clarifier failure due to the sludge blanket reaching the effluent weirs. Maintaining a low sludge blanket level via higher recycle rates (RAS) is therefore important in shallow clarifiers.
- Uneven flow distribution between parallel clarifiers can cause overload in some final settlers.
- Incorrectly levelled weirs result in uneven weir loading, thus creating local upwelling from the blanket.
- Wind exposure can affect the flow circulation pattern and result in uneven weir loading.
- Sudden temperature change may cause an unexpected layer inversion, resulting in flotation of the sludge blanket. Freezing in cold climates may cause ice build-up.
- Recycle problems caused by suction pipe design.
- Algae on weirs can result in uneven weir load.
- Anaerobic clumps, which are floating due to methane gas generation, resulting from misaligned sludge removal.
- Birds can add extra nutrient load to the effluent.
- Bulking sludge, due to bad sludge settling properties (filaments).
- Rising sludge, due to nitrogen gas bubbles produced by denitrification in the clarifier.

Sludge settleability and design measurements (solutions 12.4.5-12.4.8)

Solution 12.4.5

The Sludge Volume Index (SVI) is a common measure for the settleability of sludge. It describes the volume of 1 g sludge (MLSS) after 30 minutes of settling. It is measured by taking 1 litre of sludge sample in a graduated cylinder, and after initial mixing, leaving it to settle for 30 minutes, after which the sludge volume is read. The sludge concentration is measured from a MLSS test. Well-settling sludge has a typical SVI value of 50 ml/g; an SVI value of 150 ml/g or higher indicates potential filamentous bulking.

The main advantage of the SVI test is that it is easy to perform (simplicity). The main drawback is that the results may be influenced by the type of sludge and by the MLSS concentration: sludges which settle fast or tests done at lower MLSS concentrations are mostly finished settling in 30 minutes, so the SVI is then an indicator of sludge compactability rather than settleability.

The results of the SVI test are made more standard by:

- diluting the sludge sample so that the settled volume after 30 minutes is 150-250 ml, *i.e*., diluted SVI test = DSVI test.
- diluting the MLSS to a concentration of 3.5 gMLSS/litre and slowly stirring the settling vessel, *i.e.,* stirred SVI test performed at 3.5 gMLSS/litre = $SSVI_{3,5}$.

Solution 12.4.6

The Zone Settling Velocity (ZSV) is the velocity with which the sludge settles, more specifically the subsidence rate of the sludge blanket (solid/liquid interface). In a ZSV test, the ZSV is recorded in time at a certain MLSS concentration.

Three ZSV test charts are given below, for low, medium, and high sludge concentrations (1,000, 4,000 and 8,000 gMLSS/m^3, respectively). At low MLSS the sludge quickly settles, and it starts limiting the settling velocity, while at high MLSS the sludge settles slowly and steadily.

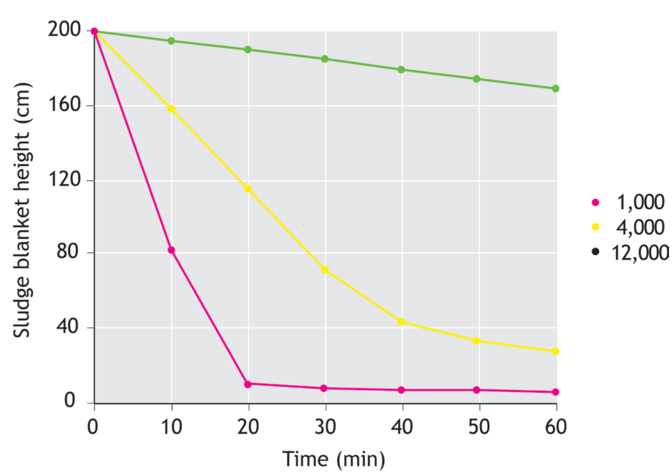


Figure 12.31 ZSV test results for varying MLSS concentrations (1,000, 4,000 and 8,000 gMLSS/m^3).

Solution 12.4.7

The ZSV test consists of the following three phases, which are reflected in three distinct zones in the obtained ZSV test curves (see Figure 12.31):

(1) the lag phase (1-2 min),
(2) the linear settling phase (3 to 30 min); a slope gives the ZSV of the sludge at the concentration with which the column was filled,
(3) an onset compression phase from the bottom, characterized by a gradual decrease in settling velocity.

Four zones can be identified in the vessel during the test: clear supernatant (discrete settling), MLSS (zone settling), a transitional zone, and sludge (a compression zone).

Solution 12.4.8

The Vesilind function describes the relation between the zone settling velocity (ZSV) and the MLSS concentration in the tank, reflecting that a higher MLSS results in a lower zone settling velocity $v_s = v_0 \cdot e^{-p_{hin} \cdot X}$ here v_s is the zone settling velocity (m/h), X denotes the MLSS concentration (g/l or kg/m^3), v_0 is the initial settling velocity (m/h), and p_{hin} is the hindered settling parameter of the Vesilind function (m^3/kg).

Flux theory (solutions 12.4.9-12.4.10)

Solution 12.4.9

The total flux (kg/m^2.h) consists of the sum of the gravity flux (also termed settling flux) and the bulk flux. The gravity flux (J_S, in kg/m^2.h) is the mass of solids transported under the influence of gravity-induced settling, $J_S = v_s \cdot X$, with v_s the zone settling velocity (m/h) at a given MLSS concentration (X, in kg/m^3). The gravity flux curve expresses the gravity flux as a function of the MLSS concentration. It first increases with increasing MLSS concentration, because of higher X, and then decreases, because of reduced settling velocity v_s; the gravity flux has a maximum usually at X = 2-3 kg/m^3 (Figure 12.32, left side).

The bulk flux (J_B, in kg/m^2.h) is the flux associated with the downward flow of the solids caused by the sludge recycle, $J_B = (Q_R / A) \cdot X$, for a given recycle flow rate Q_R (m^3/h) and settler area A (m^2). The bulk flux linearly increases with increasing MLSS concentration (Figure 12.32, right side, red curve).

The total flux curve is obtained as the sum of the gravity flux curve and the bulk flux curve and is displayed in Figure 12.32 (right side, blue curve).

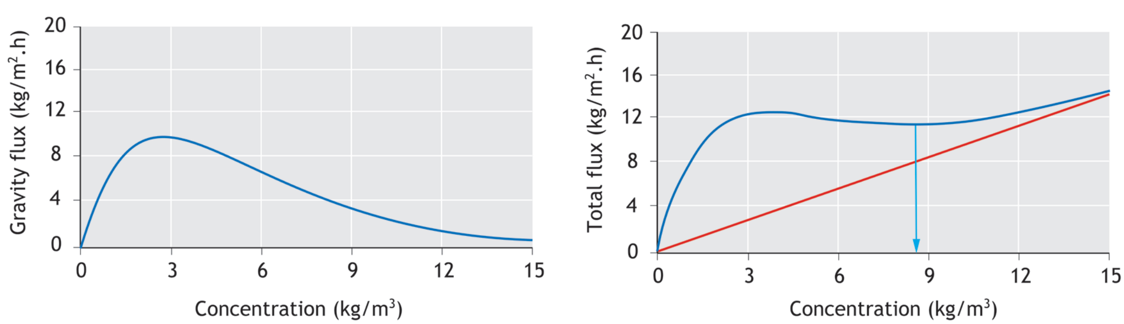


Figure 12.32 Gravity (settling) flux curve (left side), bulk flux curve (right side, red) and total flux curve (right side, blue).

Solution 12.4.10

The total flux curve displayed in Figure 12.32 has a local minimum around 8.5 kg/m^3 MLSS, which is termed the limiting concentration of the clarifier at the given underflow rate. By increasing the underflow rate, the bulk flux and total flux increase for all the MLSS concentrations (the curves rotating counter clockwise). The underflow rate where the local minimum shifts into an inflexion point is called the critical recycle flow rate; the corresponding limiting MLSS concentration is termed the lowest limiting concentration.

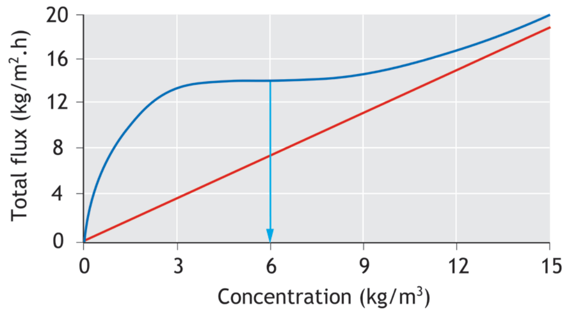


Figure 12.33 Total flux curve at critical recycle flow; determination of lowest limiting concentration.

State point analysis (solutions 12.4.11-12.4.13)

Solution 12.4.11

State point analysis is a graphical way of determining the operating conditions of the clarifier, based on its solids mass balances. The SPA method assumes steady-state conditions, it considers only the vertical dimension, it does not take into account compression, and it neglects effluent solids. The state point diagram represents various fluxes in a clarifier (the Y axis) as a function of solids concentration (the X axis). It is based on the gravity (settling) flux, on which the overflow line, the underflow line, and the feed (concentration) line are superimposed.

Solution 12.4.12

SHC I evaluates whether the applied flux to the clarifier (*i.e.*, the mass of solids applied per unit settler area) is lower than the minimum total flux (the total flux being the sum of the gravity and bulk fluxes), which is required for the clarifier not to be overloaded. In the state point diagram, SHC I is evaluated by the position of the underflow line relative to the descending limb of the gravity curve:

- SHC I is not met if the underflow line crosses the descending limb of the gravity flux curve (Figure 12.6 and Figure 12.22).
- SHC I is critical if the underflow line is tangential to the descending limb of the gravity flux curve (Figure 12.10 and Figure 12.24).
- SHC I is satisfied if the underflow line is below the descending limb of the gravity flux curve (Figure 12.8 and Figure 12.20).

SHC II requires the applied flux to be lower than the gravity flux at feed concentration. In other words, the applied overflow rate must be less than the zone settling velocity of sludge at the feed concentration. It is determined by the position of the state point relative to the gravity curve: SHC II is not met if the state point is above the gravity flux curve, SHC II is critical if the state point is on the gravity flux curve, while SHC II is satisfied if the state point is below the gravity curve.

All the nine potential combinations with SHC I and SHC II that are fulfilled, critically fulfilled, or not fulfilled, are depicted in Figure 12.26 of the main textbook.

Solution 12.4.13

The design principle is to define the clarifier surface area (A) and the recycle ratio (Q_R) to meet the SHC I and SHC II under any expected MLSS concentration and peak wet weather flow (PWWF) combination. It can be noted that SHC II is only determined by A, while SHC I is influenced by both A and Q_R. Consequently, SHC II is used to determine the minimum setter area, after which SHC I is applied to determine the minimum recycle ratio.

Ekama D&O chart (solutions 12.4.14-12.4.16)

Solution 12.4.14

The Ekama D&O chart reorganizes the information available in the flux theory and the state point diagram. It plots the overflow rate (the Y axis) against the recycle ratio (the X axis).

SHC II is judged based on a straight horizontal line representing the settling velocity at the feed concentration. Above this line, SHC II is not satisfied; the clarifier is overloaded. Below this line, *i.e.* under under-loaded conditions, SHC I remains to be evaluated.

The SHC I line describes the maximum allowable solids flux in terms of the recycle ratio. It defines a series of critical loading conditions related to the minimum flux, which are equivalent to the recycle line being tangential to the gravity flux in the state point diagram (during state point analysis).

Solution 12.4.15

Above a certain recycle ratio (R) it is not possible to determine a critical concentration and minimum solids flux. The criterion boundary line represents the boundary between lower recycle ratios where a critical flux can be found and higher recycle ratios where it cannot be found.

Solution 12.4.16

The minimum recycle ratio can be obtained from the Ekama D&O chart by reading the x value of the chart at the intersection of the SHC II and SHC I lines. For recycle ratios lower than this value, the settler is overloaded because SHC II or both SHC I and SHC II have not been met.

REFERENCES

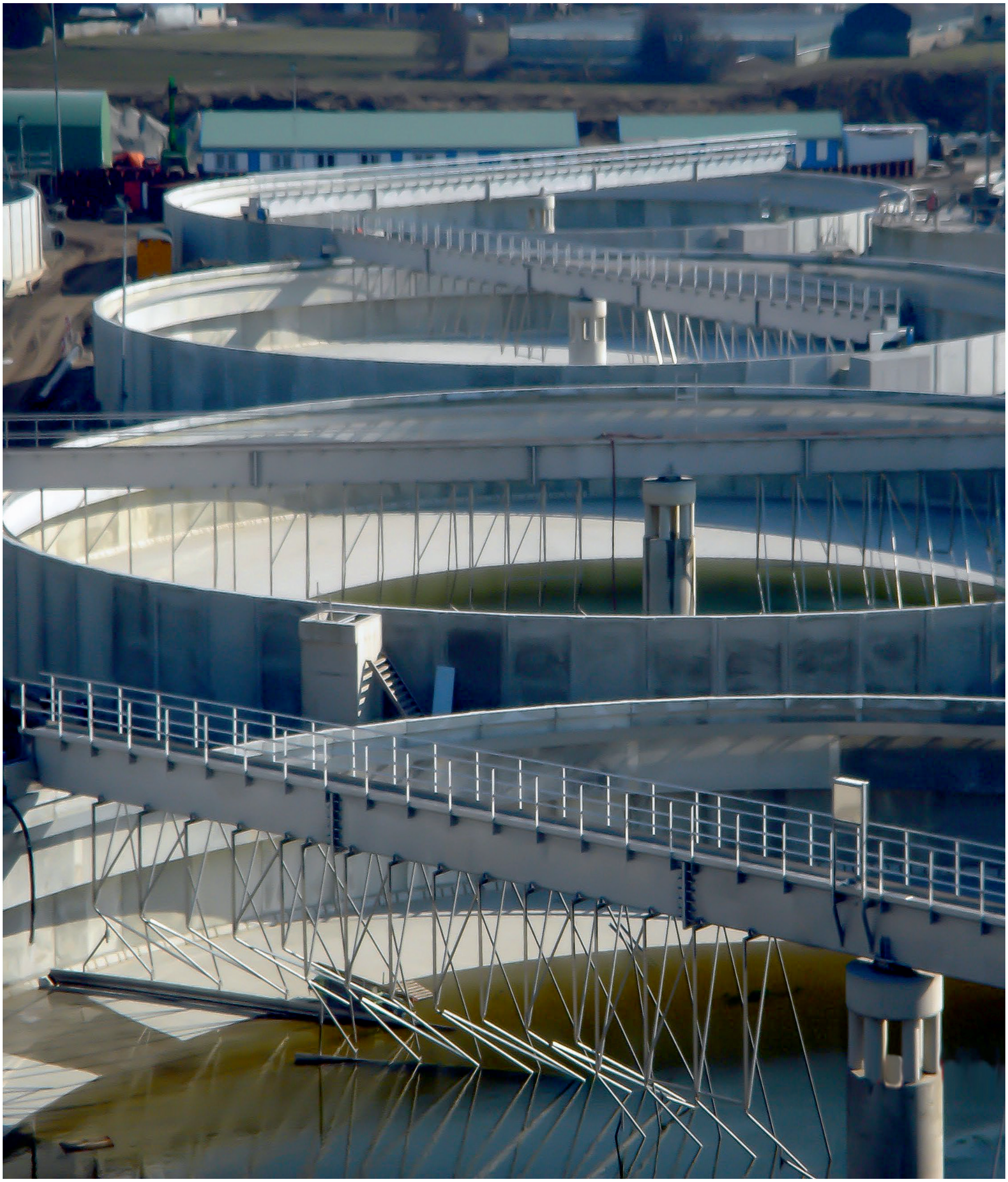
Chen G.H., Van Loosdrecht M.C.M., Ekama G.A. and Brdjanovic D. (eds.) (2020). Biological Wastewater Treatment: Principles, Modelling and Design. ISBN: 9781789060355. IWA publishing, London, UK.

Ekama G.A., Barnard J.L., Günthert F.W., Krebs P., McCorquodale J.A., Parker D.S. and Wahlberg E.J. (1997). Secondary Settling Tanks: Theory, Modeling, Design and Operation. *IAWQ Scientific and Technical Reports* #6, IAWQ London.

NOMENCLATURE

Symbol	Description	Unit
A	Area of the settler	m^2
a	SHC I line determining parameter	-
DSV_{30}	Settled volume of MLSS under test conditions	ml/l
F_{corr}	Safety factor on area	-
f_{red}	Maximum reduction due to sludge transferred at PWWF	-
G	Velocity gradient	1/s
J_{AP}	Total applied flux	$kg/m^2.h$
J_B	Bulk flux	$kg/m^2.h$
J_I	Overflow rate flux	$kg/m^2.h$
$J_{I,F}$	Limiting flux, corresponding to X_L	$kg/m^2.h$
J_S	Gravity flux	$kg/m^2.h$
J_R	Underflow rate flux	$kg/m^2.h$
$J_{R,F}$	Underflow rate flux at feed MLSS	$kg/m^2.h$
PF_{DW}	Diurnal peaking factor	-
PF_{WW}	Storm peak factor	-
p_{hin}	Hindered settling parameter	l/g or m^3/kg
Q_{ADWF}	Average dry weather flow rate	m^3/h
q_I	Hydraulic loading or overflow rate	m/h
Q_I	Influent flow	m^3/h
q_o	Permissible overflow rate	m/h
$Q_{o,max}$	Maximum overflow rate	m/h
Q_{PDWF}	Peak dry weather flow rate	m^3/h
Q_{PWWF}	Peak wet weather flow rate	m^3/h
Q_R	Recycle flow	m^3/h
q_R	Hydraulic underflow rate	m/h
$q_{R,crit}$	Critical underflow	m/h
qsv	Sludge volume loading rate	$l/m^2.h$
$q_{sv,min}$	Minimum sludge volume loading	$l/m^2.h$
$q_{sv,max}$	Maximum sludge volume loading	$l/m^2.h$
R	Recycle ratio (Q_R/Q_I)	-
R_{init}	Initial recycle ratio	-
R_{min}	Minimum recycle rate at PDWF	
SOR	Surface overflow rate	m/h
SLR	Solids loading rate	$kg/m^2.h$
v_o	Initial settling velocity	m/h
v_s	Settling velocity	m/h
x	MLSS concentration in the various ZSV tests	g/l or kg/m^3
X	Solids concentration	kg/m^3
X_F	Feed concentration	kg/m^3
X_L	Limiting concentration	kg/m^3
X_R	Recycle concentration	kg/m^3

Abbreviation	Description
ADWF	Average dry weather flow
DSVI	Diluted sludge volume index
DWA	Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall (German organization for waste management, sewage and waste)
DWF	Dry weather flow
MLSS	Mixed liquor suspended solids
PFDW	Peak dry weather flow
PWWF	Peak wet weather flow
RAS	Return activated solids
SHC	Solids Handling Criteria
SPA	State Point Analysis
SPD	State Point Diagram
$SSVI_{3.5}$	Stirred sludge volume index test performed at 3.5 g/l MLSS concentration
STOWA	Stichting Toegepast Onderzoek Waterbeheer (Dutch Foundation for Applied Water Research)
SVI	Sludge volume index
SZSV	Stirred zone settling velocity
ZSV	Zone settling velocity



Wastewater treatment infrastructure is best visible during (re)construction of a plant - settling tanks at WWTP Harnaschpolder, Den Hoorn, The Netherlands (photo: Water Board Delfland).