## 6.3.4 Applicability of the optimised settler design procedure

Several criteria are used in practice for the design of final settlers:

- Hydraulic loading rate ($m.h^{-1}$);
- Solids loading rate (kg $TSS.m^{-2}.h^{-1}$);
- Sludge volume loading rate ($litre.m^{-2}.h^{-1}$);
- Weir overflow rate ($m^3.m^{-1}.h^{-1}$).

Either based on a modelling approach of on empirical design guidelines, maximum values for one or more of the criteria above are recommended. In this section some of the most widely applied methods are briefly reviewed and compared to the solids flux design method presented in this book.

### 6.3.4.1 US EPA design guidelines

The design guidelines as formulated by the US EPA (1975) can be summarised as:

- Average superficial loading rate $T_s$ between 0.68 and 1.36 $m.h^{-1}$ (at average $Q_i$);
- Peak superficial loading rate $T_s$ between 1.7 and 2.04 $m.h^{-1}$ (at peak $Q_i$);
- Average solids loading rate $F_{sol}$ between 4.08 and 6.08 kg $TSS.m^{-2}.h^{-1}$;
- Peak solids loading rate is 10.17 kg $TSS.m^{-2}.h^{-1}$;
- Side water depth between 3.66 and 4.37 m;
- Weir loading rate < 10.35 $m^3.m^{-1}.h^{-1}$ for small clarifiers and < 15.52 $m^3.m^{-1}.h^{-1}$ for large clarifiers.

If compliance to all criteria is not possible, the designer will have to prioritise them. It can be observed that the settling characteristics of the sludge do not affect the design of the settler. Although inadequate, these guidelines are still frequently applied as they are very simple to use.

### 6.3.4.2 WRC and modified WRC design guidelines

The WRC design method is based on the solids flux theory and adapted to the conditions and sludge characteristics prevailing in the UK. White (1975) correlated the $SSVI_{3,5}$ index to the values of the settling constants and obtained the following empirical formula to determine the maximum allowable solids loading rate:

$$\begin{aligned} F_m &= X_t \cdot (T_s + u) \\ &= 8.85 \cdot (100/I_{ssv})^{0.77} \cdot u^{0.68} \end{aligned} \tag{6.40a}$$

Where:

$F_m$ = maximum solids flux (kg $TSS.m^{-2}.h^{-1}$)
$T_s$ = hydraulic overflow rate (= $Q_i/A_d$ in $m.h^{-1}$)
$u$ = underflow rate or downward velocity in the settler (= $s \cdot Q_i/A_d$ in $m.h^{-1}$)
$I_{ssv}$ = $SSVI_{3,5}$ ($ml.g^{-1}$ TSS)

Ekama et al modified the WRC design procedure (Ekama et al, 1986; Ekama et al, 1997) and noted that Eq. (6.40a) was only valid up to a certain critical value of the underflow rate u.

Again using $I_{ssv}$, the following empirical formulas were defined to determine this critical underflow rate:

$u = 1.612 - 0.00793 \cdot I_{ssv}$ for $I_{ssv} < 125$ ml.g$^{-1}$ TSS and (6.40b)

$u = 1.612 - 0.00793 \cdot I_{ssv} + 0.0015 \cdot (I_{ssv} - 125)$ for $I_{ssv} > 125$ ml.g$^{-1}$ TSS (6.40c)

### 6.3.4.3 STORA design guidelines

According to the original Dutch STORA guidelines of 1981 (STORA, 1981 and Stofkoper et al, 1982), design is based on the application of a maximum sludge volume loading rate. This sludge volume loading rate $T_{vxm}$ is defined as $v_x/A_d = X_t \cdot I_{dsv}/A_d$ (l.m$^{-2}$.h$^{-1}$). The design procedure was based on a extensive evaluation of full-scale final settlers, where the mixed liquor flow to the settler was increased until failure was observed. The maximum solids loading rate $T_{vxm}$ is a function of the sludge volume $v_x$. Using the appropriate value of $T_{vxm}$, an equivalent hydraulic overflow rate $T_{sm}$ can be calculated:

$T_{sm} = 300/v_x$ for $200 < v_x < 300$ l.m$^{-3}$ (6.40d)

$T_{sm} = {}^1/_3 + 200/v_x$ for $300 < v_x < 600$ l.m$^{-3}$ (6.40e)

$T_{sm} = 400/v_x$ for $v_x > 600$ l.m$^{-3}$ (6.40f)

Eqs (6.40 d to f) are valid for $X > 2$ g.l$^{-1}$ or $v_x > 200$ ml.l$^{-1}$, whichever is limiting. An important difference to the solids flux procedure is that the design of the final settler is based on the maximum sustained peak influent flow rate (e.g. rainwater flow conditions) instead of the average influent flow rate and that the value of X is assumed to decrease from its original value $X_t$ as part of the sludge mass is transferred to the final settler.

In a recent research project (STOWA, 2002), it was established that for 11 full-scale settlers the value of $T_{vxm}$ varied between 250 and 500 l.m$^2$.h$^{-1}$. The original guidelines from 1981 are still widely used in the Netherlands.

### 6.3.4.4 ATV design guidelines

The German ATV design procedure from 1976 precedes the STORA guideline but is similar to the STORA method in many aspects. Most importantly, the surface area of the final settler is defined by the maximum sludge volume loading rate. In the case of the ATV the maximum value of $T_{vxm}$ is approximately 400 l.m$^{-2}$.h$^{-1}$ for $v_x = 200$ ml.l$^{-1}$ and decreases slowly to a value of 200 l.m$^{-2}$.h$^{-1}$ for $v_x = 1000$ ml.l$^{-1}$. The range of $T_{vxm}$ values corresponds to a maximum concentration of 30 mg TSS.l$^{-1}$ in the effluent as observed in full-scale settlers. Multiplying the sludge volume loading rate $T_{vxm}$ with the sludge volume $v_x$, one calculates the allowed maximum hydraulic loading rate $T_{sm}$:

$T_{sm} = 2400/(v_x)^{1.34}$ (6.40g)

Similar to the STORA guideline, Eq. (6.40g) is valid for $X > 2.0$ g.l$^{-1}$ or $v_x > 200$ ml.l$^{-1}$ and sizing is based on the peak sustained rainwater flow. The main distinguishing feature from the STORA guidelines is that the depth of the settler is now an explicit design criterion: increasing the depth allows a higher proportion of the sludge mass to be stored in the final settler and thus reduces the sludge volume loading rate during peak flow. The ATV procedure therefore allows a trade-off to be made by the designer between required settler surface area and settler depth.

In 1991 the ATV guideline was revised. The main changes were that a higher sludge volume loading rate was allowed ($T_{vx} < 450$ l.m$^{-2}$.h$^{-1}$) and that settler depth was increased. The latter resulted from application of stricter effluent limits ($X_{te} < 20$ mg TSS.l$^{-1}$). The overall result was a slight increase in calculated settler volume compared to the ATV 1976 guidelines.

### 6.3.4.5 Comparison of solids flux with other design methods

When the empiric relationships of $T_{sm}$ as functions of $X_t$ are compared to the theoretical model presented in this chapter (Eqs. 6.27 and 6.29), it can be noted that the latter explicitly recognises the influence of:

- Sludge concentration;
- Sludge settleability, characterised by the constants k and $v_0$ (or $I_{ssv}$);
- The recirculation factor when it is of relevance (i.e. in the case of thickening).

The criteria of ATV and STORA also seek to quantify the influence of sludge concentration and settleability, but not of the recirculation factor. On the other hand, the ATV explicitly recognises the influence of the settler depth as a design variable. Another important difference is that the design of ATV and STORA is based on sustained peak flow, while the design according to the flux theory is based on the average influent flow.

The depth of settlers designed according to the solids flux theory is often considerably deeper than those selected according to the ATV and especially the STORA design, while the recirculation rate will also be higher. The assumption that this depth is sufficient to handle a sustained peak flow situation should be checked using the static point procedure that will be outlined in Section 6.4.

Finally, the EPA design criteria are surprisingly inadequate: they do not recognise any of the three basic factors that influence sludge settling. One should keep in mind that the STORA and ATV guidelines are empiric measures and based on observations in a single country: i.e. in The Netherlands and Germany respectively. As a result, physical design- or site characteristics, which might be country specific, are implicitly included in the design procedure.

For example the STORA guideline from 1981 was based on a set of 21 full-scale settlers with the following characteristics:

- Settler diameter > 30 m, with a sidewall depth between 1.5 – 2.5 m and a bottom inclination of 0.08 m.m$^{-1}$;
- Circular, conical settler equipped with a bottom scraper. Mixed liquor enters in a centre flocculation well (no deflection baffle) and effluent is discharged over a single peripheral effluent weir;
- The ratio between rainwater and dry weather flow in The Netherlands is quite high at typical values between 2 and 3;
- No nitrogen removal in the activated sludge process;
- High $I_{dsv}$ values (avg. 140 - 190 ml.g$^{-1}$ TSS) as sludge bulking control measures (such as a selector) had not yet been implemented.

Thus a certain precaution is required when generalising these empiric guidelines. This disadvantage does not apply to the solids flux theory, which is based on sludge characteristics and in principle is independent of settler characteristics. In the method presented in the previous section for the optimised design of the system consisting of an aeration tank and a final settler, it is assumed that Vesilind's equation is valid.

The experimental results of many researchers justify this assumption, but the practical applicability of the method depends fundamentally on the availability of the values of the two Vesilind constants: k and $v_0$. The experimental results presented in Section 6.2 show that the values of the constants can be estimated from the stirred sludge volume index:

$k = 0.16 + 0.003 \cdot I_{ssv}$ and $v_0 = 16 - 0.1 \cdot I_{ssv}$ (6.9c and 6.9d)

Where $I_{ssv} = (25 + 25 \cdot f_{av} + 5 \cdot X_t)$ (6.9a)

It should be considered that these data were obtained using sludge generated from raw sewage and that the values of the constants may be quite different for industrial waste waters. Even in the case of sewage from one source, there were large fluctuations in the data. The $I_{ssv}$ values had a standard deviation of 27 percent for sludge with a high active sludge fraction ($f_{av} = 0.76$) and 10 percent for sludge with a low active sludge fraction ($f_{av} < 0.16$). Starting from the observations above, three situations can be distinguished to characterise sludge settleability:

**(a) Good settleability**

This situation is characterised by an $I_{ssv}$ value corresponding to sludge with a low active fraction ($f_{av} < 0.3$). Using Eq.(6.9a) one has:

$I_{ssv} = 25 + 25 \cdot 0.3 + 5 \cdot 3.5 = 50$ ml.g$^{-1}$ hence $k = 0.31$ l.g$^{-1}$ and $v_0 = 11$ m.h$^{-1}$

**(b) Medium settleability**

This situation is characterised by an $I_{ssv}$ corresponding to sludge with a high active fraction ($f_{av} = 0.9$). Using again Eq. (6.9a):

$I_{ssv} = 25 + 25 \cdot 0.9 + 5 \cdot 3.5 = 65$ ml.g$^{-1}$ hence $k = 0.36$ l.g$^{-1}$ and $v_0 = 9.5$ m.h$^{-1}$

**(c) Poor settleability**

To characterise this situation an $I_{ssv}$ of 100 ml.g$^{-1}$ is adopted. This value is justified by the following reasoning: the average $I_{ssv}$ value for sludge with a high active sludge fraction is 65 ml.g$^{1}$ and has a standard deviation of 27 percent or $0.27 \cdot 65 = 17.5$ ml.g$^{-1}$.

Statistically, 95 percent of the $I_{ssv}$ will have a value below the average plus approximately two times the standard deviation: $65 + 2 \cdot 17.5 = 100$ ml.g$^{-1}$. Hence in 95 percent of all cases the $I_{ssv}$ for sludge with a high active fraction will be less than 100 ml.g$^{-1}$. In only 5 percent of the cases the sludge will have an $I_{ssv}$ above 100 ml.g$^{-1}$, so that the qualification "poor" is justified. For $I_{ssv} = 100$ ml.g$^{-1}$, one has $k = 0.46$ l.g$^{-1}$ and $v_0 = 6$ m.h$^{-1}$. It may be noted that several authors (Smollen and Ekama, 1984) consider an $I_{ssv}$ of 100 ml.g$^{-1}$ as the maximum permissible value for "normal" sludge. Sludges with a larger $I_{ssv}$ value are labelled filamentous, with atypical settling characteristics (bulking sludge).

For each of the situations characterising settling: (a) good, (b) medium, and (c) poor, the superficial loading rate can be determined as a function of the sludge concentration, using the solids flux theory explained in Section 6.3.1, especially (Eqs. 6.27 and 6.29). Using the results obtained by Stofkoper et al (1982) (Eq. 6.3) or by Catunda et al (1993) for sludge with a high active fraction one has $I_{dsv} = 1.5 \cdot I_{ssv}$. Figs. 6.12 a, b and c show the superficial loading rate as a function of the sludge concentration for a safety factor $s_f = 2$. Furthermore it is assumed that the critical recirculation factor is applied in the design procedure (clarification is limiting).

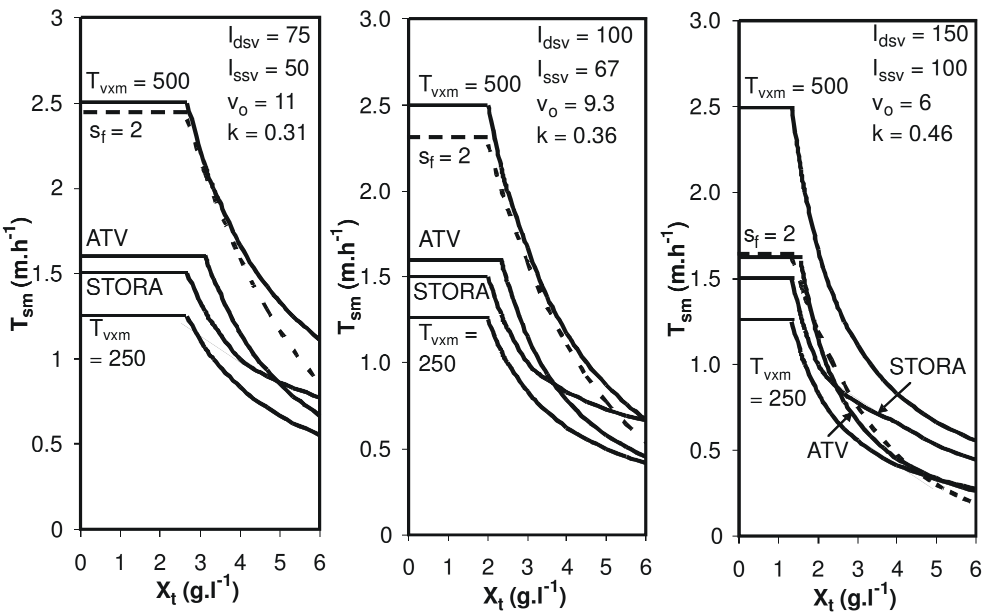

**Figure 6.12 Theoretical $T_{sm}$ values as a function of good, medium and poor settleability (for $s_f = 2$; as compared to empiric values from the ATV (1976), STORA (1981) and the experimentally determined value ranges indicated by the STOWA 2002 results ($250 < T_{vxm} < 500$ l.m$^{-2}$.h$^{-1}$)**

The applicability of the presented solids flux design method can now be evaluated by comparing the calculated maximum hydraulic overflow rate $T_{sm}$ with the results obtained from the design criteria developed by several research institutions, discussed in the previous sections: i.e. the ATV guidelines (1976) or the STORA guidelines (1981).

Furthermore, in Fig. 6.12 the STOWA results from 2002 are indicated: the upper curve corresponds to $T_{vx} = 500$ l.m$^{-2}$.h$^{-1}$, while the lower curve corresponds to $T_{vx} = 250$ l.m$^{-2}$.h$^{-1}$. The $T_{sm}$ curves shown in Fig. 6.12 should be interpreted as the maximum hydraulic loading to the settler at equilibrium: i.e. when the applied solids loading rate to the settler is equal to the solids removal capacity.

When Fig. 6.12 is analysed, it can be observed that there is a close correlation between the theoretical values of $T_{sm}$ derived in this chapter and the empiric values observed in full scale installations over the complete range of practical interest where the empiric curves are valid ($200 < v_x < 600$ l.m$^{-3}$). This close correlation is observed for poor, fair and well settling sludges. From Fig. 6.12 it is confirmed that $s_f = 2$ leads to a good correlation between empirical and theoretical results.

Having established that Eqs. (6.27 and 6.29) form an adequate basis for settler design and optimisation, it remains to be decided which values for $I_{ssv}$, $v_0$, k and $s_f$ are to be adopted. For conservative design, assuring proper settler performance when the sludge characteristics are "normal" (i.e. not filamentous), the (adapted) characteristics for poor settling sludge may be used: $k = 0.46$ l.g$^{-1}$ and $v_0 = 6$ m.h$^{-1}$. This roughly corresponds to $I_{ssv} = 100$ ml.g$^{-1}$ and $I_{dsv} = 150$ ml.g$^{-1}$. As for the value of the safety factor, $s_f = 2$ can be used, although this estimate seems to be at the lower side when designing for bad settleability. Of course a settler that is designed on this basis will also have a satisfactory performance when the sludge settleability is fair or good.

The value of the safety factor that was adopted in order to obtain a good fit between theory and the empiric data is relatively high ($s_f = 2$). However, it has to be reminded that the conditions for the theoretical and experimental curves are not equal. A first difference is that the solids flux theory is derived for a constant flow rate and its expression indicates that the settler will fail if a constant maximum flow is sustained. On the other hand, for the experimental curves the maximum influent flow could only be sustained for such a time as long as the (stored) water quantity lasted. Thus in many cases in the experimental Stora procedure the settler would have failed, had it been possible to sustain the high influent flow for a longer time. For the empiric model this would be considered as satisfactory behaviour because heavy rains (and consequential maximum flows) normally only last for a relatively short time. Another difference is that the theoretical curves are based on batch tests at constant sludge mass. In the experimental procedures the sludge concentration in the aeration tank tends to decrease as sludge accumulates in the settler. This continues until a maximum of 30% of the total sludge mass has been transferred to the settler. If it is considered that under normal conditions the amount of sludge mass in the settler would probably not exceed more than 5%, it is concluded that under maximum load the mixed liquor concentration can decrease by as much as 25%, and this reduction will of course allow application of a much higher flow rate to the settler. When the sewage flow returns to normal the sludge mass will gradually be returned to the aeration tank.