Secondary settling tank modelling and design Part 1: Review of theoretical and practical developments

AE Ozinsky and GA Ekama*
Department of Civil Engineering, University of Cape Town, Rondebosch 7700, Cape Town, South Africa

Abstract

An overview of theoretical and practical developments in modelling and design of secondary settling tanks (SST) is presented. Historically, to overcome the lack of simple, reliable measures of sludge settleability and to incorporate sludge settleability into the design of the SST, two approaches were taken:

- in English-speaking countries the flux theory was adopted and the required flux theory constants (V_0 and n) were determined from empirical relationships linking these constants to the simpler SSVI or DSVI sludge settleability measures;
- in Europe (Germany and Holland) empirical design equations were developed from observed full-scale SST performance.

The former approach provides only a surface area whereas the latter recognises sludge transfer to the SST and also provides depth, maximum underflow concentration and SST sludge storage concentration, all as functions of sludge settleability. It was noted that local conventions in the design of the internal SST features (e.g. inlet, outlet, sludge collection and baffling arrangement) which are known to influence SST performance via secondary effects such as hydraulic turbulence and density currents, are implicitly incorporated in local design procedures. In English-speaking countries, this has occurred through the verification/calibration process of the flux theory against observed full-scale SST performance, whereas, in Europe, this has occurred through the establishment of empirical design equations based on observed full-scale SST performance.

In order to bring theoretical and practical developments closer together, it was identified as necessary to establish to what extent the information embodied in the European empirical design relationships flows naturally from a dynamic SST model based on the flux theory. The outcome of this evaluation is presented in three sequel papers.

Introduction

Over the past few decades, work on secondary settling tanks (SSTs) has progressed along two parallel but distinct paths. One path has focused mainly on empirically based procedures for SST design and operation. The other path has focused on developing the flux theory and incorporating it into models of varying complexity for SST steady state, transient and dynamic simulation. Until recently, not much integration between the two paths has taken place, with the result that theoretical developments in SST modelling have not been well integrated into design and operation practice.

In this paper the basic developments in the two parallel paths are reviewed so that the principle objective of this series of four papers i.e. greater integration of theory and practice, will come into focus.

Chronological review

Theoretical developments have centred mainly on the flux theory as a means of understanding and describing the solids sedimentation process taking place in the SST and on developing mathematical models for simulation based on this theory. This flux approach presumes that the solids sedimentation and transport processes through the SST dominate the behaviour and hence performance of the SST and that these processes alone give an adequate description of the behaviour of the SST. Other processes, such as hydraulic effects, turbulence and density currents, mixing, flocculation, and influences of inlet and outlet configurations and baffling, even though they are known to take place, are assumed to be minor and not to influence the SST performance significantly. The validity of this assumption is considered in this series of papers which evaluate the flux theory as a design procedure.

At its root, the flux theory is relatively simple. Originally conceived by Coe and Clevenger in 1916 from observations on inorganic mining slurries and formally set out mathematically by Kynch (1952), it states, from a material balance, that, under ideal conditions, the rate of accumulation of material (in our case, activated sludge solids) in a particular layer over an interval of time is equal to the difference between the rates of material entering and leaving the layer i.e.

$$\frac{\delta}{\delta t}(Xdz)dt = G(z + dz)dt - G(z)dt \qquad (1)$$

which, after simplifying, yields the idealised mass balance partial differential equation (PDE):

$$\frac{\delta X}{\delta t} = \frac{\delta G}{\delta z} \qquad (2)$$

where X = solids concentration ($kgTSS \cdot m^{-3}$)
t = time (h)
z = depth (m)
G = solids flux ($kgTSS \cdot m^{-2} \cdot h^{-1}$)
= $V_s X$
V_s = solids zone settling velocity (ZSV) ($m \cdot h^{-1}$)

While the principle embodied in Eq. (2) can be applied to SST modelling without undue difficulty, its application is complicated

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* To whom all correspondence should be addressed.

☎ (021) 650-2588; Fax: (021) 650-2603; E-mail: ekama@engfac.uct.ac.za

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because it requires V_s to be defined. Because it is known that V_s varies with X, a relationship linking V_s to X needs to be established. While the **form** of this relationship has been a point of debate over the years in research circles, (Dick and Young, 1972; Vesilind, 1968a; Rachwal et al., 1982) this is much less of a problem than the **measurement** of the data required to establish the V_s-X relationship when applying the flux theory in practice.

With regard to the form of the relationship, it appears that the semi-log form proposed by Vesilind (1968a) is now generally accepted i.e. $V_s = V_o e^{-nX}$ where V_o and n are constants that define the settling behaviour of the biomass solids. In this regard, Smollen and Ekama (1984) found the semi-log form to be superior to the log-log and other forms because it best fitted a wide range of observed V_s-X data and more importantly, it yielded a more consistent integrated flux model for the SST.

With regard to the measurement of the V_s-X data, this requires multiple batch zone settling tests over a concentration range which extends at least over the concentration range expected during SST operation. This is a time-consuming and tedious undertaking, so much so that it has never been accepted in practice and therefore has been restricted to research circles. This is the underlying cause for the flux theory *per se* never having been widely accepted for design and operation of SSTs, despite the degree of development and refinement in the application of the flux theory to SST modelling since Kynch (1952) by contributions from Yoshioka et al. (1957); Vesilind (1968a; b); Dick and Ewing (1967); Dick and Young (1972); Alkema (1971); Keinath et al. (1977); Laquidara and Keinath (1983) and Ekama et al. (1984). It has been generally considered in practice that, while the flux theory was a rational and integrated theory for describing SST behaviour, its requirement for the V_s-X relationship made it impractical for routine full-scale design and operation.

With practice unable to access the flux theory, empirical design and operating procedures were developed. These centred around simpler measurements for sludge settleability. Originally, this was the sludge volume index (SVI), a sludge settleability parameter (SSP) that is still in wide usage in practice today, despite its well-recognised deficiencies (Dick and Vesilind, 1969). Some of the deficiencies of the SVI are that it is not independent of sludge concentration, it is affected by gentle stirring and it has no rational relation to the sludge's zone settling velocity (ZSV, V_s). Because of these inadequacies, it has not been possible to integrate the SVI into reliable empirical design procedures which recognise sludge settleability. As a consequence, up to the middle 1970s, sludge settleability had not been incorporated directly into design criteria or procedures for SSTs. For different types of activated sludges (with/without primary sedimentation, surface aerated/bubble aerated, high rate/extended aeration), different hydraulic and/or solids loading criteria have been established based on experience. While sludge settleability is not included explicitly in these criteria, it is included implicitly via an unknown but nevertheless real maximum sludge settleability which the sludge in the particular type of activated plant is not expected ordinarily to exceed. Examples of such empirical design criteria are those recommended by the IWPC (1973) and the USEPA (1975).

To accommodate the need for design procedures which explicitly recognise sludge settleability, considerable investigative effort has been directed at improving the simple SVI test and incorporating these improvements into empirical design procedures. This has been undertaken mainly by those in practice. Two improved sludge settleability parameters (SSP) have been developed: the diluted SVI (DSVI) (Stobbe, 1964); and the stirred specific volume index (SSVI) (White, 1975). Both these modifications (dilution and stirring) to a large extent eliminate the SVI's greatest deficiency, which is its dependence on sludge concentration (Dick and Vesilind, 1969; White, 1975 and Rachwal et al., 1982). The reduced sensitivity of the DSVI and SSVI to sludge concentration significantly improved the reliability of measuring sludge settleability and provided a basis for comparing the settleability of different activated sludges. As a consequence, the DSVI and the SSVI became integrated into different empirical SST design procedures which explicitly incorporate sludge settleability. The DSVI has been incorporated into the ATV (Abwassertechnik Vereinigung, Germany) design procedure (ATV, 1973; 1976; 1991) and SSVI into the WRc (Water Research Centre) design procedure (White, 1975). Both procedures were formulated on the basic flux theory principles but have developed so differently that there is now little resemblance between them (see Ekama and Marais, 1986). This is because local conditions have led to different traditions and conventions for SST design and layout. Consequently, when formulating these empirical design procedures and incorporating resulting additional locally obtained observed information, design procedures were force-fitted to conform to the designs and layouts of the local settling tanks. The fact that the two branches of design procedures (flux-theory based and ATV - see below) have developed so divergently and give considerably different results (see Ekama and Marais, 1986) is an indication that the sedimentation processes considered as paramount by the procedures and flux theory might well not be so, and that hydraulic effects in the different SST designs and layouts also have a significant influence. The development of these two now quite different empirical design procedures is traced below.

Empirical design procedure development

The two empirical design approaches developed within the English speaking tradition (UK, USA, RSA, Aus) and the German/Dutch speaking tradition (FRG, NL) respectively shall be referred to as the English and European design approaches respectively.

The English design approach

Flux-based design procedures

In the English-speaking countries, attention has been focused on the flux theory and empirical design and operation procedures flowing from it in a direct way. Some (Riddel et al., 1983; Wilson, 1983) used the ZSV-X relationship directly. Owing to the difficulties in measuring the ZSV-X relationship mentioned above, others accessed the flux theory by establishing empirical relationships linking the simpler SSPs (SVI, DSVI, SSVI) to constants in the ZSV-X relationship so that this relationship was fully defined in terms of either the SVI (Daigger and Roper, 1985; Pitman, 1984), SSVI (White, 1975; Rachwal et al., 1982; Pitman, 1984; Ekama and Marais, 1986; Wahlberg and Keinath, 1988) or DSVI (Koopman and Cadee, 1983; Ekama and Marais, 1986). With regard to the accuracy with which the ZSV-X relationships could be established from the simpler SSPs, Ekama and Marais (1986) demonstrated that, while considerable differences were evident between the SVI data of Daigger and Roper (1985) and Pitman (1984), the SSVI data of White (1975), Rachwal et al. (1982), Pitman (1984) and their own conformed closely, indicating the superiority of the SSVI over the SVI as an alternative SSP from which to derive the ZSV-X relationship. Ekama and Marais also established a relationship between the DSVI and SSVI (i.e. SSVI = 0.67 DSVI) from their own and literature data (STORA, 1981) and with it found that the

DSVI and ZSV-X data of Koopman and Cadee (1983) did not conform to the established SSVI and ZSV-X relationships. The relationships between the different SSP's and their use for determining the ZSV-X relationship is discussed in detail in Ozinsky and Ekama (1995) (Part 2).

Verification of the steady state flux theory embodied in the empirical procedures

While conformity between the data relating the SSVI to the ZSV-X relationship results in similar maximum solids loading estimates for the SSVI based Water Research Centre (WRc) (White, 1975) and the flux theory procedures (Pitman, 1984 and Ekama and Marais, 1986), and simplifies its application to design and operation by bypassing the tedious ZSV-X measurements, it does not verify the accuracy of the flux-based design procedures as reliable design approaches.

White (1975) and Rachwal et al. (1982) verified the WRc design procedure by conducting a number of solids loading or stress tests on a number of different settling tanks in England; White reports 8 stress tests on 8 different settling tanks and Rachwal et al. report 11 stress tests on (it seems) one settling tank. From these tests they concluded that the predicted solids loading was within ± 20% of the actual applied solids loading. Because of the conformity between White's, Rachwal's and Pitman's SSVI - ZSV-X relationship, White and Rachwal et al. indirectly verified the flux theory when verifying the WRc procedure. While the development of the SSVI and WRc procedure in England was a major advance from empirical criteria that do not recognise sludge settleability, a margin of error of ± 20% for both this procedure and the flux theory constitutes a rather large margin of error.

Ekama and Marais (1986), in attempting to reduce the margin of uncertainty, undertook a verification of the flux theory for design with the aid of the data from an extensive full-scale SST performance evaluation undertaken by STORA (Stofkoper and Trentelman, 1982; STORA, 1981a; b; c). In this evaluation, 47 solids loading tests were undertaken on 22 different circular SSTs in Holland with dia. between 30 and 48 m. Ekama and Marais (1986) concluded that the permissible solids loading predicted by the flux theory must be reduced by 25% in order to satisfactorily distinguish between over and underloaded cases. Although Ekama and Marais (1986) concluded that their steady state verification gave a more precise indication of the reliability of the flux theory for use in design than earlier, they speculated that the 25% reduction may be a consequence of hydraulic or secondary effects not taken into account in the idealised flux theory such as turbulence, density currents, inlet and outlet arrangements and baffling. The Dutch settling tanks evaluated are quite shallow (1.5 to 2 m side wall depth) due to high groundwater levels and thus may cause a reduced solids loading capacity compared with the English tanks evaluated by White (1975) and Rachwal et al. (1982). If this speculation is correct, then it is quite possible that the reduction of 25% is specific to tanks of the type tested by STORA. Differently shaped and configured tanks may well have produced a different figure.

Verification of the flux theory in dynamic simulation models

Dynamic verification of the flux theory has to a limited extent been undertaken and has taken place mainly in the context of incorporating the flux theory into dynamic simulation models. Apart from the work of Alkema (1971), Tracy and Keinath (1973), Attir et al. (1977), who all contributed to application of the flux theory to SSTs under dynamic loading conditions, the work of Anderson and Edwards (1980; 1981) is the most significant. Rather than apply the flux theory in its idealised form as set out by Eq. (2), they introduced a turbulent diffusion term into the equation in an attempt to take into account in a single lumped parameter all the secondary effects (such as turbulence) that cause deviation from the idealised conditions implicit in the flux theory *per se*. They found that, after calibration to determine the turbulent diffusion coefficient (E), their model satisfactorily predicted a clarifier upset incident in one of the Detroit WWTP circular settling tanks (B6 on 13 and 14/9/1979). This SST had a dia. of 61 m and a depth of 5.9 m. The clarifier upset was caused by the overflow rate, and as a result the applied flux, increasing from 1.67 $m\cdot h^{-1}$ and 6.07 $kgTSS\cdot m^{-2}h^{-1}$ to 2.70 $m\cdot h^{-1}$ and 7.94 $kgTSSm^{-2}\cdot h^{-1}$ respectively; while the underflow rate remained at 0.76 $m\cdot h^{-1}$. After 10 h, the upset was restored by reducing the overflow rate (and applied flux) was reduced to 2.43 $m\cdot h^{-1}$ (5.84 $kgTSS\cdot m^{-2}\cdot h^{-1}$). During the test, which lasted 16 h, concentration profiles were measured at 4 h intervals and effluent suspended solids at 1 h intervals. A fair correlation between predicted and measured results was obtained. The objective of Anderson and Edwards' (1980; 1981) work was to develop an overall Detroit WWTP model capable of simulating solids loss during wet weather and plant upset events. For this they required a good SST dynamic model because solids loss with the effluent is principally governed by this unit operation. Because of their specific interest, Anderson and Edwards (1980; 1981) did not check the applicability of their model to simulate dynamic performance of SST's in general. Verification of flux theory-based SST dynamic simulation models is discussed in Ozinsky et al. (In prep.) Part 3.

Conclusion - English/flux theory direction

The English empirical design and operation procedures are all direct derivatives of the flux theory. Access to the flux theory is gained by means of one of the simpler sludge settleability measures (SVI, SSVI or DSVI) from which are calculated either the permissible solids loading directly from a flux-based empirical relationship or the V_0 and n values required in the flux theory from an empirical SSP - ZSV-X relationship. All these flux-based design procedures are limited by the same constraints as the flux theory itself as to the design information they provide i.e. an SST surface area and associated underflow recycle ratio. No information is given regarding tank depth, maximum underflow concentration attainable, transfer of sludge to the SST, sludge storage concentration and capacity in the SST and reduction in reactor concentration during high-flow periods, all of which is useful and important design information for the construction of reliable SSTs.

The European design approach

The ATV and STORA design procedures

The large body of research and full-scale SST experience obtained in the 1970s at the Technical Universities of Aachen and Munich by Pflantz (1969), Merkel (1971; 1974) and Billmeier (1978) and additional contributions such as those by Kalbskopf (1972) and Bischofsberger and Günthert (1982) has formed the basis of the standard procedure for design of SSTs in Germany. The development of this procedure, known as the ATV procedure (ATV, 1973; 1976; 1991), and the Dutch derivative from it, known as the STORA procedure (Epskamp and Van Hernen, 1984), is summarised in Dutch by STORA (1981a) and in English by Ekama and Marais (1986). The ATV procedure, while originally formulated recognising flux theory principles (see Merkel, 1971), and the STORA procedure derived from the ATV one, now bear little resemblance to the flux theory. Both procedures are essentially a set of empirically derived relationships developed from the large body of observed information collected and both are based on the DSVI as SSP.

Both procedures provide information on four important features of the SST required for design which are:

- maximum overflow rate;
- maximum underflow concentration;
- reduction in reactor solids concentration; and
- storage of sludge transferred from the reactor in the SST during peak wet weather flow (PWWF).

These features are calculated from the established empirical relationships in terms of the DSVI and yield design values for the required surface area; the minimum underflow recycle ratio for dry and wet weather flow; and the depth of the tank to provide sufficient volume for sludge compaction in the bottom, sludge storage in the lower middle, solid/liquid separation in the upper middle and clarification in the top layers.

The structure of the ATV procedure allows a trade-off between surface area and depth for the same design condition so that, by accepting a high sludge mass transfer to the SST during WWF, it is permissible to choose a smaller but deeper tank. This flexibility is absent in the STORA modification of the ATV, where the side-wall depth of the tank is empirically fixed at between 1.5 and 2.5 m. This is probably because, in Holland, deep tanks are not ordinarily considered due to the high water table. However, transfer of sludge to the settling tank during PWWF is recognised. This reduces the reactor concentration, allows a higher overflow rate and hence a smaller area, but only up to the point where the sludge storage capacity in the SST is full. Details on how to use the ATV and STORA procedures are given by ATV (1973; 1976) (both in German), ATV(1991) in English, STORA (1981c) in Dutch, and Epskamp and Van Hernen (1984) (in English) respectively.

Because the ATV and STORA procedures are empirically based, they would be strongly subject to the type of SST on which they were developed and calibrated. Because hydrodynamic effects such as turbulent diffusion, density currents and physical features such as geometry, baffling and centre wells can influence tank performance, a knowledge of the type of settling tank studied by ATV and STORA provides a useful background to the applicability of these procedures. In so far as the ATV procedure is concerned, two tanks at Celle and Fallingsbostel tested by Pflantz (1969) (see Ekama and Marais, 1986) appear to have been used to establish the overflow rate vs. "solids loading" criterion. Features of these two tanks, which are circular and rectangular respectively, are given by Pflantz (1969). Unlike the flux theory and associated procedures, which are used to identify the solids loading capacity or equivalently the point at which gross solids loss with the effluent takes place (at several 100 $mg \cdot \ell^{-1}$), the ATV overflow rate vs. sludge volume ($m\ell \cdot \ell^{-1}$) [which is the product of the DSVI ($m\ell \cdot g^{-1}$) and the reactor concentration ($g \cdot \ell^{-1}$)] guideline was established such that the effluent suspended solids concentration would be below the German standard of 30 $mg \cdot \ell^{-1}$. The empirical formulae giving maximum underflow concentration, sludge storage concentration and depth of the sludge thickening zone were developed from the information of Merkel (1971; 1974) and Billmeier (1978) and are given in the references cited above.

Verification of the ATV and STORA procedures

The STORA design procedure (Epskamp and Van Hernen, 1984) emerged from the comprehensive full-scale SST performance and design procedure evaluation study undertaken by Stofkoper and Trentelman (1982) (see also STORA, 1981a; b; c) mentioned earlier. From the 47 solids loading tests on 22 different circular full-scale SSTs ranging in size from 30 to 48 m dia., STORA concluded that, of the design procedures available, the ATV procedure was the best predictor of settling tank failure and provided the most complete and accurate design information based on the DSVI. (In a similar study on rectangular settling tanks, 27 solids/hydraulic loading tests were conducted on 3 different tanks (see STORA, 1983)). However, it tended to be too conservative at high sludge volumes i.e. at poor sludge settleability (high DSVIs) or high reactor concentrations. The empirical formulae in the ATV procedure for the maximum underflow concentration at DWF and WWF, the required depth for thickening and the sludge storage concentrations were checked with concentration profile measurements made during the solids loading tests and found to be satisfactorily accurate. These were accepted for the STORA procedure. On the basis of their results, two modifications were made to the ATV procedure to form the STORA procedure:

- the permissible overflow rate was increased for high sludge volumes to eliminate the conservative predictions in this region; and
- the side wall depth was set empirically at 1.5 to 2.5 m by eliminating the surface area-depth trade-off, but sludge transfer to and storage in the settling tank during PWWF was retained.

With regard to Stofkoper and Trentelman's (1982) verification of the flux theory using the STORA data set, they found that this theory, while providing a good conceptual model for secondary settling tanks, was a very poor predictor of settling tank failure. On examination of their results, Ekama and Marais (1986) concluded that the concentration range over which the flux constants V_o and n were measured was too narrow (1 to 6 $g \cdot \ell^{-1}$). When V_o and n were calculated from the measured DSVI or SSVI with the aid of empirical relationships linking the different SSPs, the flux theory, like the WRC procedure, was found to overpredict the permissible solids loading by 25% i.e. the predicted solids loading needs to be reduced to 80% to give the maximum permissible applied solids loading. This specification was considerably narrower than the ±20% reported for the WRc (and flux theory) by White (1975), Rachwal et al. (1982) and Stofkoper and Trentelman (1982), (see STORA, 1981a) themselves (see Section "Verification of the steady state flux theory embodied in the empirical procedures" above).

Conclusion - European design procedures

From the above, it is clear that the ATV and STORA design procedures, although highly empirical and lacking a fundamental basis like the flux theory, are based on a large body of research and full-scale observations, which gives them considerable credibility in their countries of origin. Indeed, to the knowledge of the authors, the STORA full-scale circular and rectangular settling tank data sets (STORA, 1981b; 1983) are the most comprehensive available in the literature. The good correspondence between empirically calculated and experimentally observed results lends powerful support to the accuracy of the empirical relationships embodied in the design procedures. However, it should not be overlooked that the good correlation may be a consequence of similarity between German and Dutch SST design and layout, rather than generality of the empirical relationships.

Comparison of the flux and WRC procedures and the ATV and STORA procedures

The major differences between the flux theory and associated design procedures and the ones set down by the ATV and STORA are:

- The ATV and STORA procedures do not recognise the underflow recycle ratio as important in the estimation of the permissible overflow rate whereas the flux-based procedures do, although only up to a specific upper limit dependant on sludge settleability.
- On the basis of the most reliable relationships between the DSVI, SSVI and flux constants V_0 and n, the ATV and STORA design procedures are considerably more conservative than the flux procedure for good sludge settleability, whereas, for average to poor settling sludges, the different procedures yield approximately the same permissible overflow rates (see Ekama and Marais, 1986).
- The flux-based design procedures give only a tank surface area and associated underflow recycle ratio; it is assumed that the underflow concentration required at the particular associated recycle ratio can be achieved irrespective of the sludge settleability. In the ATV and STORA procedures, the approach is reversed in that a maximum underflow concentration at DWF and WWF depending on sludge settleability is calculated from which the required recycle ratio is determined.
- In the ATV and STORA procedures, the transfer of sludge from the biological reactor to the settling tank, which reduces the reactor concentration, is taken into account whereas in the flux theory this reactor-settling tank interaction is ignored. Also, the required sludge storage volume in the settling tank is calculated from a sludge storage concentration which is dependent on sludge settleability. These aspects, which are used to estimate the depth of the settling tank, are not considered in the flux theory-based procedures.

Reasons for differences between the English and the European paths

From the above comparison, it is clear that there are significant differences between the flux-based design procedures and the DSVI-based ATV and STORA ones. Whereas the flux-based procedures have remained closely associated with the flux theory - the only essential differences are in the relationships which link the particular SSP and V_0 and n values - the ATV and STORA procedures deviate completely from it, having established their own empirical relationships from pilot and full scale observations.

Because of their extensive testing and calibration, the ATV and STORA procedures would be more accurate and reliable estimators of settling tank performance, although their application is confined to the kind of settling tanks represented in the testing and calibration data sets. Indeed, it is possible that the reason Trentelman and Stofkoper (1982) found the ATV procedure overflow rate to be too conservative at the high sludge volumes was that the German tanks from which the overflow rate - sludge volume line was derived (Celle and Fallingsbostel) are different in geometry and hydraulic features to the Dutch circular tanks tested by STORA. In contrast, the flux theory and the procedures based on it are more general and therefore have a much wider applicability to different settling tank designs and geometries than the ATV and STORA procedures. However, the accuracy and reliability of the flux-based procedures for different tank types and geometries now becomes uncertain. It is quite possible that, had the STORA data set been collected on different types of settling tanks (side wall depths, sludge collection, inlet arrangement and baffling), a different reduction factor to 80% may have been found. Therefore, what Ekama and Marais (1986) considered a verification of the flux theory (and WRc procedure) was possibly more of a calibration of the flux theory to the Dutch type tanks tested by STORA. Therefore differences in the flux-based procedures and ATV and STORA procedures can be attributed to the following:

- The different SSPs on which the procedures are based; DSVI and SSVI (and SVI) are not completely consistently related to the flux V_0 and n values and significant differences can be obtained depending on the data set that is selected from which the relationship linking the particular SSPs is obtained.
- Local conventions and traditions for the design layout, geometry and operation of settling tanks, such as inlet and sludge collection arrangements, side-wall depth and baffling, influence settling tank performance more than recognised in the different design procedures.
- Design procedures and performance data sets reported in different languages make exchange of information difficult and result in research and development taking place in isolation.

Empirical design relationships based on observed tank performance can therefore be expected to reflect in some unknown, but probably not insignificant measure, the local conventions and traditions. Checking of the flux theory against particular performance data sets therefore will also reflect the local conventions embodied in the settling tank and constitute a calibration rather than a verification *per se*.

The differences noted in the different design procedures which result from different settling tank design features such as side-wall depth, geometry, tank type baffling and inlet and outlet arrangements, indicate that these features which influence hydrodynamic effects such as turbulent diffusion and density currents, have a greater influence on tank performance than considered earlier in the development of the flux theory, which takes account only of sedimentation of solids.

Hydrodynamic models for secondary settling of various complexity and sophistication have been developed, some including turbulence (Imam et al., 1983; McCorquodale et al., 1991; both discussed in Samstag et al., 1992), others including both turbulence and density currents (Krebs, 1991; Zhou et al., 1992). These models are able to simulate the effects of different settling tank features such as geometry, side-wall depth, baffling, inlet and sludge collection arrangements. While such models clearly are very useful as they allow the influence of these various features on the maximum solids or hydraulic loading capacity of the tank to be assessed, it is nevertheless required to check how effective the flux theory *per se* is in modelling dynamic behaviour of the settling tank, which would include considerations such as tank depth, sludge transfer to and storage in the settling tank, because, in any event, the hydrodynamic models include the flux theory in order to model the sludge sedimentation.

The settling tank design procedures, whether flux, WRc, ATV or STORA, essentially give the designer the means to determine the basic shell of the SST, i.e. surface area and for the ATV, the depth. No information regarding the optimal arrangement of various features such as inlet and sludge collection arrangements, flocculating centre wells and baffles is given. Accepting that these features as well as sludge return rate, which influences the turbulent diffusion, affect tank performance, it would be valuable to determine with the aid of the hydrodynamic models how the arrangement of these features influences the solids loading capacity of the SST in relation to the permissible solids loading calculated from the flux theory. By this means, a flux rating is established, the magnitude of which gives the measure whereby the arrangements of the physical features (and depth) within the shell of the SST have been optimised. In this respect the flux rating of the Dutch settling tanks would be 0.8 because the actual permissible solids loading was found to be only 0.8 of the flux theory predicted solids loading. With deeper tanks and with carefully designed and placed baffles and inlet and outlet arrangements determined from optimisation studies with the newly developed hydrodynamic models, the flux rating could possibly be increased. In this way the flux rating could become a means for optimising the internal features designed into the shell of the SST obtained from the simple design procedures.

The objectives of the research

From the above, it seems that the principal task in achieving the objective of bringing the theoretical developments centred around the flux theory and practical developments centred around the design procedures closer together is definitive verification of the flux theory as a reliable design, operation and simulation model for secondary settling tanks. Steady state verification/calibration of the flux theory as a design procedure was carried out by Ekama and Marais (1986) using the STORA data set as a basis. In terms of the flux rating concept, a value of 0.8 was found for the Dutch full-scale SSTs. Accepting this value for the Dutch SSTs satisfies the design requirements for the settling tank surface area from a solids loading capacity point of view for the Dutch type of SST, but it does not provide other important design information such as settling tank depth, sludge storage capacity and maximum underflow concentration which the ATV and STORA design procedures would provide. Clearly, it is necessary to verify the flux theory for dynamic loading cases to check its accuracy and reliability in providing this information from a design point of view. This verification is the principal objective of this series of papers for which the STORA data set will be used as a basis. While it is recognised that this verification may be limited to the Dutch type SSTs for the reasons mentioned earlier, it is important to establish in what measure the empirical additional information of the ATV and STORA design procedures flows naturally from the flux theory when applied to the Dutch SSTs. To achieve this objective, a number of tasks need to be accomplished.

Accomplishing these tasks requires:

1. A comprehensive set of full-scale settling tank dynamic performance data from dynamic hydraulic and solids loading tests. The STORA data set discussed above is such a data set and, to the knowledge of the authors, the only one with the necessary detail for a verification/calibration of the flux theory under dynamic loading conditions. However, in order to use this set, values for the flux constants V_0 and n need to be determined from the measured DSVI or $SSVI_{3.5}$ because the ZSV - X column tests done by STORA (1981b) were conducted over too narrow a concentration range (1 to 4.5 $g \cdot \ell^{-1}$). The only alternative method whereby V_0 and n can be obtained indirectly is to establish relationships between the $SSVI_{3.5}$ and DSVI and the V_0 and n settleability parameters. This involved collecting, evaluating and analysing as much information on sludge settleability parameters as possible and examining, refining and establishing relationships between the SVI, $SSVI_{3.5}$, DSVI and the flux constants V_0 and n. These relationships would then serve as a basis to determine the V_0 and n values from the DSVI and/or the $SSVI_{3.5}$ measured by STORA. This aspect is presented in Ozinsky and Ekama (1995) Part 2 of this series.
2. Development of a dynamic model of the settling tank incorporating the flux theory.
3. Testing and calibration of the model against the STORA full-scale data.

Objectives 2 and 3 are presented in Ozinsky et al. (in prep.) Part 3 of this series.

Once the simulation model has been tested and calibrated against the STORA data set, it will be possible to:

4. Examine whether or not the calibrated simulation model can generate information about the maximum underflow concentration sludge storage capacity and tank depth and to compare this information with calculations based on the ATV and STORA design procedures.
5. Compare the different empirical design procedures and examine the designs by means of the simulation model.
6. Explore the possibility of integrating relevant and important aspects of the ATV/STORA procedures into the flux procedure to give additional information about sludge storage capacity, tank depth, reduction in reactor concentration and maximum attainable underflow concentration.

The outcome of objectives 4 to 6 is discussed in Ozinsky and Ekama (In prep.) Part 4 of this series.

Conclusions

An overview of theoretical and practical developments in the modelling and design of secondary settling tanks (SST) has been presented. It was argued that the lack of integration between theory and design has been caused mainly by the difficulty of measuring sludge settleability simply and reliably. To meet the need for design of the external shell of the SST (surface area) in relation to sludge settleability, two approaches were taken: in English-speaking countries the flux theory was adopted and the required flux theory constants (V_0 and n) were determined from empirical relationships linking these constants to the SSVI or DSVI; in Europe (Germany and Holland) empirical design procedures and equations were developed from observed full-scale SST performance. In reviewing these design approaches it was noted that:

- The English flux-based approach provides only a surface area whereas the European empirical approach provides surface area, depth, maximum underflow concentration, sludge transfer to the settling tank and the concentration at which it is stored there, all dependent on sludge settleability.
- Local conventions in the design of the internal features of the SST such as depth, inlet, outlet, sludge collection, flocculator centre well and baffling arrangements influence SST

performance via secondary effects such as turbulent diffusion and are not only implicitly incorporated in the empirical design procedures, but also in verification/calibration of the flux theory procedures against full-scale solids loading tests.

With the advent of hydrodynamic models for SSTs, modelling of the secondary effects caused by the internal features has become possible with considerable success. The concept of a flux rating is introduced which is the ratio of the actual solids loading capacity of the settling tank to the flux theory predicted solids loading. The flux rating allows an assessment to be made of the efficacy of the design of the internal SST features in increasing the solids loading capacity in relation to the flux theory predicted solids loading; the higher the rating, the better the design of the internal features.

From the overview, the need for verification/calibration of the flux theory for modelling the dynamic performance of SST's was identified as a general objective. In particular, in order to bring theory and practice closer together it is necessary to establish to what degree the information embodied in the European empirical design relationships flows naturally from a dynamic SST model based on the flux theory. The full-scale SST data set compiled by STORA (1981a; b; c) on Dutch SSTs was established as the most comprehensive and useful for this evaluation. Ekama and Marais (1986) determined a flux rating of 0.8 for these Dutch tanks, which are relatively shallow (2 to 3 m side wall depth). However, this rather low flux rating is not a problem for meeting the particular objectives of this evaluation because the STORA data set was also used to verify the empirical relationships in the European (ATV, STORA) design procedures, which were found to give a close correspondence. The outcome of this proposed evaluation of the flux theory is given in the 3 sequel papers.

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