On-line determination of sludge settling velocity for flux-based real-time control of secondary clarifiers

Water Science & Technology **Vol 54 No 11–12 pp 249–256** © IWA Publishing 2006

A. Lynggaard-Jensen* and L. Lading**

*DHI Water&Environment, Gustav Wieds Vej 10, DK-8000 Aarhus C, Denmark (E-mail: *alj@dhi.dk*)

**Municipality of Aarhus, Soeren Frichs Vej 41, DK-8230 Aabyhoej, Denmark (E-mail: *lla@mil.aarhus.dk*)

Abstract The state diagram for operation of secondary clarifiers is used to design a control algorithm for the return sludge pumping and determination of the actual hydraulic capacity of the biological step of a wastewater treatment plant. On-line input for the control algorithm is derived from a sludge volume sensor and a suspended solids sensor in the form of software sensors giving values for the sludge settling characteristics – settling velocity, sludge volume index, initial settling velocity and the exponent in the Vesilind equation – allowing the control to accommodate the ever changing settling characteristics and thereby keep the suspended solids flux in the clarifiers in balance for both dry weather flows and during rain events. The control algorithm has been implemented, tested and set into normal operation on a full scale wastewater treatment plant.

Keywords Clarifier; control; flux; hydraulic capacity; settling velocity; sludge vol. sensor

Introduction

The wastewater treatment plant (WWTP) Aaby is operated by the municipality of Aarhus, Denmark, and is designed to remove nitrogen and phosphorus (effluent standards: Total-N = 8 g/m^3 and Total-P = 1.0 g/m^3, but decreased to 0.4 g/m^3 as of January 1st 2006) from 93,000 PE with hydraulic loads of 22,500 m^3/d and max. 1400 m^3/h (peak loads during rain: 3100 m^3/h). Due to problems caused by high and long lasting hydraulic loads during rain and demands to a high concentration of suspended solids in the activated sludge tanks, an optimised control strategy for the clarifiers during rain had to be implemented. Balslev *et al.* (1994) described a four step procedure for control of clarifiers during rain, including flux based control of the clarifiers and calculation of the max. hydraulic load to the biological part of the WWTP. Although this was implemented to run on-line, it still contained the tedious manual work of determining settling characteristics, which naturally caused the control to be less optimal. This work suggest the use of available sensors for measuring sludge volume – automatic determination of settling curves – and use of these for on-line determination of the settling characteristics. Furthermore, an improved control algorithm has been developed.

Methods

Control algorithm

The state diagram for secondary clarifiers uses the fluxes of suspended solids to define the state point and acceptable loads on the clarifiers, and the construction and practical use has been described in Keinath (1985), Daigger (1995) and Darling (2003). This work describes a control algorithm derived from the practical use of the state diagrams at a full scale wastewater treatment plant (Figure 1), and expressed through the mathematical

doi: 10.2166/wst.2006.719

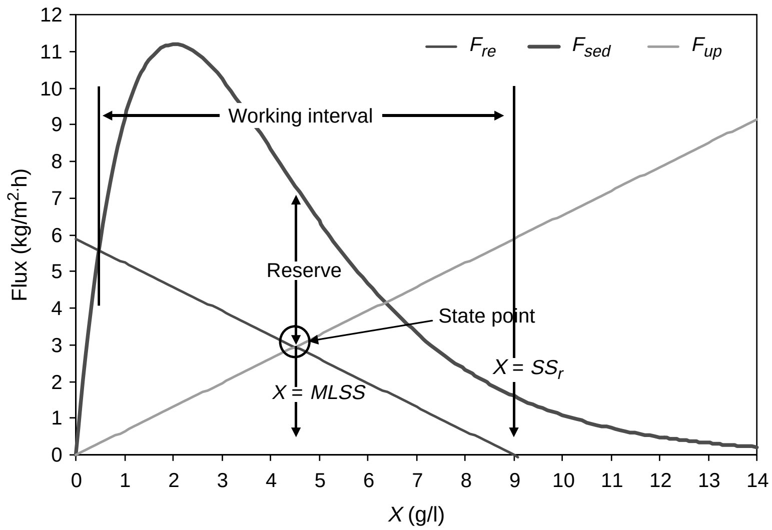

Figure 1 State diagram for the clarifiers. Values used in example are from WWTP Aaby

interpretation of the flux equations:

$$F_{sed}(X) = X^* V_{sed}(X) \quad \text{(Sedimented flux)}$$

$$Fre(X) = ((Qbio + Qr)^* MLSS - X^* Qr)/A \quad \text{(Returned flux)}$$

$$F_{up}(X) = X^* Q_{bio}/A \quad \text{(Upwards flux)}$$

where X is the suspended sludge concentration in the clarifier, Q_{bio} is the inlet flow to the biological step of the treatment plant, Q_r is the return sludge flow, A is the clarifier area, $MLSS$ is the suspended solids concentration in the activated sludge tank and V_{sed} (X) is the settling velocity, which can be described as (Vesilind, 1968):

$$V_{sed}(X) = ISV^* Exp(-nv^* X)$$

where ISV is the Initial Settling Velocity and nv an exponent, which both describes the sludge characteristics and can be determined experimentally.

The state diagram shows F_{up} as the line through 0,0 with the slope Q_{bio}/A and F_{re} as the line crossing the x-axis for $X = SS_r$ (SS_r being the suspended solids in the return sludge) with the slope $-Q_r/A$. The state point is located where these lines cross ($F_{up} = F_{re}$ at $X = MLSS$), and F_{sed} as the maximum possible sedimentation with the given sludge characteristics, gives the upper limit for the state point.

A sudden increase of Q_{bio} (Q_r and $MLSS$ constant) will move the state point vertically upwards (F_{up} fixed in 0,0 and rotating counter clockwise; F_{re} fixed in the state point and shifted upwards in parallel).

If the state point is located over F_{sed}, the hydraulic load is higher than the capacity of the clarifier (with the given sludge settling properties and $MLSS$) and sludge will escape in the outlet of the clarifier. The vertical distance between the state point and F_{sed} is therefore the maximum spare capacity available, and can for $X = MLSS$ be expressed as:

$$F(X) = F_{sed} - F_{re}$$

$$F(X) = X^* V_{sed} - ((Q_{bio} + Q_r)^* MLSS - X^* Q_r)/A$$

which becomes zero for $X = MLSS$ when $F_{sed} = F_{re}$, i.e. when Q_{bio} reaches its maximum allowable value: Q_{biomax}, which is the hydraulic capacity of the clarifier with the actual sludge settling properties and $MLSS$:

$$F(MLSS) = MLSS^* V_{sed} - ((Q_{biomax} + Q_r)^* MLSS - MLSS^* Q_r)/A = 0$$

when

$$Q_{biomax} = V_{sed}{}^* A = ISV^* \mathrm{Exp}(-nv^* MLSS)^* A$$

For given sludge characteristics ($dSVI$), flow to the biolgical step (Q_{bio}) and $MLSS$ the only control handle available is the return sludge flow, Q_r, which determines the slope of the line representing F_{re}. Different values of Q_r rotate the line which is fixed in the state point – an increase of Q_r rotates the line clockwise (decreasing SS_r) and a decrease of Q_r rotates the line counter clockwise (increasing SS_r). If the increase in Q_r causes the slope of the line to exceed the max. slope of the curve for F_{sed}, more sludge will be returned than can be settled, and the clarifier has become unstable, the sludge blanket disappears and sludge will appear in the outlet from the clarifier.

To keep the clarifier in balance and at the same time exploit the capacity using minimum return sludge pumping requires the returned flux to be the same as the sedimented flux, otherwise the sludge blanket will not be constant. In the state diagram this means that the line representing F_{re} has to be rotated counter clockwise until it touches the curve representing F_{sed}. Further rotation (further decrease of Q_r) will cause more sludge to be sedimented than returned, the sludge blanket will increase and in the end sludge will escape from the clarifier.

In other words, the control of Q_r has to minimize the difference between F_{sed} and F_{re}:

$$F(X, Q_r) = F_{sed} - F_{re} = 0$$

$$F(X, Q_r) = X^* ISV^* \mathrm{Exp}(-nv^* X) - ((Q_{bio} + Q_r)^* SS - X^* Q_r)/A = 0$$

This is the same equation which gives Q_{biomax} (for $X = MLSS$), but in this case Q_r can not be eliminated from the equation. As can be seen from the state diagram the equation can for $X > MLSS$ give zero, one or two solutions. However, it is known that for one and only one solution the line representing F_{re} will be a tangent to the curve representing F_{sed}, meaning that the line and the curve have the same slope – or in mathematical terms – the first derivatives of F_{re} and F_{sed} will have the same value at this point:

$$F'(X, Qr) = F'_{sed} - F'_{re} = 0$$

$$F'(X, Qr) = (ISV - ISV^* nv^* X)^* \mathrm{Exp}(-nv^* X) + Q_r/A = 0$$

when

$$Q_r = ISV^* A^* (nv^* X - 1)^* \mathrm{Exp}(-nv^* X)$$

The expression for Q_r is substituted into the equation for $F(X,Q_r)$, to form the equation $L(X)$:

$$L(X) = ISV^* nv^* (X^2 - SS^* X) + SS^* (ISV - Q_{bio}{}^* \mathrm{Exp}(nv^* X)/A) = 0$$

which has one and only one solution for $Q_{bio} < Q_{biomax}$, i.e. when the state point is located inside the curve representing F_{sed}. The situation $Q_{bio} = Q_{biomax}$ will give two solutions, however, one of these will be for $X = MLSS$, and can therefore be rejected.

The solution found by solving the equation $L(X) = 0$ is substituted into the expression for Q_r, producing the optimum return sludge flow with given sludge characteristics, suspended solids concentration in the activated sludge tank and hydraulic load. The control algorithm for the return sludge flow becomes:

1. Calculate Q_{biomax}
2. If $Q_{bio} < Q_{biomax}$ then solve $L(X) = 0$ using Q_{bio} and find Q_r
3. Else solve $L(X) = 0$ using Q_{biomax} and find Q_r
4. If $Q_r < Q_{r,min}$ then $Q_r = Q_{r,min}$ (taking into account a min. controllable value of Q_r)
5. If $Q_r > Q_{r,max}$ then $Q_r = Q_{r,max}$ (taking into account a max. controllable value of Q_r)

very well knowing that if Q_{biomax} is less than Q_{bio} it is only a matter of time before the sludge will escape from the clarifier. However, it is in this situation that the next step in a control strategy during rain has to be launched.

On-line determination of settling characteristics

As the practical work of determining *ISV* and *nv* using the Vesilind equation

$$V_{sed}(X) = ISV^{*}\text{Exp}(-nv^{*}X)$$

is quite tedious, and as the *ISV* and the *nv* changes with sludge characteristics in time, several equations including the *SVI* (Sludge Volume Index) or *dSVI* (diluted *SVI*) to compensate for this have been suggested (Daigger and Roper, 1985; Härtel and Pöbel, 1992; Ozinsky and Ekama, 1995). In this work the expression for *nv* as suggested by Härtel and Pöbel (1992):

$$nv = K1^{*}\text{Exp}(K2^{*}dSVI) + K3 \quad (K_1 = -0.9834;\ K_2 = -0.00581;\ K_3 = 1.043)$$

has been used, as the constants have been shown to be relatively independent at different wastewater treatment plants. As

$$dSVI = dSV30/MLSS$$

where *dSV*30 is the diluted sludge volume after 30 min.

From a sensor measuring the settling curve – the sludge volume as a function of time – the diluted sludge volume can be determined, but also V_{sed} can be determined from this curve (Sekine *et al.*, 1989; Vanrolleghem *et al.*, 1996; Vanderhasselt *et al.*, 1999; Vanderhasselt and Vanrolleghem, 2000; Weyershausen, 2002). As the *MLSS* can be measured by a suspended solids sensor, *ISV* can be calculated from the Vesilind equation at each measuring cycle of the SV-sensor. In practice settling characteristics are thus determined every 40 min.

The sensor used in this work is described in detail in VOLITAX Operating instructions (2002), and as an output gives the settling curve described by the diluted sludge volume value *dSV* in ml/l as a function of time. The output is logged every minute (example included in Figure 3) and *dSV* is determined as the constant lower value, whereas V_{sed} is calculated as the max. slope of the settling curve (Sekine *et al.*, 1989; Darling, 2003).

However, as the output from the SV-sensor has the unit of ml/l, V_{sed} will be in the units of ml/l/min, and a calibration of this signal to give V_{sed} in the unit m/h is needed. The SV-sensor was placed in a tank with a height of 1.30 m and a diameter of 1.5 m, and sludge from the activated sludge tanks was filled in the tank to a height of 1 m. The sludge was totally mixed with a submerged pump, and when the pump was stopped, the SV-sensor was started together with readings every minute of the sludge blanket in the tank.

The max settling velocities were calculated from the settling curve of the sludge blanket in the tank in m/h and from the SV-sensor in ml/l/min. The test was repeated several times with different suspended solids concentrations in the tank (obtained by dilution), in order to check if the calibration factor is independent of the suspended solids concentration. Max. settling velocities of the sludge blanket as a function of max. settling velocities from the SV-sensor express a linear relationship with a slope of 0.024 and a small offset of -0.08. At forced trough 0,0 the slope is nearly the same, 0.023, suggesting that the calibration can be done by a factor independent of the sludge concentration in the interval tested.

Software sensors

The control algorithm and all necessary calculations are implemented using software sensors (DIMS, 2005), which constitutes the nodes in a real time calculation framework (Figure 2) provided as a service "on the top of" SCADA systems/PLCs.

Real time calculations from a node has exactly the same properties as the values from a normal sensor – hence the term software sensor – and can therefore be treated exactly like sensor signals – used as input for calculations, stored in a database, validated, plotted, etc., making it easy to schedule and analyze the calculation sequence towards the set point (no node is calculated before its inputs are ready). In Figure 3 the normal sensors are located to the left followed by the software sensors providing the input to the control algorithm (to the right). The control algorithm itself is a software sensor with the special capability to write its value to a set point in a SCADA/PLC, and thereby conducting real time process control on set point level. Table 1 gives a summary of the inputs and calculations carried out according to the equations derived in the previous sections.

Results and discussion

A part of the inlet to the WWTP Aaby was collected in a storage basin during some hours and released at 14:30 creating a step change in the inlet. Figure 3 shows the software sensor framework response. The *dSVprofile* from the SV-sensor fails around 16:00, but the setup of the calculation of the *dSV* compensates for this.

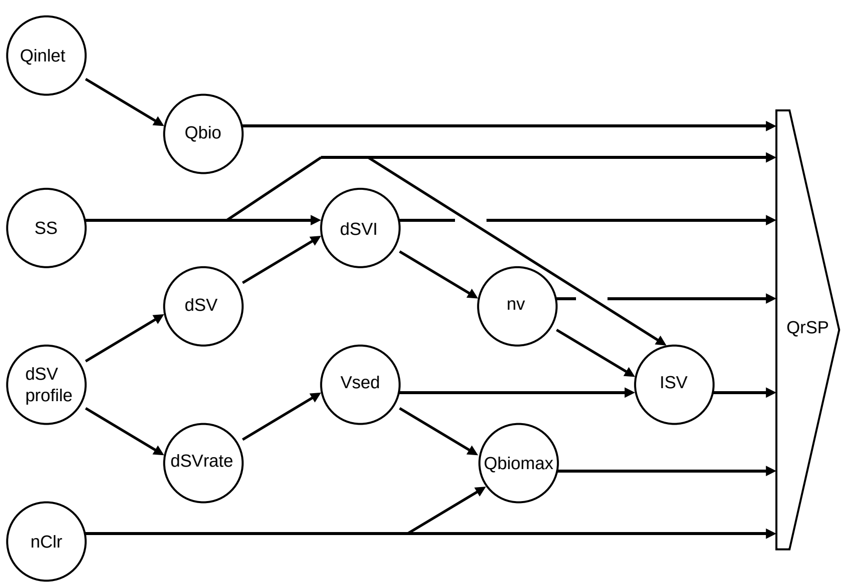

Figure 2 Real time calculation framework organized using software sensors (nodes)

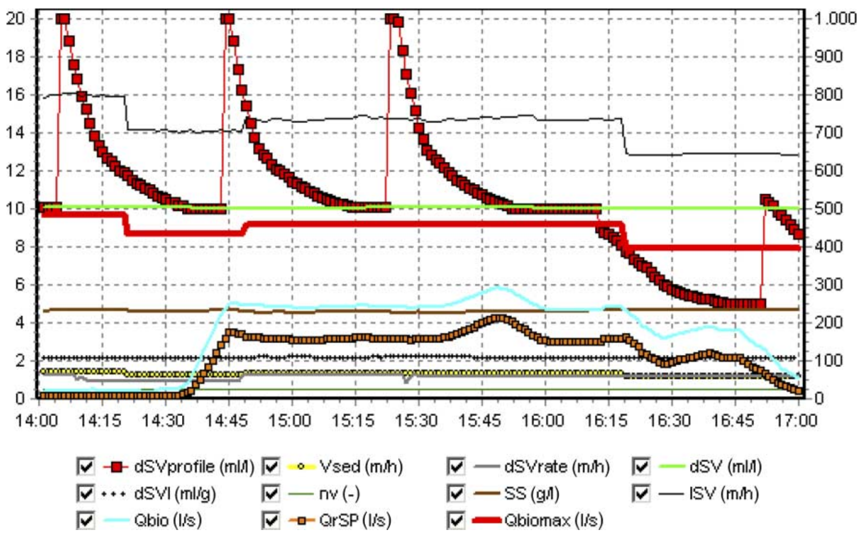

Figure 3 Software sensor framework response to a step change in the inlet flow. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst

The calculation of *dSVrate* also compensates for the sensor failure, but the relatively small stepwise change in value – although compensated a bit in the calculation of V_{sed} can be seen to give quite large stepwise changes in Q_{biomax} and *ISV*, but affects the Q_rSp much less. However, there is more work to be done on signal handling of the *dSVprofile*.

Figure 4 shows how the control algorithm handles a rain event, through presentation of relevant variables including the controlled variable Q_r – the "noise" in this caused by the actual possible control of the return sludge pumps. The $SS_r(Q_rSP)$ is a software sensor calculating the expected concentration of the return sludge from the mass balance using the set point value for the return sludge flow: $SS_r(Q_rSP) = MLSS^*(Q_{bio} + Q_{r,sp})/Q_{r,sp}$. As can be seen there are some delays in the system caused by the transfer of sludge from the activated sludge tank to the clarifiers and back (lower plot shows the sludge blanket $SLB,_{filt}$ (exponentially filtered to remove noise) and the rate of change in the sludge

Table 1 Summary of calculations done by the software sensor framework at Aaby WWTP

Sensor name	Measurement or calculation
Qinlet	Measured flow at the inlet to the wastewater treatment plant
SS	Measured suspended solids concentration in activated sludge tanks (MLSS)
dSVprofile	Measured sludge volume following the curve in each cycle of the sensor
nClr	Reported number of clarifiers in operation at one treatment line (usually 4)
Qbio	Qinlet/2
dSV	3 constant dSVprofle values in a row if $350 < \text{values} < 800$ else last calc. Value
dSVrate	Moving trend of dSVprofile last 5 values scaled by 0.023 if $700 < \text{values} < 1050$ else last calc. value
dSVI	dSV/SS
Vsed	Moving max. of dSVrate last 50 values
nv	$K1^*Exp(K2^*dSVI) + K3$; $K_1 = -0.9834$; $K_2 = -0.00581$; $K_3 = 1.043$
Qbiomax	Vsed * nClr * A; A = 306
ISV	Vsed * Exp (nv * SS)
QrSp	$ISV^*A^*(nv^*X - 1)^*Exp(-nv^*X)$ where X is the solution to $L(X) = 0$

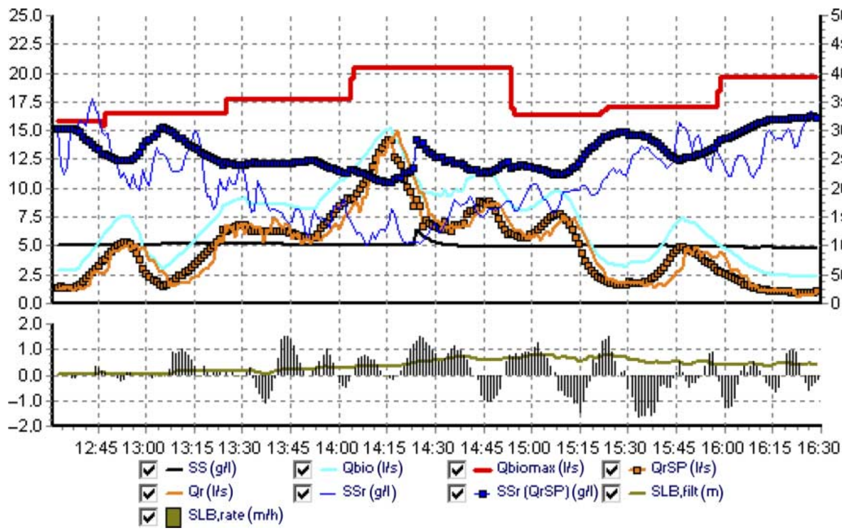

Figure 4 Controller and WWTP response to a step change in Q_{bio}. Subscribers to the online version of *Water Science and Technology* can access the colour version of this figure from http://www.iwaponline.com/wst

blanket level, $SLB_{,rate}$), but the expected concentration fits otherwise quite well with the measured concentration SS_r, which alternates due to sludgescraper movement (can possibly give a smooth value using a moving average).

Conclusions

This work has demonstrated the design and implementation of an easy configurable framework for implementation of controllers through the use of software sensors for:

- On-line determination of sludge settling characteristics from a SV-sensor, which as an output gives the settling curve described by the diluted sludge volume value *dSV* in ml/l as a function of time.
- Control of clarifiers according to the flux based state diagrams using the return sludge rate to maintain the flux balance and thereby keeping the return sludge rate at its allowable minimum.
- Real time determination of the maximum allowable hydraulic load on the biological step of a wastewater treatment plant to be used to control further steps in a control strategy during rain, these being stepfeed, utilisation of basins in the catchment or – as a last possibility – to by-pass the biological step of the WWTP.

Also it has been demonstrated that more work has to be done on the very central sensor for the controller. The SV-sensor has to improve its reliability, although failures to a certain degree can be compensated in the software sensors using the SV-sensor. Further, the stepwise change in the derived settling velocity should be filtered in order to give a more smooth output from the control algorithm.

References

Balslev, P., Nickelsen, C. and Lynggaard-Jensen, A. (1994). On-line flux-theory based control of secondary clarifiers. *Wat. Sci. Tech.*, **30**(2), 209–218.

Daigger, G.T. (1995). Development of refined clarifier operating diagrams using an updated settling characteristics database. *Water Environ. Res.*, **67**, 95–100.

Daigger, G.T. and Roper, R.E. (1985). The relationship between SVI and activated sludge settling characteristics. *J. WPCF*, **57**(8), 859–886.

Darling, D. (2003). *Clarifier Performance*. O&M Newsletters, Bureau of Land & Water Quality, Department of Environmental Protection, State of Maine. Monthly issues January – April.

DIMS (2005). *DIMS – Dynamic Integrated Monitoring System – an overview*. Product information, DHI Water&Environment.

Härtel, L. and Pöbel, H.J. (1992). A dynamic secondary clarifier model including processes of sludge thickening. *Wat. Sci. Tech.*, **25**(6), 267–284.

Keinath, T.M. (1985). Operational dynamics and control of secondary clarifiers. *J. WPCF*, **57**, 770–776.

Ozinsky, A.E. and Ekama, G.A. (1995). Secondary settling tank modeling and design. Part 2. Linking sludge settling ability measures. *Water SA*, **21**, 333–349.

Sekine, T., Tsugura, H., Urushibara, S., Furuya, N., Fujimoto, E. and Matsui, S. (1989). Evaluation of settleability of activated sludge using a sludge settling analyzer. *Wat. Res.*, **23**(3), 361–367.

Vanderhasselt, A. and Vanrolleghem, P.A. (2000). Estimation of sludge sedimentation parameters from single batch settling curves. *Wat. Res.*, **34**(2), 395–406.

Vanderhasselt, A., Aspegren, H., Vanrolleghem, P. and Willy Verstraete, W. (1999). Settling characterisation using on-line sensors at a full-scale wastewater treatment plant. *Water SA*, **25**(4), 453–458.

Vanrolleghem, P., Van Der Schueren, D., Krikilion, G., Grijspeerdt, K., Willems, P. and Verstraete, W. (1996). On-line quantification of settling properties with in-sensor-experiments in an automated settlometer. *Wat. Sci. Tech.*, **33**(1), 37–51.

Vesilind, P.A. (1968). Design of prototype thickeners from batch settling tests. *Water and Sewage Works* **114**(7), 302–306.

VOLITAX Operating instructions (2002). *Sludge volume/SV index measurement*. Hach-Lange Instrument Manual, DOC023.52.03095, August 2002.

Weyershausen, Häck, Voith (2002). Monitoring the sludge volume and the sludge volume index in activated sludge tanks with the aid of VOLITAX. Hach-Lange Application Note, DOC043.52.03192, December 2002.