Full-scale evaluation of activated sludge thickening by dissolved air flotation

Johannes Haarhoff and Erno Bezuidenhout
Department of Civil and Urban Engineering, Rand Afrikaans University, PO Box 524, Auckland Park 2006, South Africa

Abstract

This paper presents an overview of waste activated sludge thickening with dissolved air flotation (DAF). The most pertinent parameters that could influence DAF thickening performance are first identified, followed by a thorough review of the design models of Bratby and Marais (1975) and Bratby and Ambrose (1994) - the only rational theories available at this point. These theories are then tested against a comprehensive data set collected over a period of eight months during 22 site visits at five full-scale operating plants. The design models are poorly supported by the operational data. Black-box regression analyses are next performed on the data set to obtain estimates for sludge concentration, float-layer depth and clarity of the underflow. The regression analyses do not show strong correlation, but do demonstrate that, in three of the five plants visited, the float layers are too thin to withstand the disruptive action of the float scrapers. Without these disruptions, the existing models may very well be supported. Despite these data limitations, it can be concluded that float-layer depths of at least 150 mm should be maintained to prevent disruption by the scrapers, and that the design models in general do include the most pertinent variables controlling DAF thickening.

Nomenclature

a_s	dimensionless air-to-solids mass ratio	(-)
C_F	float-layer concentration	%
COD_{in}	chemical oxygen demand of incoming sludge	$g\cdot m^{-3}$
COD_{out}	chemical oxygen demand of underflow	$g.m^{-3}$
d_b	float-layer depth below the water level	m
d_w	float-layer depth above the water level (from lower edge of scraper blade)	m
L	effective length or periphery over which scraper travels	m
P	saturator pressure	kPa
Q	flow rate	
Q_s	solids loading rate on separation zone	$kg\cdot m^{-2}\cdot h^{-1}$
SS	suspended solids	
SS_{in}	suspended solids in the incoming sludge	$g\cdot m^{-3}$
SS_{out}	suspended solids in the underflow	$g\cdot m^{-3}$
SVI	sludge volume index	$m\ell\cdot g^{-1}$
t_c	hydraulic residence time in contact zone	s
t_e	effective drainage time in float layer	min
t_{on}	time during which scraper is scraping	min
t_{off}	time during which scraper is not scraping	min
v	scraper speed	$m\cdot min^{-1}$
v_c	hydraulic loading on contact zone	$m\cdot h^{-1}$
v_d	cross-flow velocity between contact and separation zone	$m\cdot h^{-1}$
v_L	hydraulic loading on separation zone	$m\cdot h^{-1}$
VSS_{in}	volatile suspended solids of incoming sludge	$g\cdot m^{-3}$
θ	sludge age	day

Introduction

This paper deals with our present ability to predict the efficiency of sludge thickening by dissolved air flotation (DAF). If the crucial design variables cannot be isolated, and mathematically related to the performance of DAF thickening, then these systems also cannot be rationally designed with an adequate degree of confidence.

The work reported here followed from a design guide commissioned by the South African Water Research Commission (WRC) (Haarhoff and Van Vuuren, 1993). In this publication, design and operational data from a survey of South African DAF plants were used in conjunction with published literature and theory to suggest a number of empirical guideline values for practical design. In this process, it was noted that there seemed to be a wide discrepancy between values actually measured on site, and the values predicted by the design model of Bratby and Marais developed more than 20 years ago, also under the direction of the WRC (summarised in Bratby and Marais, 1976). This prompted a third WRC project, with the specific objective to systematically measure the performance of a number of thickening plants, and to compare it with available design models (Bezuidenhout, 1995). This paper summarises the main findings from the latter project.

The specific objectives of this paper are to:

- review the variables which are usually used in DAF thickening models,
- summarise the principal design guidelines for waste activated sludge thickening,
- present the results of a detailed, extended survey of five South African DAF systems where waste activated sludge is thickened,
- compare the predicted with the actual performance, and
- offer possible explanations for the discrepancies found.

This study is confined to the thickening of waste activated sludge by DAF, without the use of any chemical conditioning.

Selection of experimental variables

A number of potentially important variables were identified by previous reports. They can be broadly classified into a number of categories:

---

* To whom all correspondence should be addressed.
☎ (011) 489-2148; fax(011) 489-2148; e-mail jh@ing1.rau.ac.za

Received 21 August 1998; accepted in revised form 1 December 1998.

TABLE 1
DEPENDENT AND INDEPENDENT VARIABLES SELECTED IN PREVIOUS STUDIES, AS WELL AS VARIABLES SELECTED FOR THIS STUDY

	Vrablik (1959)	Ettelt (1964)	Bratby and Marais (1975)	Lange-negger and Viviers (1978)	Gulas *et al.* (1980)	Haarhoff and Van Vuuren (1993)	Bratby and Ambrose (1994)	This study
C_F	✓		✓	✓	✓	✓	✓	✓
SS_{out}	✓				✓	✓		✓
d_b			✓				✓	✓
COD_{out}					✓			
SS_{in}	✓	✓		✓	✓	✓		✓
VSS_{in}				✓				
COD_{in}					✓			
SVI		✓		✓		✓	✓	✓
θ				✓	✓			
Q_s			✓			✓	✓	✓
v_L			✓			✓		✓
a_s		✓	✓	✓	✓	✓	✓	✓
P	✓					✓		
v_c						✓		✓
t_c						✓		✓
v_d						✓		✓
d_w			✓	✓			✓	✓
t_e			✓				✓	✓

- Properties of incoming sludge
- Applied air concentration
- Flotation reactor geometry
- Properties of float layer
- Properties of underflow

Some mechanistic explanations of how these parameters may play a role will be presented in a later section of this paper. For the purpose of the regression analyses which follow, it is also essential to separate the *dependent* variables from the *independent* variables. There are only three dependent parameters which are practically measurable:

- The float-layer solids concentration is designated as C_F , measured as total suspended solids and expressed as a mass-to-volume percentage. For thickening, the main emphasis is usually on C_F, which should be as high as could be practically pumped or drained.
- The clarity of the underflow is designated as SS_{out} , measured as total suspended solids and expressed as $g \cdot m^{-3}$.
- There is a third dependent parameter which comes into play during thickening, which is the thickness of the float layer *below* the water level, designated as d_b. The float layer will float partially above and partially below the water level, which is set by the hydraulic conditions at the tank outlet. The depth of the float layer *above* the water level, designated as d_w, is an independent parameter determined by the distance between the water level and the level of the lower scraper edge. (It should be noted that the lower scraper edge determines the top of the float layer immediately behind the scraper. With time, the float layer will gradually rise until the next pass of the scraper. In this paper, however, d_w will be used as a fixed value for each case, as defined. This may be slightly different from how other researchers dealt with this parameter.)

Table 1 contains a list of the most commonly reported variables measured in a number of important previous studies. The definition of each variable is given under **Nomenclature**. From these variables, ten independent variables and three dependent variables were chosen for inclusion in this study, indicated in the last column of Table 1.

Experimental investigation

Field investigation

Five treatment plants were selected for this study. Four of them are situated in the Pretoria area, operated by two different municipalities, while the fifth is in the Vereeniging area, south of Johannesburg. All five plants are activated sludge treatment plants for predominantly domestic wastewater, and the DAF

TABLE 2
SUMMARY OF DATA OBTAINED FROM FIELD INVESTIGATION

Plant #	Visit #	SS_{in}	SVI	a_s	Q_s	v_L	d_w	t_e	v_c	v_d	t	C_F	SS_{out}	d_b
		$mg \cdot \ell^{-1}$	$m\ell \cdot g^{-1}$	-	$kg \cdot m^{-2} \cdot h^{-1}$	$m \cdot h^{-1}$	m	min	$m \cdot h^{-1}$	$m \cdot h^{-1}$	s	%	$mg \cdot \ell^{-1}$	m
1	1	2 870	97	.0020	3.88	2.44	0.165	2.62	51	51	135	2.58	7	0.350
	2	2 560	172	.0218	3.79	2.57	0.170	2.53	53	53	128	3.69	8	0.348
	3	2 560	59	.0191	3.71	2.38	0.190	2.60	49	49	138	3.41	7	0.395
	4	2 020	168	.0679	1.08	1.49	0.170	2.53	31	31	221	3.51	6	0.298
	5	2 740	124	.0138	4.04	2.25	0.170	2.52	47	47	146	3.50	6	0.200
	6	3 210	65	.0217	3.24	1.97	0.170	2.62	41	47	168	3.13	5	0.285
1	median	2 650	111	.0218	3.75	2.23	0.170	2.57	48	48	142	3.46	7	0.258
2	1	2 380	100	.0238	1.42	1.16	0.030	7.39	234	197	8.4	5.00	35	0.285
	2	1 700	94	.0669	1.08	1.72	0.030	10.8	349	293	5.7	2.30	62	0.285
	3	2 280	101	.0410	1.42	1.72	0.030	3.57	347	292	5.7	2.90	22	0.150
	4	2 310	100	.0448	1.33	1.67	0.020	3.57	339	285	5.8	2.60	20	0.090
	5	2 000	100	.0254	2.46	2.58	0.060	3.57	522	439	3.8	3.30	17	0.265
	6	2 620	130	.0201	3.33	2.72	0.040	6.33	550	462	3.6	3.70	44	0.250
2	median	2 295	100	.0332	1.42	1.72	0.030	4.95	348	292	5.7	3.10	28	0.258
3	1	6 040	73	.0322	3.38	2.22		1.05	289	272	35.7	4.00	69	
	2	4 590	52	.0118	2.92	1.38		1.72	179	169	57.4	2.20	115	
	3	5 230	65	.0272	1.50	1.40	0.005	1.88	182	172	56.6	4.10	76	0.035
	4	4 780	86	.0229	2.42	1.62	0.015	1.10	210	198	49.1	3.20	85	0.020
3	median	5 005	69	.0251	2.67	1.51	0.010	1.41	196	185	52.9	3.60	81	0.028
4	1	2 950	197	.0398	1.29	1.27	0.170	2.96	20	39	371	3.50	18	0.550
	2	2 960	264	.1053	0.79	1.27	0.200	5.21	20	39	370	5.10	19	0.820
4	median	2 955	231	.0726	1.04	1.27	0.185	4.09	20	39	370	4.30	18	0.685
5	1	1 550	239	.0438	2.00	2.70	0.040	9.65	18	18	241	3.40	19	0.390
	2	2 590	158	.0151	3.21	2.60	0.041	8.28	18	18	246	3.10	63	0.079
	3	1 730	179	.0175	3.38	3.30	0.040	11.0	22	22	194	2.00	52	0.410
	4	3 610	139	.0121	5.75	3.40	0.060	9.32	23	23	188	2.40	45	0.380
	5	6 380	149	.0089	7.75	2.80	0.060	13.2	19	19	228	2.70	48	0.155
	6	3 760	144	.0146	5.21	3.10	0.135	8.78	21	21	207	3.60	36	0.265
5	median	3 100	154	.0149	4.29	2.95	0.051	9.49	20	20	217	2.90	47	0.323
all	max	6 380	264	.1053	7.75	3.40	0.200	13.2	550	462	371	5.10	115	0.820
all	min	1 550	52	.0089	0.79	1.16	0.005	1.05	18	18	3.6	2.00	5	0.020
all	median	2 680	113	.0225	3.06	2.24	0.060	3.57	50	50	137	3.35	28	0.285

units are used for thickening of the waste activated sludge. In all cases, the thickened waste activated sludge is discharged to either aerobic or anaerobic digestion, in some cases mixed with raw sludge from primary settling tanks, before eventual land disposal. There is no direct processing of the thickened waste activated sludge, such as centrifuging or mechanical dewatering, at any of the plants. The primary focus of the DAF units, therefore, is not necessarily to obtain the highest possible sludge concentration or the clearest possible underflow, but to separate and recover the bulk of the water within the waste activated sludge.

The five treatment plants (numbered #1 to #5 in this paper) were first visited to check on available instrumentation, sampling points and to refine analytical techniques. Once all procedures had been verified for reproducibility, the treatment plants were visited on a periodic basis. Each visit took most of a day and 22 site visits were made in total. Plants #1, #2 and #5 were visited six times each, Plant #3 four times and Plant #4 twice. Some analytical determinations were performed on site, while others were performed in the laboratory.

The treatment plants covered a considerable range of design and operational parameters. Not only were there considerable differences amongst plants, but there were also considerable differences over time at each individual plant.

Methods

Analytical measurements (SS and SVI) were done according to *Standard Methods* (1985). Total incoming flow measurements were obtained with the flumes, gauges and meters provided on site. Recycle flows were generally poorly instrumented or gauges were not working - they had therefore been measured with a portable clip-on type ultrasonic flow meter which had been calibrated against a magnetic flow meter in the laboratory. Pressure readings were done with a calibrated pressure gauge; the same gauge used on all sites. Saturator efficiency was measured with a batch-measurement apparatus which measured the air volume precipitated after pressure release. The top of the float layer and the water level were determined with a tape measure from a horizontal reference line. The total float-layer depth was measured with a thin glass tube connected to a peristaltic pump. As the tube was slowly lowered or lifted through the float layer, the bottom of the float layer could be detected quite precisely by watching when the liquid in the tube changed from sludge to clear water, or *vice versa*. These measurements were performed at three positions in the tank 120° apart and averaged. It should be noted that the individual measurements differed substantially, especially when the total float layer was thin.

Results of treatment plant survey

The results of the treatment plant survey are shown in Table 2.

Current design models

Empirical design guidelines

Flotation thickeners have traditionally been designed according to previous experience and empirical guidelines. A comprehensive compilation of design values was published (Haarhoff and Van Vuuren, 1993) from values found in the literature, and plant surveys done in Finland, England, the Netherlands and South Africa. On the basis of this compilation, a number of quantitative guidelines were suggested. Some of these values are shown in Table 3.

TABLE 3
SUMMARY OF EMPIRICAL DESIGN GUIDELINES (FROM HAARHOFF AND VAN VUUREN, 1993)

	Units	Minimum	Maximum
Hydraulic loading in contact zone	$m \cdot h^{-1}$	100	200
Residence time in contact zone	s	30	120
Saturation pressure	kPa	400	600
Air-solids mass ratio	-	0.02	0.04
Cross-flow velocity	$m \cdot h^{-1}$	50	200
Solids loading without coagulants	$kg \cdot m^{-2} \cdot h^{-1}$	2	6
Solids loading with coagulants	$kg \cdot m^{-2} \cdot h^{-1}$	6	12

The design model of Bratby and Marais (1975)

This model was presented as two equations which predicted C_F and d_b as follows:

$$C_F = K_4 . d_w^{K_5} . Q_s^{-K_6} \tag{1}$$

and

$$\left(d_b + d_w\right) = d_w . \left(a_s^{K_7} + K_8\right) . a_s^{-K_7} \tag{2}$$

Equation (2) can be rewritten to separate the dependent variable d_b from the independent variables:

$$d_b = d_w . K_8 . a_s^{-K_7} \tag{3}$$

Guideline values for the constant K_4 tot K_8 were suggested. For the sludge type considered in this study (i.e. activated sludge without chemical addition), two sets of constants are relevant; for "normal" and "poorly settling" sludge respectively. The guideline values are shown in Table 4.

TABLE 4
GUIDELINE CONSTANTS FOR THE MODELS OF BRATBY AND MARAIS (1975) AND BRATBY AND AMBROSE (1994). THESE CONSTANTS ARE CONSISTENT WITH UNITS OF METRE (LENGTH), KILOGRAM (MASS) AND DAYS (TIME)

Constant	Normal activated sludge	Poorly settling activated sludge
K_4	30.00	31.75
K_5	0.22	0.20
K_6	0.30	0.50
K_7	0.45	0.45
K_8	0.76	0.76

In this paper, length and mass are consistently expressed in metre (m) and kilogram (kg). For time, different units are used. The solids loading Q_s is expressed in terms of *hours* (h) as $kg \cdot m^{-2} \cdot h^{-1}$ and the effective drainage time is expressed in *minutes* (min). With this choice of units and substitution of the constants in Table 4, Eq. (1) can be adapted for *normal* activated sludge:

$$C_F = 11.6 . d_w^{0.22} . Q_s^{-0.30} \tag{4}$$

In the same way, the expression for *poorly settling* sludge is:

$$C_F = 6.12 . d_w^{0.20} . Q_s^{-0.50} \tag{5}$$

Equation (3) can be similarly adapted to an expression which is valid for both *normal* and *poorly settling* sludge:

$$d_b = 0.76 . d_w . a_s^{-0.45} \tag{6}$$

The model of Bratby and Marais (1975) therefore allows prediction of two dependent parameters, namely C_F and d_b. Both are predicted with two-parameter multiplicative models. The model does not allow prediction of SS_{out}.

The design model of Bratby and Ambrose (1994)

This model was presented as an adaptation of the earlier model of

Bratby and Marais (1975). A new parameter t_e was introduced, called the effective drainage time in the float layer:

$$t_e = \frac{t_{on} + t_{off}}{t_{on}} . \frac{L}{v} \tag{7}$$

Predictions for C_F and d_b are now made with:

$$C_F = K' . t_e^{\frac{K_5}{1+K_5}} \tag{8}$$

$$d_b = \frac{Q_s . t_e^{\frac{1}{1+K_5}}}{10.K'} . \left(1 + \frac{K_8}{a_s^{K_7}} \right) - d_w \tag{9}$$

The intermediate parameter K' is given by:

$$K' = \left(\frac{K_4}{Q_s^{K_6 - K_5} . 10^{K_5}} \right)^{\frac{1}{1+K_5}} \tag{10}$$

The same guideline constants in Table 4 are also valid for this model. Substitution of constants and correction for different units transform Eq. (8) into a predictor for *normal* activated sludge:

$$C_F = 2.35 . Q_s^{-0.0656} . t_e^{0.180} \tag{11}$$

For *poorly settling* sludge, Eq. (8) becomes:

$$C_F = 1.63 . Q_s^{-0.25} . t_e^{0.167} \tag{12}$$

Equation (9), similarly transformed for *normal* activated sludge, becomes:

$$d_b = 7.10 . 10^{-4} . Q_s^{1.07} . t_e^{0.820} . \left(1 + 0.76 . a_s^{-0.45} \right) - d_w \tag{13}$$

For *poorly settling* sludge, it is:

$$d_b = 1.02 . 10^{-3} . Q_s^{1.25} . t_e^{0.833} . \left(1 + 0.76 . a_s^{-0.45} \right) - d_w \tag{14}$$

Although the model of Bratby and Ambrose (1994) is an adaptation of the model of Bratby and Marais (1975), it does differ in a number of important respects:

- For the prediction of C_F, both models use two-parameter multiplicative models, but with different independent parameters. The one model uses Q_s and d_w, the other Q_s and t_e.
- For the prediction of d_b, the model by Bratby and Ambrose (1994) requires four parameters to predict d_b, as opposed to the model of Bratby and Marais (1975), which only uses two parameters. The later model estimates the total float-layer depth independent of d_w, and then obtains d_b by subtracting d_w.

The model of Bratby and Ambrose (1994) was tested on a system where the effective drainage time ranged between approximately 1 to 8 h, and where the average total float-layer thickness was approximately 1 000 mm, reaching up to 1 800 mm at times. This will be important when testing the model for other systems.

Prediction of the float-layer concentration

The data obtained during field investigations were used to test both the design models described in the previous section. The independent parameters in Table 2 were used with Eqs. (4), (5), (11) and (12) to obtain predicted values of C_F, which could then be compared with the measured values of C_F. These comparisons are shown in Fig. 1, where the predicted values are plotted against the measured values.

The model of Bratby and Marais (1975) provides an acceptable *range* of values between normal and poorly settling sludge, with 16 of the measured values within the range, and 6 outside the range. There is, however, not much evidence that the *trend* of the data is closely predicted. There is also no clear indication that there are consistent differences amongst the different plants.

The model of Bratby and Ambrose (1994) does not predict C_F as well as the model of Bratby and Marais (1975). The predicted values for normal sludge do approximately intersect the main data cluster, but the predicted values for poorly settling sludge are obviously too low. In this case, there is even less evidence that the underlying structure of the model is mirrored by the data. In both cases, the predicted values show much less variation than the measured values.

Prediction of the float-layer depth under the water level

Similar to the above, Eqs. (6), (13) and (14) were used to obtain predicted values of d_b, which could then be compared with the measured values of d_b. These comparisons are shown in Fig. 2, where the predicted values are plotted against the measured values.

The model of Bratby and Marais (1975) does intersect the data cluster approximately through the middle, but there is no indication that the underlying structure of the model is supported. The model of Bratby and Ambrose (1994) provides neither a good fit, nor does its structure match the data. In fact, the data indicate a trend opposite to that of the model. The negative values are obviously physically impossible.

Regression models from survey data

Statistical screening and model development

With the data set used in this investigation, some mutual correlation, or collinearity amongst the “independent” variables is inevitable. For example; all the hydraulic loadings such as v_L, v_c and v_d are calculated from the physical dimensions of the relevant zones (which are different for each variable) as well as Q (which is the same in all cases). Another example; SS_{in} is used as an independent variable, but is also used to calculate Q_s. The data were therefore firstly screened for collinearity. Evidence for collinearity was found amongst almost all variables. Unusually strong correlation was found only between v_c and v_d (due to the fact that both are strongly tied to the geometry of the contact zone), which indicated that one of them should be dropped from the data set as they contribute very similar information. In this case, v_c was judged to be of lesser importance and was dropped from further consideration, which reduced the data set in Table 2 to nine independent and three dependent variables.

Two regression models were applied in this investigation. The first is a linear additive model:

$$Y = a + b.X_1 + c.X_2 + \;..... \tag{15}$$

The second is an exponential multiplicative model:

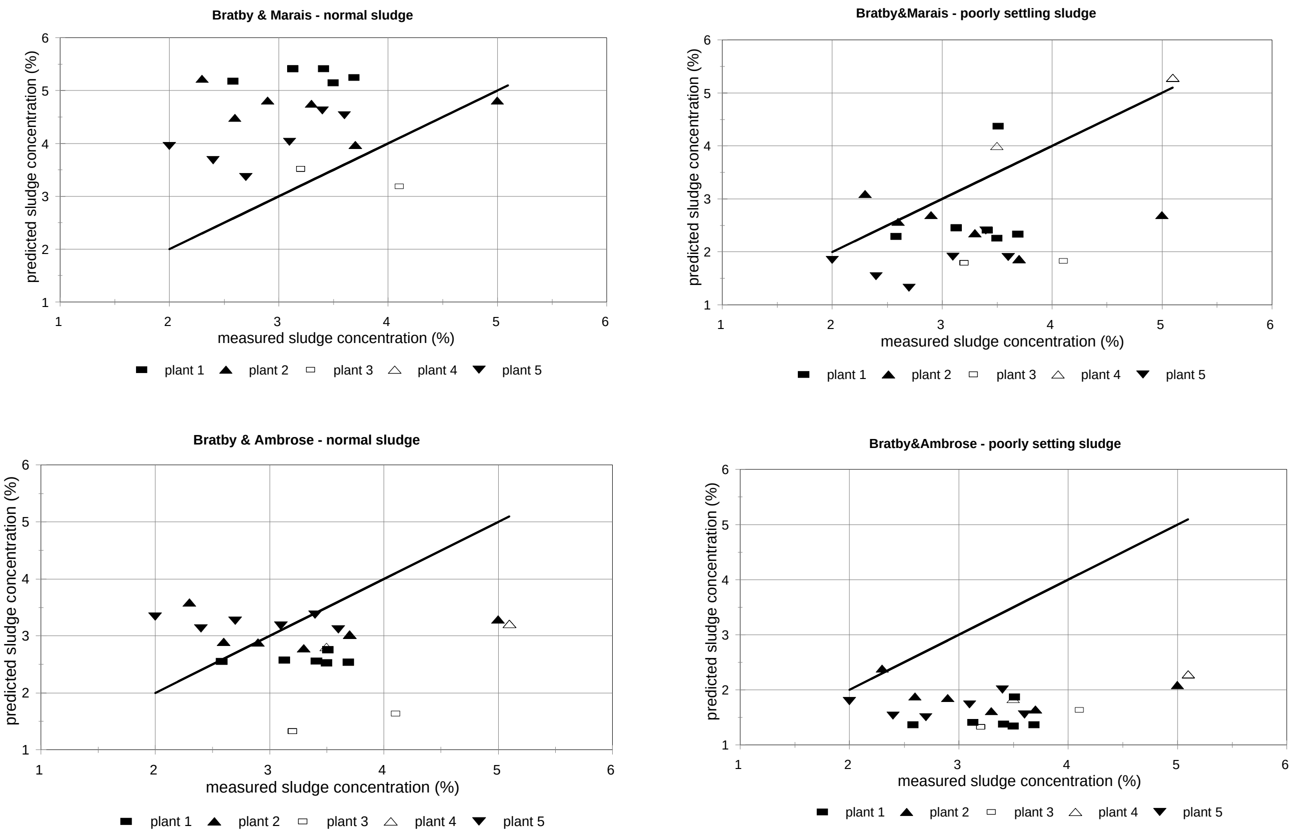

Figure 1

Predicted vs. *measured values of the float-layer concentration C_F.*
Top left : Bratby and Marais (1975) - normal sludge.
Top right : Bratby and Marais (1975) - poorly settling sludge.
Bottom left : Bratby and Ambrose (1994) - normal sludge.
Bottom right : Bratby and Ambrose (1994) - poorly settling sludge.

TABEL 5
BEST-FIT REGRESSION MODELS FOR THE FLOAT-LAYER CONCENTRATION C_F

Number of parameters	Constant	Exponent				r^2
	(-)	V_L ($m \cdot h^{-1}$)	d_w (m)	SS_{in} ($mg \cdot \ell^{-1}$)	SVI ($m\ell \cdot g^{-1}$)	(-)
1	4.19	-0.359				0.270
2	4.93	-0.386	0.0514			0.319
3	2.08	-0.384	0.0565	0.111		0.348
4	1.09	-0.395	0.0460	0.132	0.0951	0.373

$$Y = a.X_1^b.X_2^c. \quad ..... \qquad (16)$$

Both model types were tested for all the dependent variables. Each model was fitted with one, two, three and four independent variables respectively, leading to what will be designated in this paper as one-parameter, two-parameter, three-parameter and four-parameter models. No models beyond four independent variables are presented. Not only are such complicated models of limited practical value, but the incremental improvement in fit with more variables beyond four was minimal.

The regression models were developed by forward selection. The single best predictor was found amongst the independent variables, resulting in the best one-parameter model. A second independent variable is then selected to give the best two-parameter model, etc.

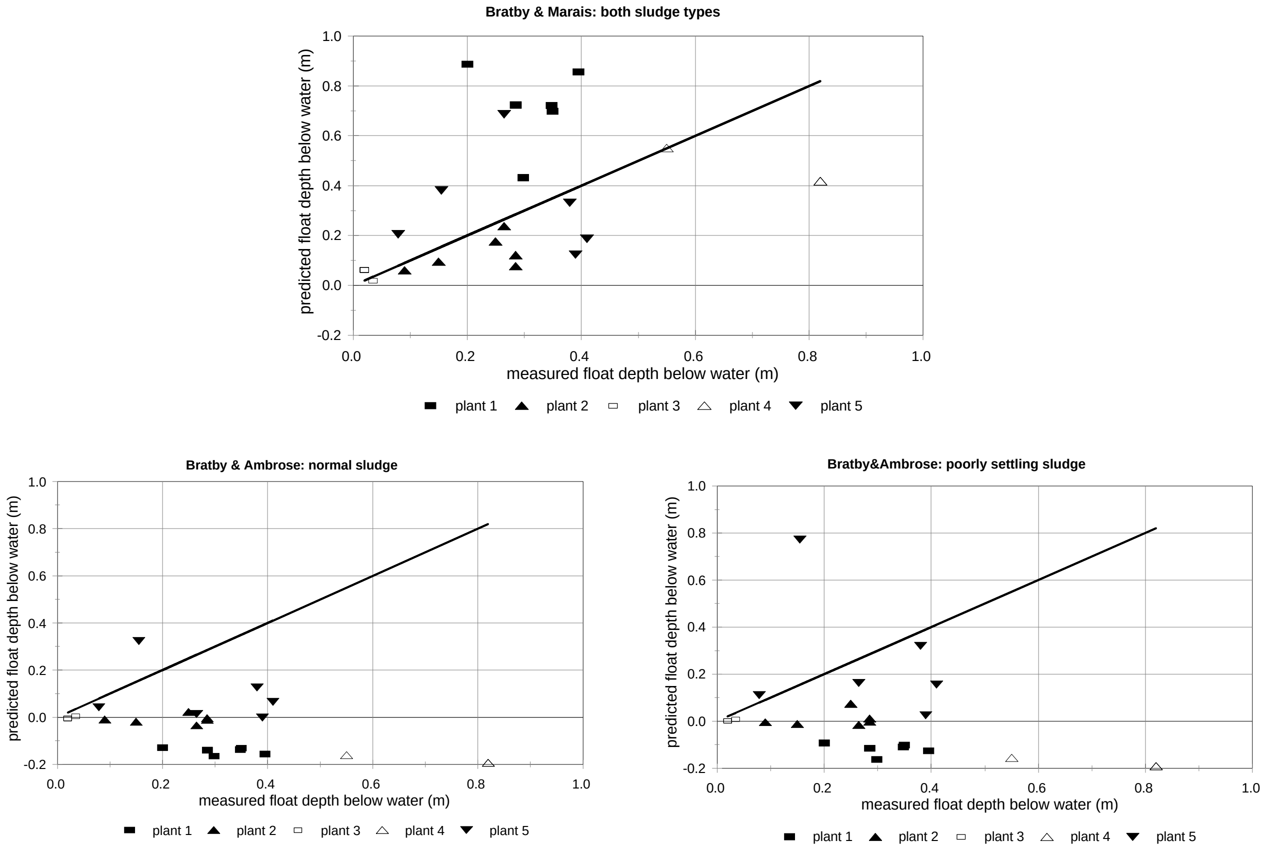

Figure 2

Predicted vs. *measured values of the float-layer depth below the water level* d_b.

Top centre : Bratby and Marais (1975) - normal sludge as well as poorly settling sludge.

Bottom left : Bratby and Ambrose (1994) - normal sludge.

Bottom right : Bratby and Ambrose (1994) - poorly settling sludge.

TABLE 6

BEST-FIT REGRESSION MODELS FOR THE DEPTH OF FLOAT LAYER BELOW WATER LEVEL D_B

Number of parameters	Constant	Exponent				r^2
	(-)	d_w (m)	t_e (min)	Q_s $kg \cdot m^{-2} \cdot h^{-1}$	SS_{in} $(mg \cdot \ell^{-1})$	(-)
1	1.28	0.632				0.531
2	0.606	0.650	0.533			0.708
3	0.936	0.713	0.617	-0.432		0.794
4	34.9	0.668	0.534	-0.287	-0.473	0.819

Regression model for float-layer concentration

The multiplicative model provided a better fit than the additive model. The best-fit multiplicative models with one, two, three and four parameters are summarised in Table 5.

The four models in Table 5 are shown in Fig. 3 as plots of predicted vs. measured values. Also shown in Fig. 3 is a plot of the one-parameter model in terms of the independent variable.

Table 5 shows that C_F cannot be predicted very well from the independent parameters. The one-parameter model has a correlation coefficient of only 0.27 and this improves only to 0.37 after three more independent variables are added. There is also no evidence of consistent differences amongst the different plants.

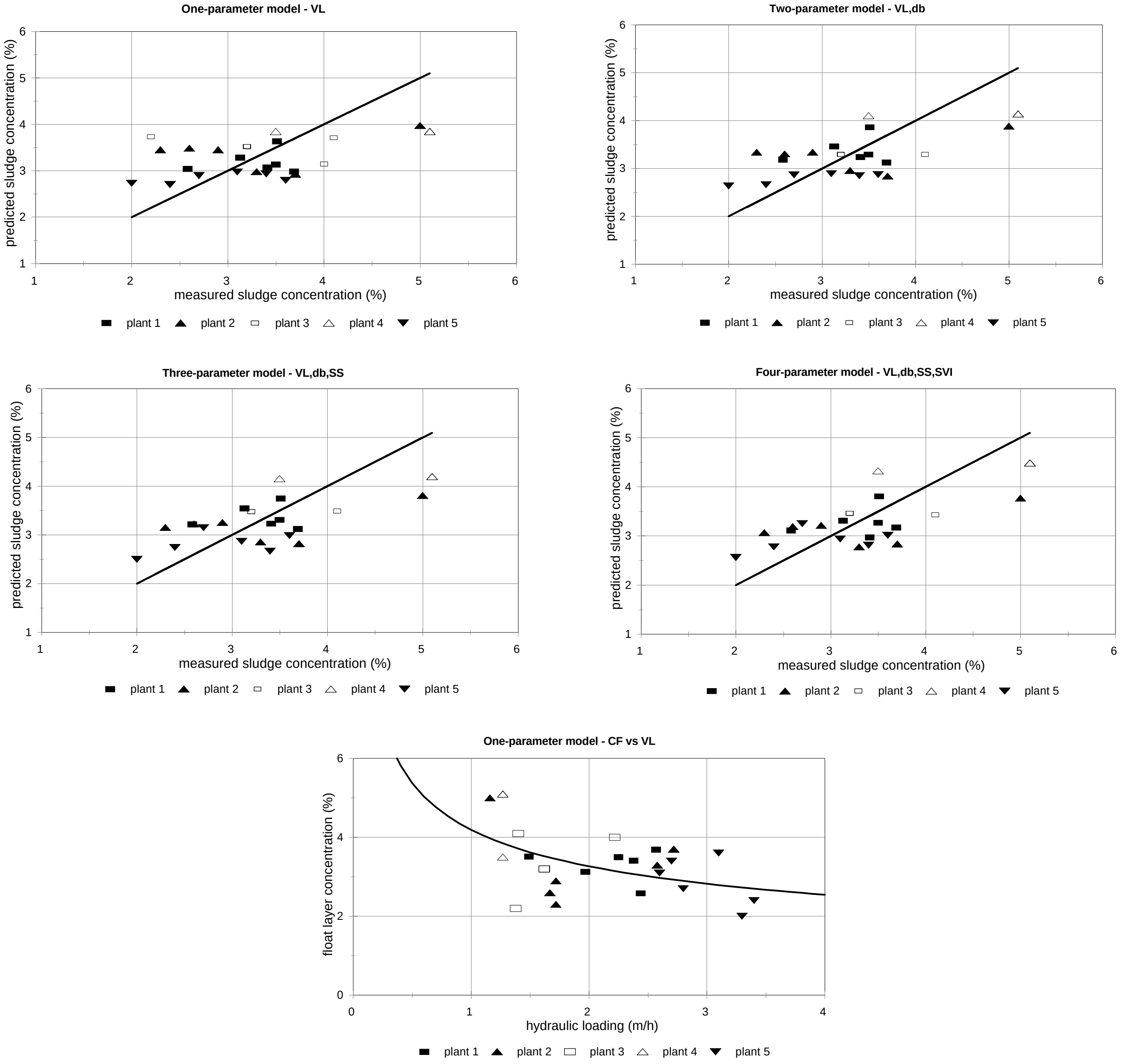

Figure 3

Predicted vs. *measured values for float-layer concentration C_F.*
Top four graphs show the fit obtained with one-, two- three- and four-parameter models respectively.
Bottom graph shows the regression line for the one-parameter model.

Regression model for float-layer depth below water level

The multiplicative model provided a better fit than the additive model. The best-fit multiplicative models with one, two, three and four parameters are summarised in Table 6.

The four models in Table 6 are shown in Fig. 4 as plots of predicted vs. measured values. Also shown in Fig. 4 is a plot of the one-parameter model in terms of the independent variable.

In this case, a reasonably good prediction of d_b is possible. The one-parameter model has a correlation coefficient of 0.53 and the addition of two more variables improves this to 0.79. There is very little benefit in adding the fourth independent variable SS_{in}. Plant 4 has lower d_b values than the other plants (consistent for all models), while Plant 1 has higher d_b values (notably for the one-parameter model).

Regression model for SS in underflow

The multiplicative and additive models provided approximately equally good fits for SS_{out}. The multiplicative model was judged to be physically more realistic, and the best-fit multiplicative models with one, two, three and four parameters are summarised in Table 7.

The four models in Table 7 are shown in Fig. 5 as plots of predicted vs. measured values. Also shown in Fig. 5 is a plot of the one-parameter model in terms of the independent variable.

A reasonably good prediction of SS_{out} is possible. The one-parameter model has a correlation coefficient of 0.57 and the addition of two more variables improves this to 0.80. There is very little benefit in adding the fourth independent variable SVI. There is no evidence of consistent differences amongst the different plants.

TABLE 7
BEST-FIT REGRESSION MODELS FOR THE SUSPENDED SOLIDS IN THE UNDERFLOW SS_{OUT}

Number of parameters	Constant	Exponent				r^2
	(-)	d_w (m)	t_e (min)	SS_{in} ($mg \cdot \ell^{-1}$)	SVI ($m\ell \cdot g^{-1}$)	(-)
1	3.31	-0.690				0.570
2	1.60	-0.672	0.517			0.721
3	$4.91x10^{-3}$	-0.634	0.602	0.728		0.796
4	$4.74x10^{-4}$	-0.689	0.492	0.772	0.416	0.819

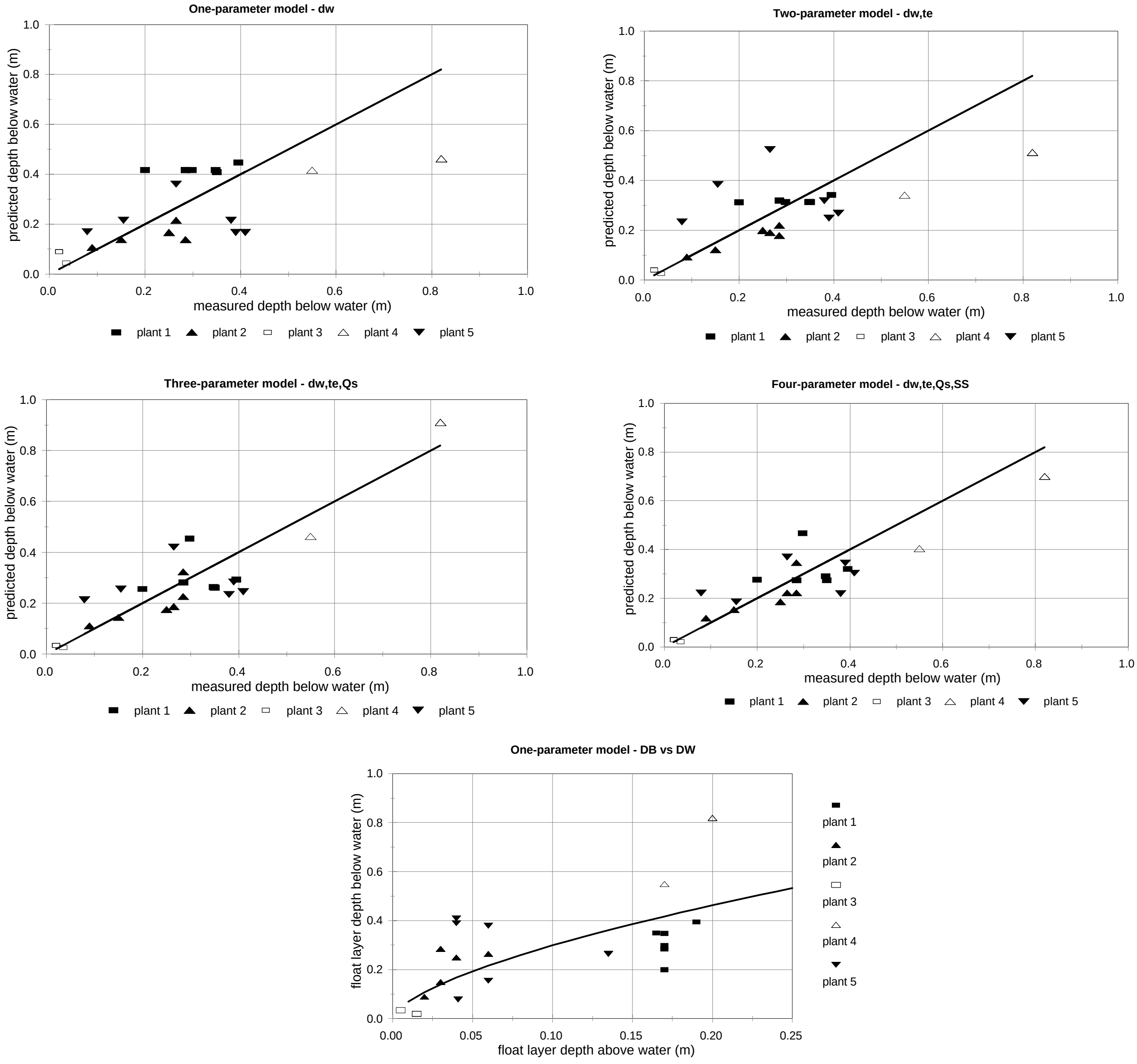

Figure 4

Predicted vs. *measured values for the float-layer depth below the water level d_b*
Top four graphs show the fit obtained with one-, two- three- and four-parameter models respectively.
Bottom graph shows the regression line for the one-parameter model.

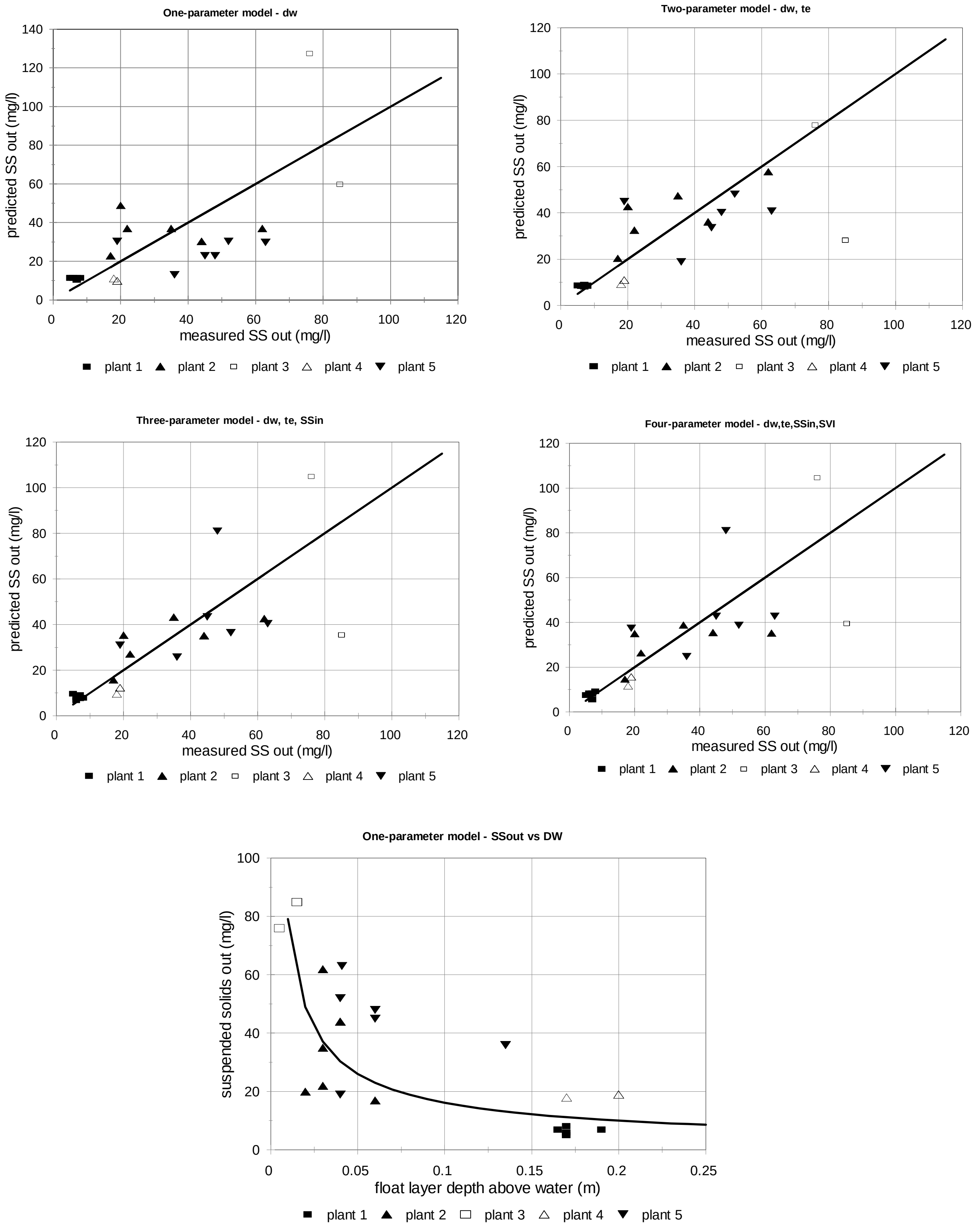

Figure 5

Predicted vs. *measured values for the suspended solids in the underflow* SS_{out}

Top four graphs show the fit obtained with one-, two- three- and four-parameter models respectively.

Bottom graph shows the regression line for the one-parameter model.

Discussion of process variables

In this section, the role of each of the process variables will be discussed in terms of fundamental mechanisms, previously published findings, and the extent to which they have been illuminated by the data of this study.

Air requirements

A key parameter for DAF thickening is the volume of air released in the contact zone (e.g. Bratby and Marais, 1976; Langenegger and Viviers, 1978; Roberts et al., 1978). To move the solids in the sludge to the surface, enough air has to be attached to the solids to attain positive buoyancy. The more solids, the more air is required; this led to the concept of maintaining a constant mass ratio of air to solids, designated as a_s. It was shown earlier that the air is not utilised efficiently (Ettelt, 1964). By comparison of the experimentally observed rise rates of agglomerates with the calculated buoyancy of the agglomerates, the *air-adhesion efficiency* could be determined, which ranged only between less than 5% and 11%. This means that a large fraction of the air does no useful work at all. A number of potential air "losses" in DAF were recently enumerated (Haarhoff and Steinbach, 1997) which showed that the air application efficiency could indeed be much lower than generally thought. Different plants could have very different air-application efficiencies. Furthermore, for DAF thickening very little had been reported on injection nozzle design, in stark contrast to the application of DAF to clarification in water treatment, where the importance of injection nozzle design, and bubble size distribution, had been evident for years and reported on in much more detail (Rykaart and Haarhoff, 1995). Important other aspects affecting the air-application efficiency may be overlooked by characterising the air requirement for thickening simply by a_s. However, there is no doubt that an adequate a_s is at least a necessary prerequisite for effective thickening, albeit crude.

The models of Bratby and Marais (1975) and Bratby and Ambrose (1994) do not include include a_s as a predictor of C_F. Both models do, however, include a_s as a predictor for d_b. It was argued that a_s influences both the rise rate of the agglomerates and d_b and therefore can indirectly lead to higher C_F. For a given set of parameters, however, there should be no direct link between a_s and C_F.

In this study, a_s was not amongst the top four predictors for either C_F, d_b or SS_{out}. This could only indicate that a_s is important up to a certain point, but that more air beyond that point does not improve the flotation performance. In this study, a_s was usually higher than the minimum of 0.02 which is usually recommended.

Sludge properties

It had been shown in a number of studies that not all sludges respond similarly to DAF thickening (e.g. Bratby and Marais, 1975; Langenegger and Viviers, 1978; Roberts et al., 1978). Bratby and Marais (1975) allowed for this phenomenon by providing the two categories presented earlier, namely "poorly settling sludge" or "normal sludge". With the exception of zeta potential (Roberts et al., 1978). which incidentally did not show any systematic effect, very little has been published in the DAF thickening literature on fundamental sludge properties and rheology.

The role of SVI

Some researchers (Langenegger and Viviers, 1978; Gulas et al., 1980) did find a definite relationship between C_F and the SVI which is widely used as a measure of sludge settleability. The higher the SVI, the lower the C_F that could be attained by DAF thickening. Bratby and Marais (1975) did not find this consistent dependence on SVI. It was also argued (Halliday, 1978) that SVI is not an adequate descriptor of the sludge properties and that more sophisticated measures should be used. Bratby and Ambrose (1994) later did use SVI as a measure to distinguish between time periods when sludge was more efficiently thickened than others.

The regression models derived from this study do not assign significant importance to SVI. For the prediction of C_F, it only enters as the fourth most important predictor. For d_b it does not enter in the top four independent variables. For SS_{out} it enters again as the fourth best predictor, but its addition to the regression model contributes very little to the overall fit.

The role of SS_{in}

Langenegger and Viviers (1978) found with batch tests that C_F was influenced by SS_{in} ; the higher SS_{in}, the higher C_F. This finding was supported by further experimental work (Gulas et al., 1980). It was further reinforced by the regression model of this study, which found SS_{in} to be the third best predictor of C_F.

Contact-zone parameters

The contact zone of a DAF reactor is the zone where sludge particles and air mix for the first time to form stable, buoyant agglomerates. This zone was earlier also called the whitewater zone, reaction zone or mixing zone, but the term "contact zone" was adopted at the 1994 International AWWA/IAWQ /IWSA Conference in Orlando in the interests of standard nomenclature. The processes within the contact zone can be likened to three-phase flocculation, where bubbles, particles and water are mixed. Analogous to conventional two-phase flocculation, the *intensity* of mixing as well as the *time* of mixing should be of importance. In one of the earliest papers on sludge thickening (Ettelt, 1964) it was indeed shown that the contact zone "...was the most critical structural feature for flotation..." Six different inlet configurations were experimentally tested and significant differences in performance were observed, all other conditions being unchanged. Despite this early finding, the research since has concentrated almost exclusively on appropriate parameters for the separation zone. There are, therefore, no generally accepted parameters for the characterisation of the contact zone. A first attempt was made (Haarhoff and Van Vuuren, 1993) to use the hydraulic retention time in the contact zone and the average velocity or *hydraulic loading* through the contact zone as crude measures of the mixing time and mixing intensity, with a further proposal to limit the *cross-flow* velocity from the contact zone to the separation zone in order not to introduce unacceptable turbulence to the flotation zone.

The regression models developed in this study assign very litttle significance to any of the contact-zone parameters; they do not enter as in the top four predictors for any one of C_F, d_b or SS_{out}. This does not necessarily rule out the importance of the contact zone, but it does mean that perhaps other parameters have to be found which provide a better description of contact-zone turbulence and retention time.

Separation-zone parameters

Following the contact zone, the flow enters into the *separation* zone, where quiescent conditions are required for the particle/bubble agglomerates to separate and be buoyed into the float layer. The separation zone is sized to limit either Q_s (expressed as $kg\cdot m^{-2}\cdot h^{-1}$), or v_L (expressed as $m\cdot h^{-1}$). For clarification applications with low SS_{in}, the hydraulic loading is limiting, but for thickening with high SS_{in}, Q_s is the limiting parameter (Bratby and Marais, 1975). The importance of the solids loading for thickening is recognised by most (Ettelt, 1964; Langenegger and Viviers, 1978; Roberts et al., 1978). The depth of flotation tanks is not considered to have a direct influence on the thickening performance, except if the tank becomes excessively shallow.

The role of Q_s

The early work by Ettelt (1964) suggested a low limiting value for Q_s of 3 $kg\cdot m^{-2}\cdot h^{-1}$. Later, higher values were suggested; values of 8 $kg\cdot m^{-2}\cdot h^{-1}$ (Halliday, 1978) and 10 $kg\cdot m^{-2}\cdot h^{-1}$ (Langenegger and Viviers, 1978). More recently, a design guideline of 2 to 6 $kg\cdot m^{-2}\cdot h^{-1}$ was suggested for activated sludge without coagulants (Haarhoff and Van Vuuren, 1993).

Q_s was included in the prediction of C_F in the model of Bratby and Marais (1975); C_F being approximately inversely proportional to the square root of Q_s. In the later model by Bratby and Ambrose (1994), Q_s is also included, but with significantly smaller exponents, thereby reducing its effect. Its importance was rationalised by the logical argument that Q_s controls the rise rate of the float above the water level, thereby directly governing the effective drainage time t_e. In the regression model for C_F of this study, surprisingly, Q_s was not one of the top four predictors.

The model of Bratby and Marais (1975) did not include Q_s in its prediction of d_b, but the later model of Bratby and Ambrose (1994) did include it with approximately a linear correlation between d_b and Q_s. The regression model of this study did not show Q_s to be one of the top four predictors for d_b.

The role of v_L

v_L was not recognised as an important variable for thickening applications. Somewhat surprisingly, v_L turned out to be the best single predictor in this study for C_F. Although the correlation between v_L and C_F is weak, it suggests that hydraulic loading should not be completely ignored for predictions of C_F.

Float-layer depth and position

A clear, elegant explanation was developed by Bratby and Marais (1975) of the thickening mechanism within the float layer. Three important elevations are recognised; the top of the float layer (theoretically determined by the bottom edge of the sludge scraper), the water level (the elevation on the top of the water surface at the separation zone outlet), and the bottom of the float layer. The depth of the float layer above the water level is designated as d_w and the depth of the float layer below the water line is designated as d_b, with the total float-layer depth thus (d_w+d_b). The thickening is partly caused by the air pushing on the bottom of the float layer, thereby squeezing out some of the interstitial water (analogous to compression settling). The most important thickening mechanism, however, is the draining of interstitial water from the part of the float layer above the water line. This was experimentally demonstrated in a small batch system (Langenegger and Viviers, 1978) for a typical sludge which showed C_F to be 5.0% at the top of the float layer, 3.3% at the water level and 2.8% below the water level. For a large full-scale plant, increasing d_w also led to higher C_F (Halliday, 1978). The independent variable d_w is therefore of importance for C_F. The depth below the water level d_b is a dependent variable, and also important for design. An excessively deep build-up of sludge below the water level could increase the lateral flow velocity under the float layer to the extent that the float layer is eroded from below.

The role of d_w

The model by Bratby and Marais (1975) included d_w in both their predictions of C_F and d_b. In the later model by Bratby and Ambrose (1994), d_w was dropped from the prediction of C_F, and its role in its prediction for d_b was changed, as is evident from Eqs. (6), (13) and (14).

The regression models of this study assign an important role to d_w. It is the second most important predictor for C_F, which agrees with the mechanism above. It is obviously also the most important predictor for d_b, for any given d_w will require adequate d_b to remain floating. Somewhat surprising, d_w is also the most important predictor for SS_{out}. This may be indirectly related to the practical problems of float-layer scraping, as will be discussed further on.

The role of t_e

Bratby and Ambrose (1994) introduced t_e into their prediction for both C_F and d_b. The regression models of this study do not include t_e as one of the top four predictors for C_F, but do include t_e as the second most important predictor for both d_b and SS_{out} . This suggests that t_e is an important parameter which plays an important role in DAF thickening.

Float-layer removal

The conceptual model of float scraping is that the scraper blade cuts cleanly into the float layer and only slices off the top part of the layer, without disturbing or moving the rest of the float layer. In a very small tank or a circular test column, float scraping may approximate this ideal situation. For example, only the top 5 mm of the float layer could be removed in one study (Langenegger and Viviers, 1978). In another study, stabilising vanes were used (Bratby and Marais, 1975) to maintain the float layer in position while the top is being sliced off. In a full-scale tank, however, there is a tendency for the entire depth of the float layer to be affected by the scraper, identified in one of the very first studies (Ettelt, 1964) which warned against "excessive flight and scraper operation". A number of problems have been identified; namely knockdown (parts of the float layer break loose when the scraper moves over the float layer), depression (the float layer is pushed downward by the scraper and pushes up again after the scraper has passed) and rolling (the float layer breaks into strips which roll and partially decompose as the scraper passes over). The problems and suggested improvements for float-layer removal in large tanks have been reported on by many and are reviewed elsewhere (Haarhoff and Van Vuuren, 1993). The fact is that most plants, including those surveyed in this study, have float-scraping mechanisms which are imperfect and do not come close to the ideal case. Float layers are visibly pushed around and white water is momentarily visible at the trailing edge of the scraper blade. This explains the difficulty, reported earlier, in attaining reproducibility and precision when measuring d_b and d_w.

The regression models developed in this study, even with inclusion of up to four independent parameters, showed poor correlation with C_F and only mediocre correlation with d_b and SS_{out}, despite the fact that almost all the potentially significant process parameters were considered. The main reasons for the generally poor predictive power of all the models presented in this paper, in the opinion of the authors, are the often-observed imperfect float-scraping systems of the plants studied. This is evidenced by the fact that d_w was the single best predictor of the quality of the underflow SS_{out}, despite the fact that these two parameters have no physical connection - in a flotation tank the part of the float layer below the water level acts as a barrier between them! The explanation of this apparent paradox is that the float layer is significantly disrupted by the float scraper, and parts of the float layer are "mixed" with the underflow when the scraper passes overhead. The thinner the float layer, the more severe this mixing becomes. The two plants with the thickest float layers were the two plants with lowest SS_{out}, while the plant with the very thin float layer had the highest SS_{out} .

It seems reasonable to suggest that float-scraping imperfections will be amplified when the total float layer is thin. With a thick layer, it will be more difficult to push the entire float layer laterally or vertically, and therefore easier to slice off the top part of the layer. This is especially evident in the bottom graph of Fig. 5, which shows a marked deterioration of SS_{out} when d_w drops below about 150 mm. For three of the plants studied, d_w was consistently below this value. This fits in well with the suggested minimum d_w of 300 mm put forward for practical design (Langenegger and Viviers,1978).

Conclusions

Published surveys of full-scale DAF thickening plants showed wide scatter in performance (Roberts et al., 1978; Haarhoff and Van Vuuren, 1993). In order to eliminate sampling or measurement errors, considerable care was taken in this study to measure as many variables as practically possible, to measure them in a consistent way at all five plants surveyed, and to make repeat measurements at all five plants to ensure a more reliable assessment of each plant's performance. There was considerable variation in the activated sludge properties over time, and also a wide range in the design parameters for each plant. This explains the fairly wide variation in day-to-day operational performance of the DAF thickeners.

A primary finding of this study is that three of the five plants do not allow the float layer to accumulate sufficiently to adequately allow the drainage of water from the float layer above the water level, and to provide enough stability to protect the float layer from being destabilised by the sludge scrapers. The data from this study can therefore not be used as absolute verification of the published design models. The model of Bratby and Marais (1975) was calibrated at laboratory and pilot-scale where the float layer could be removed in an ideal way. The later model of Bratby and Ambrose (1994) was calibrated on a full-scale plant where the float layer was allowed to accumulate much more than reported here. Given these constraints, the following conclusions pertain to these models:

- The model of Bratby and Marais (1975) made the important distinction between the parts of the float layer which are above and below the water level. The importance of the depth above the water level d_w is demonstrated in this study by the fact that it features as one of the top two predictors in all three correlations reported in this study.
- The role of the air-to-solids ratio a_s does not appear to be so important, as it did not feature amongst the top four parameters in any of the three reported correlations. This indicates that air seems to be a necessary condition up to a point, but that it has no further effect once a certain threshold concentration is reached.
- The main contribution of the model of Bratby and Ambrose (1994) is the introduction of the effective drainage time t_e. It features as the second best predictor in two of the reported correlations.

The correlations developed in this study cannot be directly used for design, as they are based on limited data, which were collected under non-optimal conditions. Given these constraints, they are nevertheless useful in reaching the following general conclusions:

- The depth of the float layer should be at least 150 mm above the water level to ensure reasonable stability of the float layer during sludge scraping.
- The best correlation coefficient between the float-layer concentration C_F and the independent variables is poor, due to the disruption of the float layer by the scraping equipment.
- The depth of the float layer below the water level is approximately proportional to the square root of the effective drainage time.
- The best correlation coefficient between the suspended solids in the underflow and the independent variables appears reasonably high. This is misleading as it is partially based on data derived from plants with disrupted float layers. With all data derived from plants with thicker float layers, the correlation could be significantly different.

Acknowledgments

The financial support provided by the WRC, as well as the enthusiastic assistance rendered by the personnel at the five participating treatment plants, are gratefully acknowledged. Prof. John Buonoaccorsi at the University of Massachusetts at Amherst provided valuable guidance with the statistical analysis and interpretation.

References

BEZUIDENHOUT E (1995) Evaluasie van Volskaalse Geaktiveerde Slykverdikking met Opgelostelugflottasie (Evaluation of Full-scale Thickening of Activated Sludge With Dissolved Air Flotation). M.Eng. Thesis, Rand Afrikaans Univ., Johannesburg.

BRATBY JR and MARAIS GvR (1975) Dissolved air (pressure) flotation - An evaluation of inter-relationships between process variables and their optimisation for design. *Water SA* **1** (2) 57-69.

BRATBY JR and MARAIS GvR (1976) A guide for the design of dissolved air (pressure) flotation systems for activated sludge processes. *Water SA* **2** (2) 87-100.

BRATBY JR and AMBROSE WA (1994) Design and control of flotation thickeners. In: *Proc. Conf. on Flotation Processes in Water and Sludge Treatment*, 24-26 April, Orlando, Florida. 181-196.

ETTELT GA (1964) Activated sludge thickening by dissolved air flotation system. In: *Proc. 19th Ind. Waste Conf.*, Purdue Univ. 210-244.

GULAS V, BENEFIELD L, LINDSAY R and RANDALL C (1980) Design considerations for dissolved air flotation. *Water and Sewage Works* **127** (7) 30-31, 42.

HAARHOFF J and VAN VUUREN LRJ (1993) A South African Design Guide for Dissolved Air Flotation. Report to the Water Research Commission, Pretoria.

HAARHOFF J and STEINBACH S (1997) Towards the maximal utilization of air in dissolved air flotation. In: *Dissolved Air Flotation*, *Proc. of an Int. Conf.*, London, April, Chartered Inst. of Water and Environ. Manag. 25-34.

HALLIDAY J (1978) Discussion on paper by Langenegger and Viviers (1978) referenced further on.

LANGENEGGER O and VIVIERS JMP (1978) Thickening of waste activated sludge with a dissolved air flotation unit. *J. Water Pollut. Control* 79-84.

ROBERTS KL, WEETER DW and BALL RO (1978) Dissolved air flotation performance. In: *Proc. 33th Ind. Waste Conf*, Ann Arbor. 194-199.

RYKAART EM and HAARHOFF J (1995) Behaviour of air injection nozzles in dissolved air flotation. *Water Sci. and Technol.* **31** (3-4) 25-35.

STANDARD METHODS (1985) *Standard Methods for the Examination of Water and Wastewater* (16th edn.) APHA/AWWA/WPCF.

VRABLIK ER (1959) Fundamental pinciples of dissolved-air flotation of industrial wastes. In: *Proc. 14th Ind. Waste Conf*, Purdue Univ. 743-779.