System analysis for optimal control of a wastewater treatment benchmark

D. Vrečko*, N. Hvala*, J. Kocijan,* and M. Zec*****
*J. Stefan Institute, Jamova 39, SI-1000 Ljubljana, Slovenia
**Nova Gorica Polytechnic, Vipavska 13, SI-5000 Nova Gorica, Slovenia
***Ministry of Environment and Physical Planning, Vojkova 1b,SI-1000 Ljubljana, Slovenia

Water Science and Technology **Vol 43 No 7 pp 199–206** © 2001 IWA Publishing and the authors

Abstract The paper presents an analysis and optimisation of a wastewater treatment benchmark. The benchmark is a simulation environment defining a plant layout, simulation model, influent data, test procedures and evaluating criteria that should be used for comparing different control strategies. In this paper an analysis of the benchmark which addresses the influences of potential manipulated variables on control performance under different operating conditions is presented. In the study optimisation is used to define the optimal values of the manipulated variables under constant as well as dynamic influent conditions. The results indicate that such an analysis and optimisation give important information about the manipulated variables under varying influent conditions and consequently about possible control strategies.

Keywords Activated sludge process; benchmark; control; optimisation; wastewater treatment plant

Introduction

Wastewater treatment is one of the very active research areas from both the technological and control points of view. The new plant configurations for the removal or organic, nitrogen and phosphorus compounds require several basins and recycle flows and are therefore becoming very complex. Hence, they also require a higher level of process control and automation, which is becoming an integral part of the technological solution.

The importance of control in wastewater treatment has in the past stimulated a lot of research in this area. However, the proposed control strategies and algorithms are often tested for slightly different plant configurations, under different operating conditions and showing plant performance only in relation to some of the operating goals. A need for a fair comparison under well-defined conditions initiated the work in the European research programme COST 624, wherein Working Group No. 1 has defined a wastewater treatment benchmark for evaluating different control strategies. The benchmark is a platform-independent simulation environment defining a wastewater treatment plant layout, simulation model, influent data, test procedures and evaluating criteria for comparing control performance (Pons *et al.*, 1999; Alex *et al.*, 1999). More information about the COST 624 action and the benchmark can be found on the website *http://www.ensic.u-nancy.fr/COSTWWTP*.

In the control design of a given benchmark problem it is to be expected that the proposed control schemes will be based on several control loops acting on different and interrelated process variables. For a system with such complexity it is therefore reasonable to assess the plant behaviour and performance in relation to operating goals. Such an analysis performed by simulation is a valuable tool in assessing control needs prior to control design.

In this paper a simulation analysis of the benchmark problem is performed. The analysis addresses the influence of potential manipulated variables on the control performance under different operating conditions. Optimisation is used to define optimal operating points in steady state as well as under dynamic influent conditions. The results indicate that such an analysis provides the information about the relative importance of different manipulated variables and about the need for control under varying influent conditions.

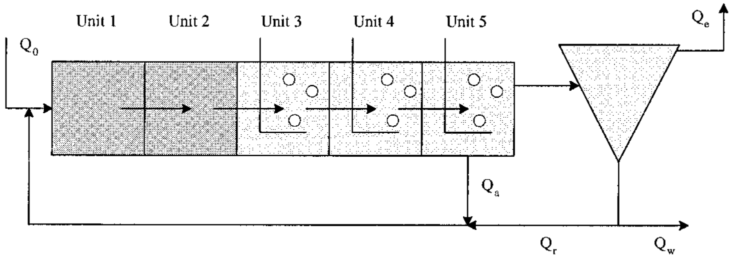

Figure 1 Benchmark plant layout

The paper is organised as follows: in the next section the plant layout of the benchmark problem is given; then the steady state analysis is described; then optimisations with constant influent and dynamic influent conditions are presented. At the end some conclusions are drawn.

The benchmark problem

The benchmark plant layout is shown in Figure 1. The plant is designed as an activated sludge process removing organic and nitrogen compounds from wastewater. The plant consists of the anoxic (units 1 and 2) and oxic (units 3–5) zones and a settler. In the benchmark plant layout Q_0, Q_a, Q_r, Q_w and Q_e represent influent flow, internal recycle flow, external recycle flow, waste sludge flow and effluent flow respectively.

To represent the biological processes in the benchmark the ASM1 (Henze *et al.*, 1987) model was used, while for the settling processes the Takács (Takács *et al.*, 1991) ten-layers model was selected. Influent data for the benchmark is available in three influent files containing 14-day dynamic input data for different weather conditions, the dry weather file, the rainy weather file and the stormy weather file. To calculate the benchmark performance, first the benchmark has to be run to the steady state by simulating the plant at the defined constant influent. Then the simulation continues by twice applying one of the dynamic weather influent files. The performance of the benchmark is evaluated for the last seven days of simulation and includes different criteria such as effluent quality, aeration energy, pumping energy and sludge production.

Steady-state analysis

The aim of the steady state analysis was to find out the influence of influent and manipulated variables on the effluent in order to build the appropriate control strategies for the benchmark. All simulations were performed in Simulink.

In the analysis the following potential manipulated variables were addressed: K_La in unit 5 (K_La 5), internal recycle flow Q_a, external recycle flow Q_r and waste sludge flow Q_w.

The following effluent components were chosen as observed output variables: total nitrogen $N_{tot,e}$, COD_e, ammonium $S_{NH,e}$, total suspended solids TSS_e, $BOD_{5,e}$ and nitrates $S_{NO,e}$.

Steady-state analysis was performed by changing the manipulated variables around the predefined operating point. The latter was specified in Pons *et al.* (1999) and Alex *et al.* (1999) as $K_La\ 5=84\ d^{-1}$, $Q_a=55338\ m^3 \cdot d^{-1}$, $Q_r=18446\ m^3 \cdot d^{-1}$ and $Q_w=385\ m^3 \cdot d^{-1}$.

Steady-state values (static characteristics) of the output variables were obtained by simulating the plant operation for 150 days so that it reached the steady state. In order also to consider the influence of influent on effluent, simulations were performed for three different influent conditions: low, mean and high. The mean influent was an average influent flow with average component concentrations computed from data in the dry-weather file. The low and

Table 1 Values of influent components and influent flows in different constant influent conditions

Influent component	Low influent conditions	Mean influent conditions	High influent conditions
S_I (g · m^{-3})	30	30	30
S_S (g · m^{-3})	40.8	69.5	83.8
X_I (g · m^{-3})	19.9	51.2	67.8
X_S (g · m^{-3})	134.2	202.3	224.9
X_{BH} (g · m^{-3})	17.1	28.2	32.5
X_{BA} (g · m^{-3})	0	0	0
X_P (g · m^{-3})	0	0	0
S_O (g · m^{-3})	0	0	0
S_{NO} (g · m^{-3})	0	0	0
S_{NH} (g · m^{-3})	20.7	31.5	35.9
S_{ND}(g · m^{-3})	4.1	7.0	8.4
X_{ND}(g · m^{-3})	6.5	10.6	12.2
S_{ALK} (mol · m^{-3})	7	7	7
Q_0 (m^{-3} · d^{-1})	12195	18446	24479

Table 2 Boundaries for manipulated variables

Manipulated variable	Lower boundary	Upper boundary
K_La_5 (d^{-1})	0	240
Q_a (m^3· d^{-1})	0	92230
Q_r (m^3 · d^{-1})	0	92230
Q_w (m^3· d^{-1})	0	770

high influent were selected from samples in the dry-weather file which had low and high influent flows and component concentrations respectively. The values of influent components and influent flows in different constant influent conditions are shown in Table 1. A further possible input scenario is an increase in influent flow and a decrease in component concentration, which is typical for rainy weather conditions. This case has not been considered in the study.

In the steady-state analyses only one manipulated variable was changed at a time, while the remaining manipulated variables were set constant at values specified by the predefined operating point. Due to process non-linearity and the interactions between the manipulated variables, the steady state characteristics change at different operating points. However, a few simulations have shown that the shapes of the steady-state characteristics remain approximately the same.

The chosen ranges for the changes in manipulated variables are shown in Table 2.

The results of the steady-state analysis are shown in Figures 2 to 5.

Figure 2 shows that K_La_5 has a strong influence on $S_{NH,e}$, $N_{tot,e}$ and $S_{NO,e}$ but a low influence on COD_e, TSS_e and $BOD_{5,e}$. It is also apparent that in cases where the influence can be observed, the optimal value of K_La_5 (the value of K_La_5 where a certain output variable has an optimal value) is different for different influent conditions. This means that the optimal operating point in relation to K_La_5 depends to a great extent on influent conditions. Another important feature that can be seen is that the static characteristics of $S_{NH,e}$ decrease while the static characteristics of $S_{NO,e}$ increase in the entire operating range. Therefore, $S_{NH,e}$ or $S_{NO,e}$ can be controlled in the entire operating range with a linear controller (e.g. PI controller) by K_La_5 as a manipulated variable. On the other hand, the static characteristics of $N_{tot,e}$ have different shapes under different influent conditions. In a low influent situation the static characteristic of

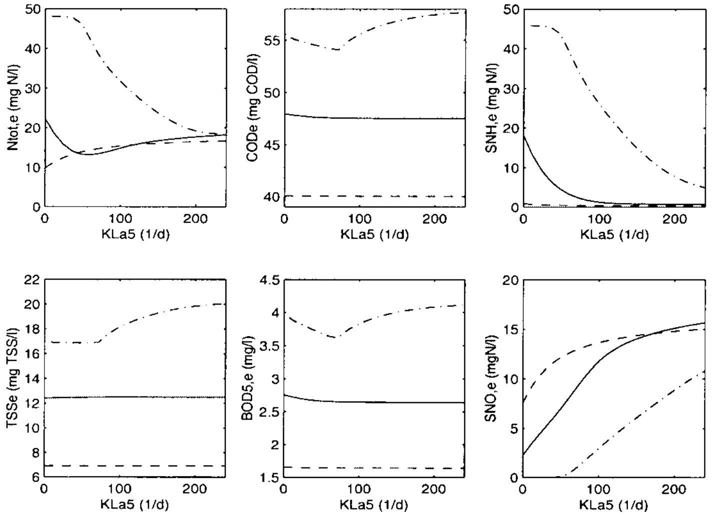

Figure 2 Static characteristics of the output variables as a function of K_La_5 in the case of mean influent (solid line), low influent (dashed line) and high influent (dash-doted line) conditions

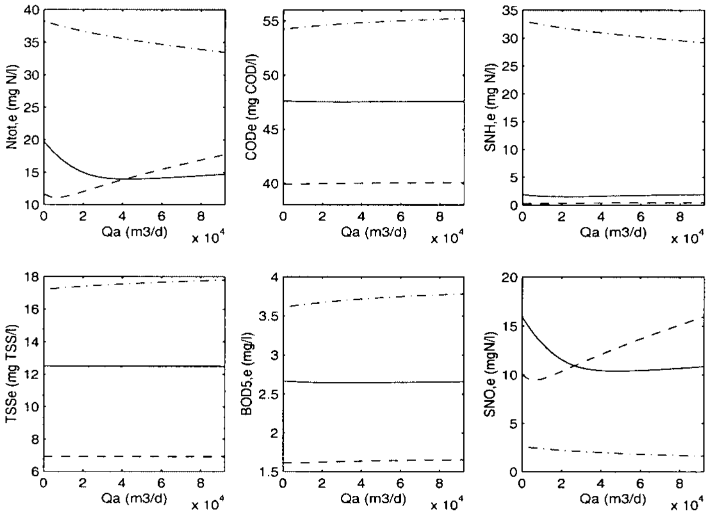

Figure 3 Static characteristics of the output variables as a function of Q_a in the case of mean influent (solid line), low influent (dashed line) and high influent (dash-doted line) conditions

$N_{tot,e}$ increases with increasing K_La_5, in a high influent situation it decreases and in a mean influent situation it has the form of a convex function with the minimum value between the boundary values. Hence, if $N_{tot,e}$ is directly controlled by K_La_5 in the entire operating range with a linear controller (e.g. PI controller), oscillations in the control loop may occur.

Figure 3 shows that Q_a has a strong influence on $N_{tot,e}$ and $S_{NO,e}$ but a low influence on other output variables. It can also be seen that the optimal value of Q_a increases with increasing influent. The shapes of the static characteristics of $N_{tot,e}$ and $S_{NO,e}$ are, as in the previous case where $N_{tot,e}$ was considered as a function of K_La_5, different for different influent conditions. These indicate that if $N_{tot,e}$ or $S_{NO,e}$ is controlled by Q_a in the entire operating range with a linear controller (e.g. PI controller), oscillations in the control loop may occur. Therefore, the non-linear controller, for example that used in Singman (1999), has to be used to control $N_{tot,e}$ or $S_{NO,e}$ successfully by Q_a as a manipulated variable.

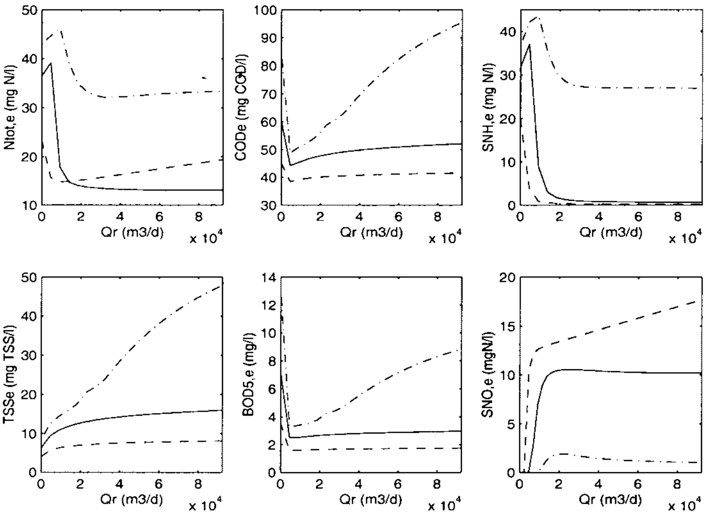

Figure 4 Static characteristics of the output variables as a function of Q_r in case of mean influent (solid line), low influent (dashed line) and high influent (dash-doted line) conditions

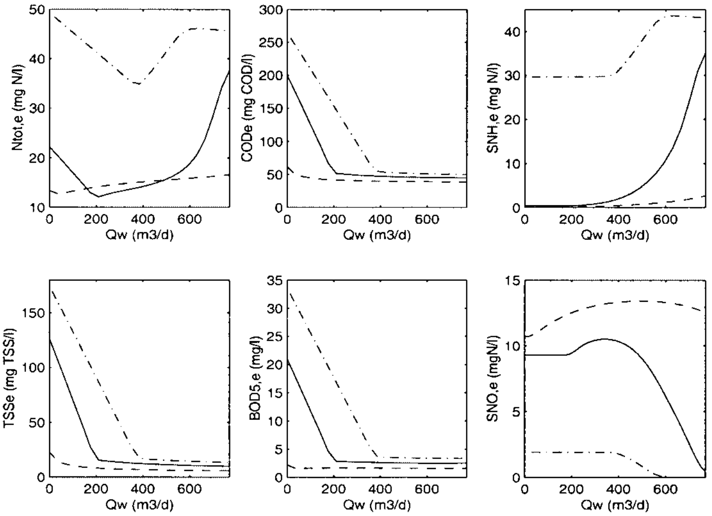

Figure 5 Static characteristics of output variables as a function of Q_w in case of mean influent (solid line), low influent (dashed line) and high influent (dash-doted line) conditions

Figure 4 shows that Q_r has a large influence on all output variables. It is also apparent that Q_r should not be increased too much, otherwise COD_e, TSS_e and $BOD_{5,e}$ greatly deteriorate, and that for $N_{tot,e}$ and $S_{NO,e}$ the optimal value of Q_r slowly increases with influent and is approximately the same as the influent flow Q_0 (see Table 1). Therefore a successful control strategy for Q_r might be a simple feedforward control that sets Q_r to Q_0.

Figure 5 shows that Q_w also has a large influence on all output variables. It is also apparent that an optimal value of Q_w increases with increasing influent. However, Q_w should not be increased too much otherwise $N_{tot,e}$, and $S_{NH,e}$ deteriorate. On the other hand Q_w should not be decreased too much in order to avoid settler overload and the corresponding increase of $N_{tot,e}$, COD_e, TSS_e and $BOD_{5,e}$. Another interesting factor is that the static characteristics of COD_e, TSS_e and $BOD_{5,e}$ always decrease, and up to a certain value of Q_w (which depends on influent conditions) express linear characteristics. Therefore COD_e, TSS_e and $BOD_{5,e}$

can be controlled with a linear controller (e.g. PI controller) by Q_w as a manipulated variable.

Optimisation in the case of constant influent conditions

To find out the optimal values of manipulated variables (optimal operating point) for different constant influent conditions (low influent conditions, mean influent conditions and high influent conditions) and under steady state conditions, optimisation was used. For the objective function (*OF)* used in the optimisation, the following function was chosen:

$$OF = \frac{1}{7\ \text{days}} \int_{t=7\ \text{days}}^{t=14\ \text{days}} \left(\begin{array}{l} \left(\dfrac{N_{\mathrm{tot,e}}}{18}\right)^2 + \left(\dfrac{COD_\mathrm{e}}{100}\right)^2 + \left(\dfrac{S_{\mathrm{NH,e}}}{4}\right)^2 \\ + \left(\dfrac{TSS_\mathrm{e}}{30}\right)^2 + \left(\dfrac{BOD_{5,\mathrm{e}}}{10}\right)^2 \end{array} \right) dt, \tag{1}$$

where the nominators are the effluent concentrations, while the values in the denominators represent their limit values, which should not be violated, as specified in the benchmark. Such an *OF* actually measures only the violation of output variables over the defined limits, and represents a simplification of an overall plant performance evaluation criterion, which also considers aeration energy, pumping energy, etc (see Table 5). A simplified criterion was chosen in this case for two reasons: (i) because violation requirements were considered of primary importance and (ii) to simplify the optimisation problem.

The initial values of manipulated variables used in the optimisation were set to the values as defined by the predefined operating point. The ranges of allowable changes in manipulated variables were the same as shown in Table 2. For optimisation a Sequential Quadratic Programming (SQP) with quasi-Newton line search (*Optimisation Toolbox User's Guide*, 1999) was used. The results of the optimisation of the manipulated variables under different constant influent conditions are presented in Table 3.

The results of the optimisation are seen to be in accordance with the results of the steady state analysis described above. All optimal values of manipulated variables increase with increasing influent. Moreover, in case of high influent conditions, the optimal values of $K_\mathrm{L}a_5$ and Q_a almost reach the upper boundary, while the optimal values of Q_r remain approximately between Q_0 and $2Q_0$.

Optimisation in the case of dynamic influent conditions

Optimisation was also performed for the dynamic influent conditions specified for dry, rainy and stormy weather defined in the benchmark. For the optimisation, the same objective function, optimisation method, initial values and ranges of allowable changes of manipulated variables were used as in the optimisation under constant influent conditions. Throughout the optimisation horizon, a constant setting of the manipulated variables was assumed despite the changing influent conditions.

Table 3 Optimal values of manipulated variables in case of constant influent conditions

Manipulated variable	**Low influent conditions**	**Mean influent conditions**	**High influent conditions**
$K_\mathrm{L}a_5$ (d^{-1})	0	68	238
Q_a ($\mathrm{m}^3 \cdot \mathrm{d}^{-1}$)	29382	55920	92208
Q_r ($\mathrm{m}^3 \cdot \mathrm{d}^{-1}$)	12670	33571	49485
Q_w ($\mathrm{m}^3 \cdot \mathrm{d}^{-1}$)	201	322	481

Table 4 Optimal values of manipulated variables in case of dynamic influent conditions

Manipulated variable	**Dry influent conditions**	**Rainy influent conditions**	**Stormy influent conditions**
K_La_5 (d^{-1})	141	130	136
Q_a ($m^3 \cdot d^{-1}$)	59189	61509	67646
Q_r ($m^3 \cdot d^{-1}$)	44050	40363	38028
Q_w($m^3 \cdot d^{-1}$)	251	271	293

Table 5 Plant performance obtained with optimal values of manipulated variables in case of dynamic influent conditions

Performance criteria	**Dry influent conditions**	**Rainy influent conditions**	**Stormy influent conditions**
EQ ($kg \cdot d^{-1}$)	6827	8324	7668
P_{disp_sludge} ($kg \cdot d^{-1}$)	1944	1897	2228
AE ($kWh \cdot d^{-1}$)	7138	7002	7076
PE ($kWh \cdot d^{-1}$)	4139	4086	4239
Nb Viol. $N_{tot,e}$	1	1	1
Nb Viol. $S_{NH,e}$	4	5	6
Nb Viol. TSS_e	0	1	2
% T_{viol} $N_{tot,e}$	0.7	0.9	1.8
% T_{viol} $S_{NH,e}$	6	9.3	14.6
% T_{viol} TSS_e	0	0.7	3.3

Table 6 Proposed manipulated variables, controlled variables and control strategies

Manipulated variable	**Controlled variable**	**Control strategy**
K_La_5	$S_{NH,e}$	PI controller
Q_a	$S_{NO,e}$	Non-linear controller
Q_r	–	Feedforward ($Q_r \approx Q_0$)
Q_w	TSS_e	PI controller

The results of the optimisation under dynamic influent conditions are presented in Tables 4 and 5. Table 4 shows the optimal values of manipulated variables obtained for each dynamic influent condition; Table 5 gives the results of the plant performance obtained with these operating conditions. The plant performance is evaluated in relation to different criteria as specified in Pons *et al.* (1999) and Alex *et al.* (1999). The performance criteria shown in Table 5 are effluent quality (EQ), average daily sludge production for disposal (P_{disp_sludge}), aeration energy (AE), pumping energy (PE), number of times the limit has been violated (Nb Viol.) and percentage of time the limit has been violated (% T_{viol}).

Table 4 shows that the optimal values of manipulated variables do not change much with different dynamic influent conditions. This shows that the rainy and stormy parts of the rainy and stormy dynamic influent conditions have a low influence on the choice of optimal values of manipulated variables. More variation in optimal values of manipulated variables might be obtained if only those parts of the rainy and stormy weather influent conditions were used where a significant change of influent conditions actually exists. But in such a case, manipulated variables would have to be switched to different values in the corresponding parts of the influent weather files.

An interesting conclusion derived from the results in Table 5 is that the plant performance obtained with constant and optimal values of manipulated variables is quite good and comparable to the results obtained in Singman (1999), where a dynamic scheme with three controllers is used to improve plant performance.

Conclusion

The paper presents simulation analysis and optimisation for the assessment of the system to be controlled. The system under investigation is the COST 624 wastewater treatment benchmark.

The main conclusions drawn from the study confirm some known characteristics of wastewater treatment processes and also point to some interesting facts, which are as follows.

Steady-state analysis and optimisation under different constant influent conditions show that changes in process influent conditions require changes in process manipulated variables as well in order to approach optimal operating conditions. In general, when influent is increased, all potential manipulated variables (K_La_5, Q_a, Q_r and Q_w) have to be increased to obtain optimal plant performance. Based on the steady state analysis and optimisation under different constant influent conditions, the proposed manipulated variables, controlled variables and control strategies are as in Table 6.

Optimisation with dynamic influent data for three typical influent conditions (dry, rainy and stormy weather) reveals that quite good results can be achieved by setting the manipulated variables to constant optimal values. These values are not very different for the different types of weather files. Such an operating strategy is, however, difficult to apply in practice as the optimal values of manipulated variables are computed based on known future influent characteristics, which are usually not available in advance.

Our future work will be directed towards the design of control algorithms as specified above.

Acknowledgement

We would like to thank Dr. Ulf Jeppsson, IEA, Lund Institute of Technology, for letting us use his Simulink benchmark.

References

Alex, J., Beteau, J.F., Copp, J.B., Hellinga, C., Jeppsson, U., Marsili-Libelli, S., Pons, M.N., Spanjers, H. and Vanhooren, H. (1999). Benchmark for Evaluation Control Strategies in Wastewater Treatment Plants. *ECC'99 (European Control Conference),* Karlsruhe, August 31-September 3.

Henze, M., Grady, C.P.L., Gujer, W., Marais, G.v.R. and Matsuo, T. (1987). *Activated Sludge Model No.1*. IAWPRC Scientific and Technical Report No.1, IAWPRC, London.

Optimisation Toolbox User's Guide. (1999). The Math Works, Inc.

Pons, M.N., Spanjers, H. and Jeppson, U. (1999). Towards a Benchmark for Evaluating Control Strategies in Wastewater Treatment Plants by Simulation. *Escape 9 (European Symposium on Computer Aided Process Engineering-9),* Budapest, May 31-June 2.

Singman, J. (1999). *Efficient Control of Wastewater Treatment Plants – A Benchmark Study*. MSc thesis. Systems and Control Group, Uppsala University, Sweden.

Takács, I., Patry, G.G. and Nolasco, D. (1991). A dynamic model of the clarification thickening process. *Wat. Res*., **25**(10), 1263–1271.