AN ADVANCED TECHNIQUE FOR DESIGNING AND OPERATING WHITE WATER SETTLERS

M. Tarek Sorour
Sanitary Engineering Department, Faculty of Engineering
Alexandria University, Alexandria, Egypt

ABSTRACT

Little information is available on designing and operating settlers treating white water. Most of the conventional design methods are based on steady-state analysis, which is not suitable for industrial applications due to its dynamical conditions. This study presents a procedure which could be used for designing and operating white water settlers. The procedure is based on dynamic modeling and computer simulation technique. The application of an advanced dynamic settler model is described for the removal of fibers from white water . A 5 month experimental study was carried out on a pilot-scale settler of 1.42 m^2 surface area, to investigate the model validity. The model was verified under both a quasi steady-state and under two dynamic events. An example of a full-scale settler is presented to explain the potential use of computer simulation for evaluating design and operation under time varying inputs.

Keywords:* *Dynamic modeling, Settling, Clarification, Thickening, White water, Pulp and paper, Waste water treatment.

Nomenclature

Ac	surface area of the settler (m)
Jdn	downward solids flux due to the bulk movement of the liquid ($g/m^2.d$)
Ji	solids flux in layer i ($g/m^2.d$)
Js	solids flux due to gravity settling ($g/m^2.d$)
Jup	upward solids flux due to the bulk movement of the liquid ($g/m^2.d$)
Qe	effluent flow rate (m^3/d)
Qin	influent flow rate (m^3/d)
Qu	underflow flow rate (m^3/d)
X	suspended solids concentration (g/m^3)
Xi	suspended solids concentration in layer i (g/m^3)
Xin	influent suspended solids concentration (g/m^3)
Xnon	minimum attainable suspended solids concentration in effluent (g/m^3)
fns	non-settleable fraction of the influent suspended solids
n	settling parameter in the Veslind model (m^3/kg)
n′	settling parameter in the Yoshioka model
rp	settling parameter associated with low concentration and slowly settling component of the suspension (m^3/g)
rh	settling parameter associated with hindered settling component of settling velocity equation (m^3/g)
Vo	max. theoretical settling velocity (m/d)
Vo′	max. practical settling velocity (m/d)
Vs	settling velocity (m/d)
α	settling parameter in the Vesilind model (m/d)
α'	settling parameter in the Yoshioka model ($m^4/kg.d$)

INTRODUCTION

The manufacture of paper can be divided into 2 phases: pulping the wood and making the final paper product. In the pulping phase, the raw materials generally used are wood, cotton, rice straw, hemp, and jute or waste paper. These materials are reduced to fibers which are subsequently refined, sometimes bleached, and dried. At the paper mill, the pulps are combined and loaded with fillers; finishes are added and the products transformed into sheets.

Fiber industries produce 2 main wastes, namely pulp-mill and paper-mill wastes. Pulp-mill wastes come from grinding, digester cooking, washing, bleaching, thickening and defibering. Paper-mill wastes originate in water which passes through the screen wires, showers, and felts of the paper machines, beaters and mixing tanks. These paper-machine wastes (known as white water) contain a considerable amount of dissolved and suspended solids. It is believed that the major constituents of that suspended solids are the cellulosic fibers, which represent a valuable recoverable material (1).

On the eastern side of Alexandria, Egypt, The RAKTA factory discharges about 4 million m^3/year of white water, containing about 3000 tons of solids, to the Abu Quir bay, causing an environmental problem (2). There is no doubt that, the treatment of this white water will improve environmental conditions in the bay, Moreover, the recovered fibers would represent an added value to the economy of the company. The treated water could be reused or recycled in the plant in any process according to its required quality.

Despite the great deal of research, paper-mill treatment is still in its early stages. Actual treatment equipment is installed only after exhaustive study of all other possibilities, since the cost of treatment is considered high comparing to the cost of the product produced. Therefore, it was decided to develop a process to handle the white water of RAKTA, to separate the solids from the discharged suspension. Several alternatives were investigated, sedimentation was the selected process.

Although the separation of solids from water by sedimentation is one of the most important physical processes in wastewater treatment, little information is available on the design and operation of settlers treating pulp and paper wastes. One more problem is that most conventional design methods are based on steady-state analysis, which is not suitable for industrial wastes treatment due to its dynamical conditions.

The major aim of this study is to develop a procedure which could be used for designing and operating white water settlers. This procedure is based on dynamic modeling and computer simulation technique, where settler dimensions can be evaluated under time varying influent load conditions instead of, as is done conventionally, limiting analyses to anticipated steady-state conditions for low, average and high flows. Moreover, during operation, alternative operational variables can be examined prior to actual implementation.

The proposed technique consists of the following steps:

a) Model selection and adaptation;
b) Model calibration and verification using pilot plant data;
c) Design and operation using computer simulation.

I. *MODEL SELECTION AND ADAPTATION*

Recently, modeling of the processes in settler is used for design, flow analysis, and operational control. Most of the settler models are based on the flux theory (3). This theory applies for hindered settling and thickening. A dependence of the relative settling velocity V_s on the local solids concentration X is stated. For the mathematical presentation of sedimentation it is necessary to propose a functional relationship between V_s and X. Several models are available in the literature, but in practice the power model of Yoshioka (4) and the exponential model of Vesilind (5) are the most used (6).

Power model :

$$V_s = \alpha' . X^{-n} \tag{1}$$

Exponential model :

$$V_s = \alpha . \exp(-n . X) \tag{2}$$

The power model is easy to handle for graphical analysis of the limiting solids flux capacity or of various underflow rates. The exponential function requires numerical treatment for flux analysis. Both approaches are purely empirical, usually the exponential model of Vesilind (5) is considered to be more accurate.

On the basis of a settling function, a vertical, one-dimensional, continuous flow model can be introduced. The model employed in this study is a modification of that originally developed by Vitasovic (6). The settler is divided into horizontal layers (10 layers in this study). The influent flow enters the settler in the feed layer (f) and is assumed to be instantly and completely distributed in the layer. To handle the solids concentration of all layers a vector of (n) element (Xi where i = 1 .... f .... n) is set up.

The solids are moving in the settler due to two effects: bulk fluid movement [upward (J_{up}) and downward (J_{dn}) and settling (J_s).

Solids fluxes due to bulk fluid movement are calculated by:

i) upward bulk movement

$$J_{upi} = Q_e \, . \, Xi / A_c \qquad (3)$$

i = 1 to f

ii) downward bulk movement

$$J_{dni} = Q_u \, . \, Xi / A_c \qquad (4)$$

i = f to n

Settling solids flux can be calculated by:

$$J_{si} = V_{si} \, . \, Xi \qquad (5)$$

i = 1 to n

In a continuous flow settler, the downward solids flux is the sum of the gravity settling flux J_s and the solids flux due to the bulk movement of the liquid J_{dn} i.e the underflow:

$$J = J_s + J_{dn} \qquad (6)$$

$$Ji = Xi \, . \, V_{si} + Xi \, . \, V_u \qquad (7)$$

The mass balance is calculated for each layer, the mass balance around each type of layer is summarized in Figure (1).

Vitasovic (6) in his model used the empirical relationship of Vesilind (5) to predict V_s:

$$V_{si} = V_o \exp(- a \, . \, Xi) \qquad (8)$$

Because Vesilind's settling velocity equation applies only to hindered settling conditions, and solids concentration in the upper layers of the settler decreases below the hindered settling concentration, settling velocities predicted by Vesilind's equation will exceed the actual settling velocity of the floc particles. In order to overcome this problem Takacs et al. (7) proposed the following double exponential equation:

$$V_{si} = V_o \exp[-rh. (Xi - Xnon) - V_o \exp -rp.(Xi-Xnon)] \qquad (9)$$

$$0 \leq V_{si} \leq Vo' \qquad (10)$$

$$Xnon = fns \, . \, Xin \qquad (11)$$

The settling function is divided into 4 regions (Figure 2), where the double exponential equation applies to regions II and IV. Region I is defined by a non-settleable fraction Xnon, which is used in turn for definition of the settling function (Eq.9). The function of the double exponential equation (Eq.9) is cut by region III corresponding to a maximum settling velocity Vo′, which leads to the restriction Vs ≤ Vo′ of the settling velocity. Region IV is predominated by the expression Vo. exp [-rh . (Xi - Xnon)], and corresponds to the classical solids flux theory. For the low concentration (region II), the second term Vo. exp [-rp (Xi - Xnon)] becomes determining.

The selected model at this stage, at least from the theoretical point of view, could be considered valid to predict settler effluent and underflow suspended solids concentrations for any sort of wastewater. The crucial point of these study is to investigate the applicability of this model to pulp and paper white water. This application would allow the model to be used for design and operation purposes.

The model was coded in **SIMNON** (8) which is a continuous simulation language program based on the **MS.DOS** operating system for personal computers.

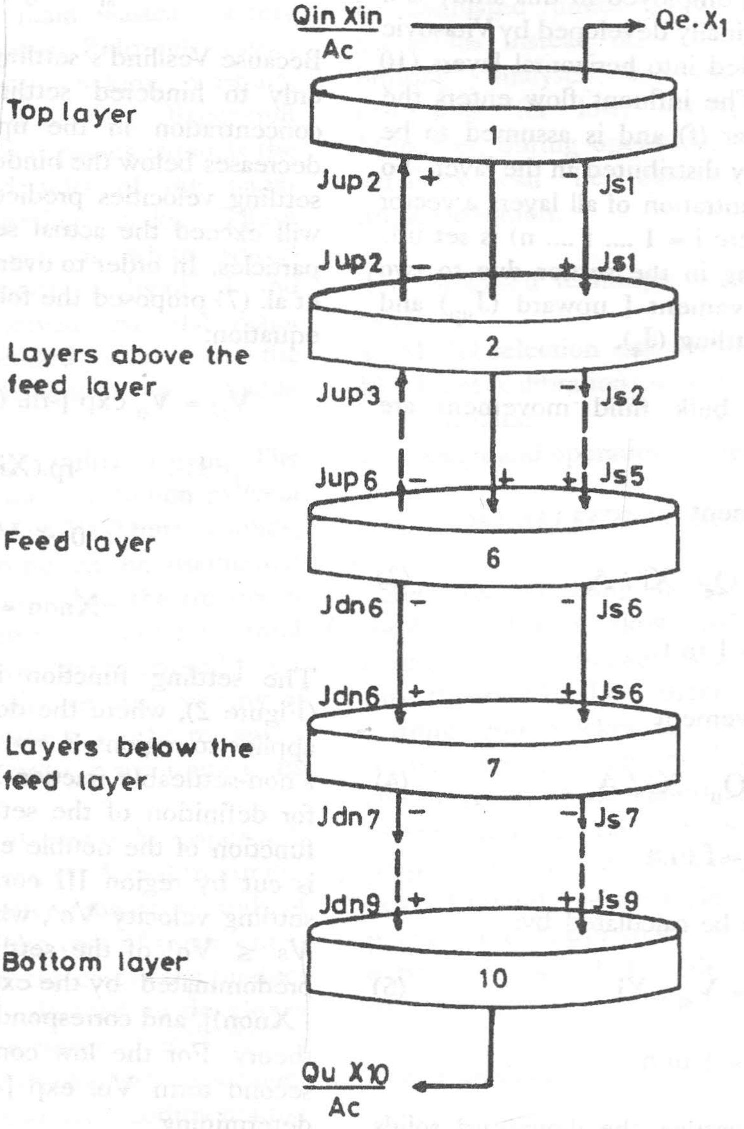

Figure 1. Summary of the settler model.

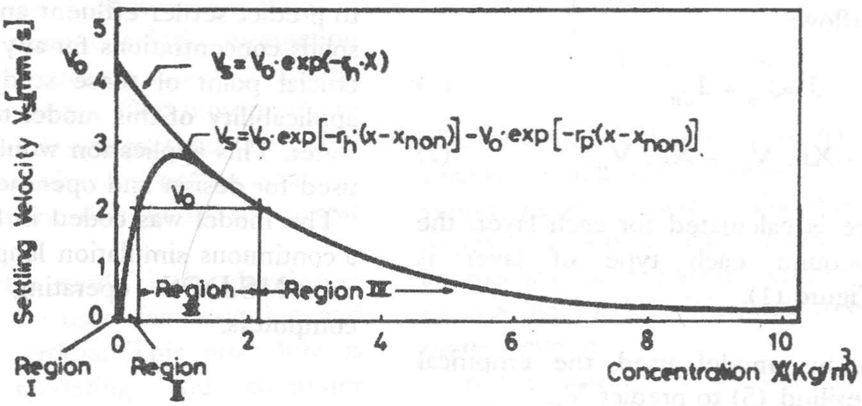

Figure 2. Settling function of the model.

II *MODEL VALIDITY FOR PULP AND PAPER WHITE WATER*

The second step in the proposed technique is to investigate model validity for white water, using computer simulation, against pilot plant data.

Pilot Plant Experiments

In order to verify the qualitative validity of the settler model when treating white water, pilot plant experiments were performed. Five months of experimental work were carried out on a settler pilot plant fed with raw white water.

The settler pilot plant was located in the RAKTA factory and comprised a 1.8 m^3 settler with 1.42 m^2 surface area. The body of the basin was fabricated from Plexiglas to allow monitoring of sedimentation patterns and to observe the sludge blanket level. The wasted white water from two machines, (no.1 and 2) in the factory was pumped in one line from waste stream in an equalization tank, while the white water of machine no.3 was pumped in a separate line into the same tank. The two streams were mixed at a ratio of 7:6 respectively to represent the actual mixture of the wasted white water of RAKTA. The equalization tank was made from galvanized mild steel with a 1.0 m^3 volume. In the equalization tank gentle mixing was needed to keep solids in suspension. Flow meters with suitable specifications were installed to monitor the flow rates. Figure (3) shows the layout of the pilot plant.

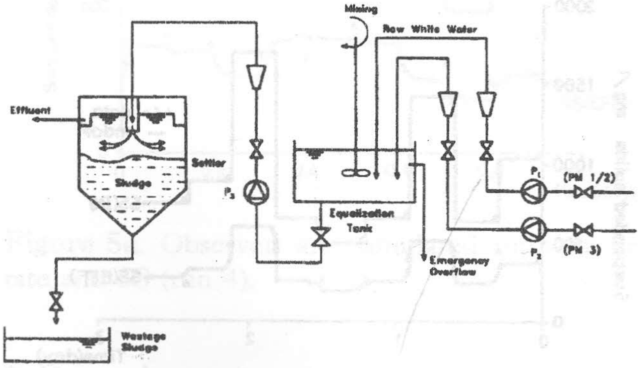

Figure 3. Layout of the pilot plant.

The pilot plant continuous operating program originally planned, consisted of 3 phases:

Phase 1: Start-up to adjust the operating conditions;
Phase 2 : Quasi steady state with different constant flow rates for both influent (Q_{in}) and underflow (Q_u). 7 runs were performed, in each run Q_{in} and Q_u were maintained constant at the selected flow rate according to the experimental plan, the run length was about 3 days. Samples were taken after 16 hours from the beginning of each run to avoid any disturbances from the previous one;
Phase 3: Dynamic experiments with different fluctuating influent flow patterns, 5 dynamic runs were performed, the length of each was about one day. The Q_{in} and Q_u were kept constant for 2 days between every 2 dynamic runs.

Grab samples from influent, effluent and underflow were collected every 2 hours. Daily 24h composite samples were also routinely analyzed. Samples were stored in refrigerator at 5°c until analyses were made during day. Samples were analyzed for suspended solids (SS), COD (total, soluble), BOD, and pH, according to Standard Methods (9).

Generally, the composition of white water depends on the type of stock, which in RAKTA is composed of rice straw pulp, bagasse and long fiber wood pulp. RAKTA's white water, contains fiber debris, small fibers, soluble matters and non fibrous suspended solids (about 25 % on average). During the pilot plant experiments, it was also observed that, the influent had different suspended solids concentrations from hour to hour, as well as different BOD and COD contents. This could be expected in such a big paper mill due to the great fluctuations in production conditions.

As indicated before 7 quasi steady state runs with different Q_{in} and Q_u were performed. The averages of the influent and effluent suspended solids and % reduction of SS, BOD, and COD during these runs are summarized in Table (1).

Model Calibration

Calibration of the model requires that the parameters are quantified, in order to simulate with acceptable precision, the pilot plant performance. This step is very important because all simulations will be based on the identified parameters

Table 1. Results of quasi steady-state runs.

Run No.	Q_{in} l/min	Q_u l/hr	Influent SS mg/l	Effluent SS mg/l	% Reduction SS	COD	BOD
1*	10	100	982.00	347.50	64.66	77.30	75.00
2	10	50	1130.00	480.00	57.50	86.50	–
3	15	100	851.80	332.10	65.10	83.30	–
4**	15	150	880.00	425.10	51.70	77.70	67.50
5	15	50	952.40	446.00	53.20	47.50	48.80
6**	20	100	1322.70	500.80	62.13	69.40	–
7	20	150	1347.40	442.00	67.20	76.60	50.50

* Data used for model calibration ** Data used for model verification

The model contains 5 parameters (V_o ; V'_o; rh; rp; and fns). These parameters were divided into two groups. The parameters of the first group were measured experimentally, where an estimate of V_o and V'_o were obtained through a series of column settling tests according to the procedure in Vesilind (1968).

For the second group (rh, rp, fns), default values available in the literature (7) were initially incorporated, and then adjusted using computer simulation to fit more closely the actual data of the pilot plant. The set of parameters giving the best prediction is shows in Table (2).

Table 2. Calibrated parameters values

Parameter	Value	Reference
V_o	139.2 m/d	Experimental
V'_o	122.4 m/d	Experimental
rh	0.0004 m^3/g	Model calibration
rp	0.0024 m^3/d	Model calibration
fns	0.035	Model calibration

Figure (4) shows the observed and simulated influent and effluent SS, during run1 (quasi steady state) which was selected as a database for model calibration.

Model Verification

The acceptability of the model is promoted if, on applying it to a range of situations, one can find consistency between observations and prediction. The model was verified against two sets of experiments: 1) quasi steady state; 2) dynamic events.

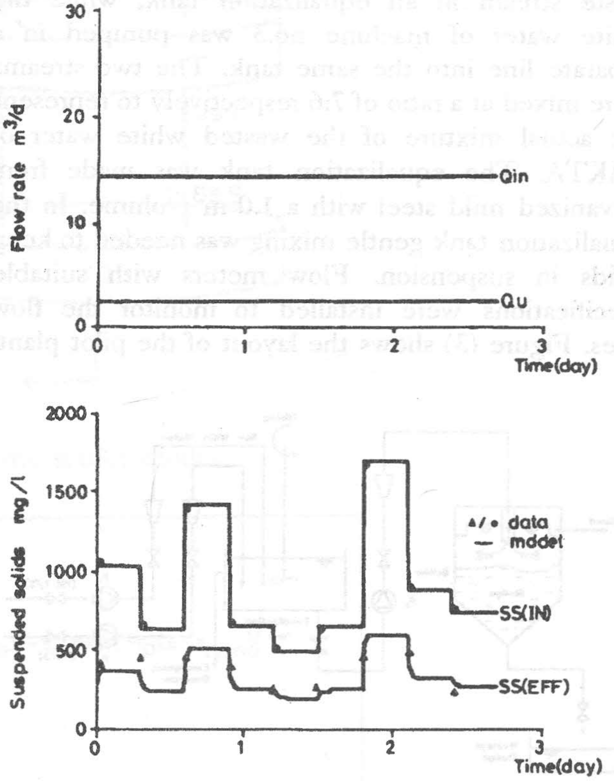

Figure 4. Model calibration-observed and simulated influent flow rate and SS.

1) Quasi steady state

Results of simulation under quasi steady conditions are shown in Figure (5) and compared with the recorded observations of the pilot plant (run 4, and 6). For both cases the Qin and Qu were kept constant at two different levels, while the influent suspended solids concentration was varied (as stated before) due to the factory operating conditions. It is obvious that, the model output (effluent suspended solids concentration) is in a good agreement with the observed data for both cases.

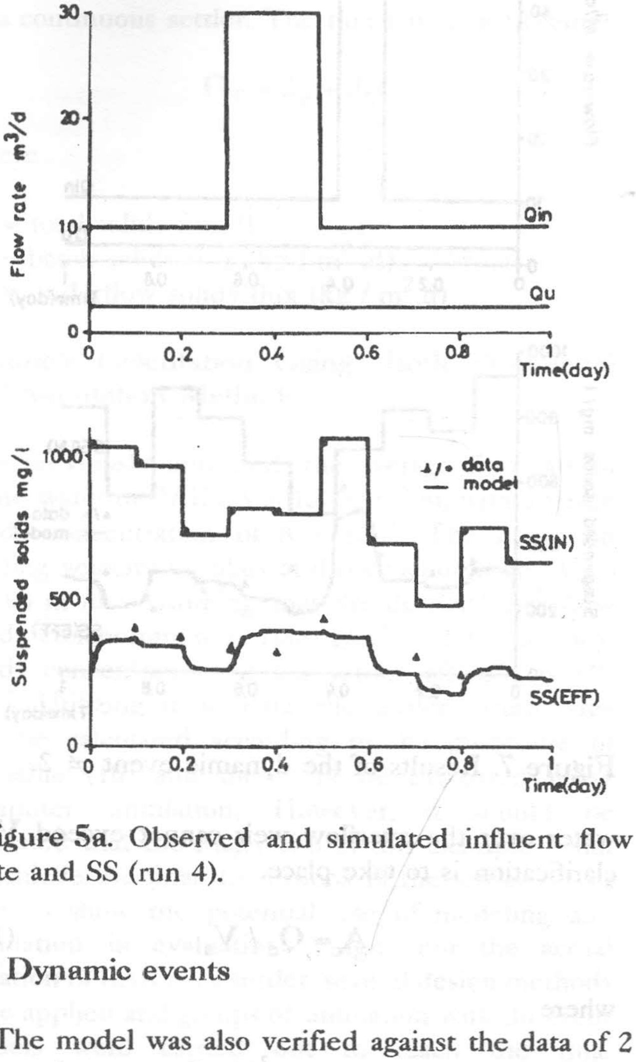

Figure 5a. Observed and simulated influent flow rate and SS (run 4).

2) Dynamic events

The model was also verified against the data of 2 dynamic events. Results from event #1 are shown in Figure (6) and compared with the recorded observations. This event was a short hydraulic shock load for a period of 4.8 hours. The influent flow rate was increased from 10.0 to 30.0 m^3/day, while the Qu was kept constant at 2.4 m^3/d. For event #2 the influent flow rate was increased from 10.0 to 50.0 m^3/d for a period of 2.4 hours, the Qu was kept at 2.4 m^3/d. The results of this event is shown in Figure (7).

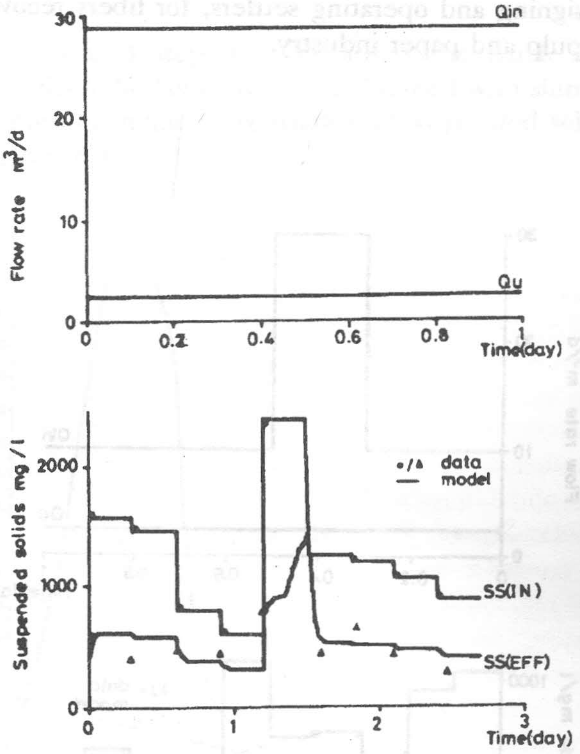

Figure 5b. Observed and simulated influent flow rate and SS (run 6).

Comparing the both dynamic events, it is clear that the settler pilot plant can cope with the short term shock load (event #1), however, the very high and short term shock load from event #2 caused solids washout. By examining Figure (7) one can realize that, although the influent SS concentration decreased from 929 mg/l at time 0.0 day to 494 mg/l at time 0.4 d, the effluent SS concentration increased from 220 to 520 mg/l due to the very high hydraulic shock load. At time 0.4 d the effluent SS concentration is approximately equal to the influent

SS concentration i.e. there is no solids removal. After time 0.4 d when Qin was reduced to 10 m^3/d, the effluent SS concentration decreased to its normal level again. The model predicted the effluent suspended solids for both events correctly.

Generally, the model was able to replicate closely the effluent suspended solids under a variety of quasi steady state and dynamic events, which reflects the acceptability of applying the model for designing and operating settlers, for fibers recovery in pulp and paper industry.

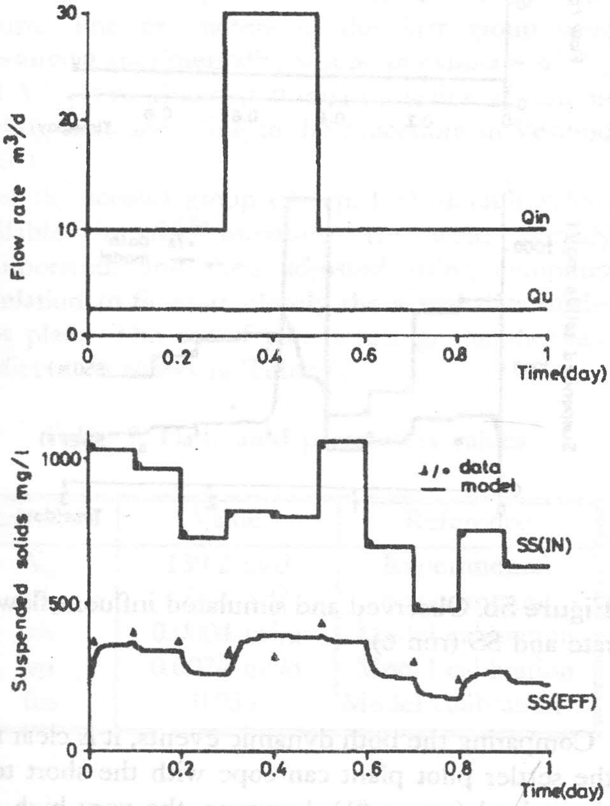

Figure 6. Results of the dynamic event ≠ 1.

III. DESIGN AND OPERATION USING COMPUTER SIMULATION

The third step in the proposed technique is to use computer simulation for designing and operating settler treating white water under dynamical conditions.

Traditional Settler Design and Operating Procedure

For designing settler operating under zone settling conditions, Ramalho (10) suggested that the design surface area for the settler is the larger of the surface area required to allow clarification of sludge, and the surface area required to provide for thickening of sludge to the desired underflow concentration.

The surface area required for clarification (A_c) depends on velocity (V_s) at which the suspension settles before reaching the critical concentration (Xc). Under continuous flow conditions, velocity of water over the overflow weir cannot exceed V_s if clarification is to take place.

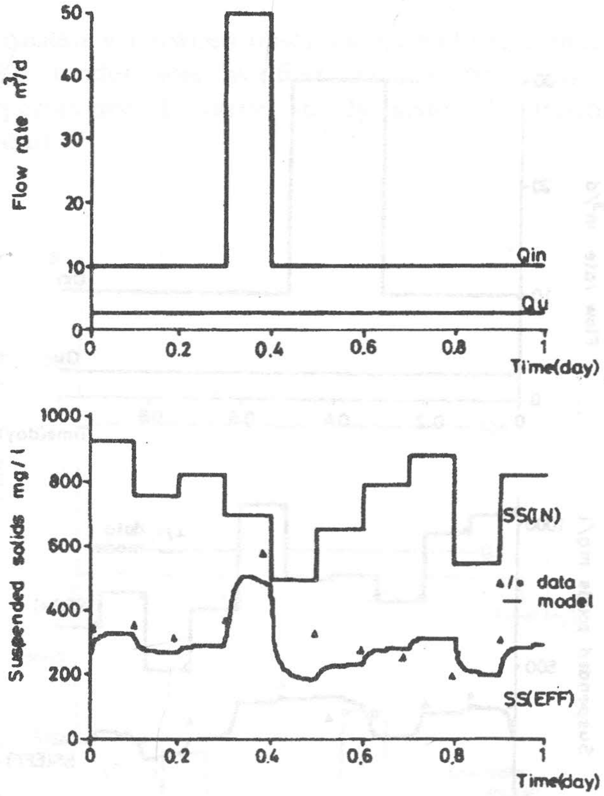

Figure 7. Results of the dynamic event ≠ 2.

$$A_c = Q_e / V_s \tag{12}$$

where

Q_e = effluent flow rate (m^3/d)

V_s = settling velocity (m/d)

A_c = minimum surface area required for clarification (m^2)

The procedure for determination of the surface area required for thickening (A_t) is based upon the batch sedimentation carried out for carrying solids downwards at a concentration X_i by gravity is :

$$J_B = X_i \cdot V_{si} \qquad (13)$$

where

J_B = batch solids flux (kg/ m^2 .d)
V_{si} = settling velocity at concentration X_i (m/d)

From eq. (13) a batch flux curve can be constructed. Consider the sedimentation carried out in a continuous settler. The flux equation becomes:

$$G_T = J_B + J_U \qquad (14)$$

where

G_T= total solids flux (kg/ m^2 .d)
J_B = batch solids flux (kg / m^2 .d)
J_U = underflow solids flux (kg / m^2.d)

Example Calculation Using Both Traditional and Simulation Methods

As previously indicated, the average flow rate of white water in RAKTA is 13000 m^3 /d, with average solids concentration of 854 g/m^3. The measured settling velocity of solids at this concentration (V_{sin}) is 100 m /d . Assuming that the desired underflow solids concentration is 7000 g/m^3, and the average solids concentration in the settler effluent is 100 g/m^3. Utilizing these data, the settler surface area will be calculated according to the procedure of Ramalho (10) and then will be evaluated using computer simulation. However, it should be indicated that the major aim of this example is not to achieve the final dimensions of the settler rather than to show the potential use of modeling and simulation in evaluating design. For the actual situation of RAKTA's settler, several design methods were applied and groups of simulation with different models were carried out to reach the final dimensions.

The first step is to determine the surface area required for clarification (A_c):

$$Q_e = Q_{in} \cdot (Xe - Xin) / (X_u - X_e)$$

$$= 13000 * (7000\text{-}854)/(7000\text{-}100) = 11579.5 \ m^3/d$$

$$A_c = Q_e / V_{sin}$$

$$= 11579.5 / 100.0 = 115.7 \ m^2$$

The second step is to construct the batch flux curve from the laboratory data obtained with slurries of different initial concentration of suspended solids (Figure (8)).

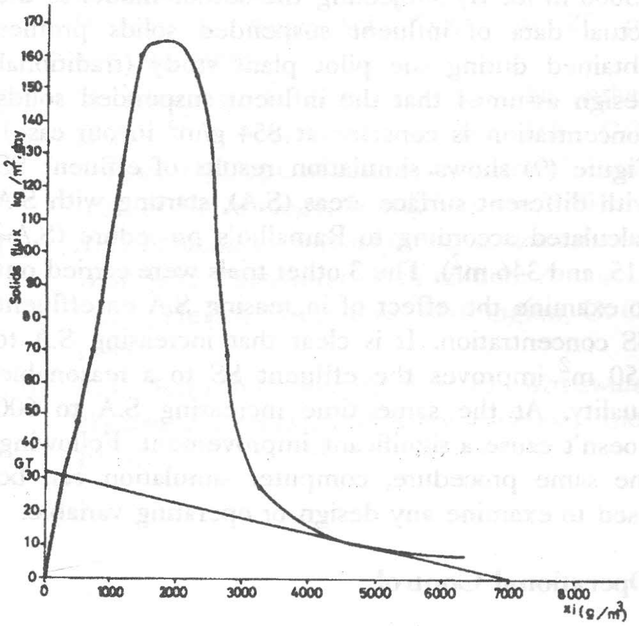

Figure 8. Graphical procedure for determination of G_T.

For operating the settler, the total flux G_T can be varied by controlling the sludge velocity due to underflow removal (V_u) since this is determined by the underflow pumping rate. Therefore, in the third step the surface area required for thickening (A_t) is determined as follows:

From Figure (8), G_T = 32 kg/m^2.day

$$M = Q_{in} \cdot X_{in}$$

$$= 13000 * 854 = 11102 \text{ kg/d}$$

$$A_t = M / G_T$$

$$= 11102 / 32 = 346.9 \text{ m}^2$$

According to Ramalho (10) the design surface area is the larger of these both areas i.e. 346.9 m^2. For detention time 2 hours, the corresponding depth is 3.12 m.

The major advantage of using computer simulation in settler design is to examine the proposed dimensions under time varying influent load conditions. In step four, computer simulations were carried out to examine the initially proposed settler dimensions, under the expected influent flow rate of 13000 m^3/d. By subjecting the settler model to the actual data of influent suspended solids profiles obtained during the pilot plant study (traditional design assumes that the influent suspended solids concentration is constant at 854 g/m^3 in our case). Figure (9) shows simulation results of effluent SS with different surface areas (S.A), starting with S.A calculated according to Ramalho's procedure (S.A= 115, and 346 m^2). The 3 other trials were carried out to examine the effect of increasing S.A on effluent SS concentration. It is clear that increasing S.A to 550 m^2 improves the effluent SS to a reasonable quality. At the same time increasing S.A to 600 doesn't cause a significant improvement. Following the same procedure, computer simulation can be used to examine any design or operating variable.

Operational Control

Generally, process simulation based on dynamic models is considered to be very useful for controlling industrial wastes treatment. Such technique assists in the operation of the treatment units to aid in the development and testing of control strategies before implementation.

Considering settlers operation, for example at the start of severe shock load (due to production fluctuations) the behavior of the system is simulated to estimate the output concentrations for several hours into the future. Based on the results of the simulation, initial starting positions for gates and flow rates for pumps are established.

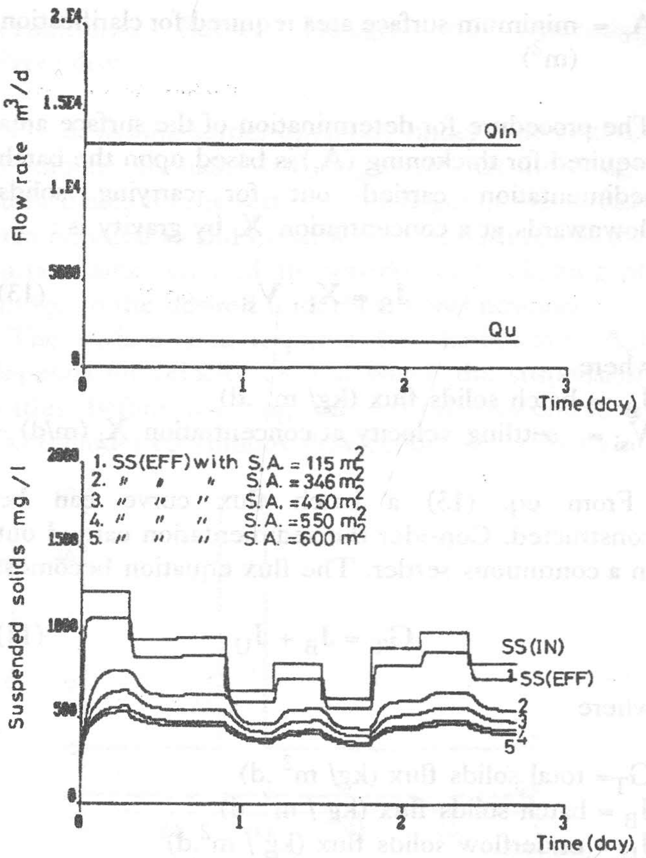

Figure 9. Simulation results with different surface area.

CONCLUSIONS

An advanced technique is proposed for designing and operating white water settler. The proposed procedure is based on dynamic modeling and computer simulation. This procedure consists of 3 steps:
a) Model selection and adaptation; b) Model calibration and verification using pilot plant data; c) Design and operation using computer simulation.

A dynamic settler model was adopted for the white water of pulp and paper. Based on the solids flux concept and a mass balance around each layer of a one dimensional settler, the model is able to predict the solids profile along the settler, including the effluent and the underflow suspended solids. The model can be considered as a conceptual frame work upon which both steady - state and dynamic conditions could be simulated.

The model was applied to a wide range of pilot plant experimental data to investigate its applicability for white water. The computer simulations showed a good consistency regarding effluent SS concentration for all cases.

The settler surface area required for treating white water of RAKTA was calculated according to the steady state analysis (10) and the proposed technique. The major advantage of the proposed technique is the capability of examining the settler dimensions under time varying influent load conditions.

The model is recommended to be used for designing and operating settler for liquid wastes from pulp and paper industry after identifying model parameters for each certain waste.

Acknowledgments

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