REAL TIME CONTROL OF SECONDARY CLARIFIERS – ENHANCING HYDRAULIC CAPACITIES DURING RAIN

BY ANDERS LYNGGAARD-JENSEN

Secondary clarifiers are usually the limiting factor for the hydraulic load on wastewater treatment plants (WWTP). This is specifically the case during rain, when the WWTP is located downstream a combined sewer system. The hydraulic capacity, Q_{biomax}, of the WWTP is given by the sludge settling velocity multiplied by the secondary clarifier area. Therefore, efficient real time control of the secondary clarifiers can increase the hydraulic capacity of the WWTP during rain by increasing the sludge settling velocity.

Introduction

The sludge settling velocity, V_{sed}, decreases exponentially with increasing suspended solids concentration, SS, in the inlet to the clarifier. In order to increase the sludge settling velocity the suspended solids concentration to the clarifiers therefore has to be reduced. This article describes a methodology where the clarifiers themselves are used as a well-controlled sludge storage, in order not to return all the sludge flushed to the clarifiers during start of rain to the process tanks again immediately.

The designed and implemented controller is combined of a feed forward control for balanced (minimum) return sludge flow and a feedback control of the distribution of the return sludge flow between clarifiers. The feed forward control is based on an estimate of V_{sed} (therefore also calculates Q_{biomax}) and uses a flux balance to calculate the minimal return sludge flow, $Q_{r,min}$.

The feedback control uses sludge blanket measurements, SB (the level where sludge is separated from clear water), in clarifiers to distribute the pumping of $Q_{r,min}$, in order to make all sludge blankets follow each other. The feedback control therefore ensures full storage capacity, or in other words ensures that the entire clarifier area is equally useable, as the controller compensates for any skewness in the load distribution to the clarifiers.

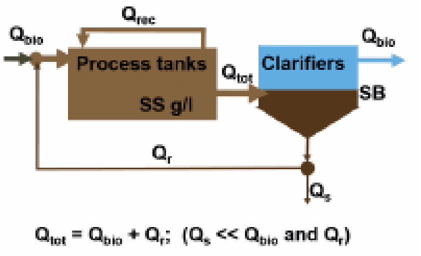


Figure 1. Overview of the biological treatment and the used nomenclature

Depending on the design of the wastewater treatment plant, i.e. if more secondary clarifier lines are present – it is possible to extend the controller to accommodate them by including a feedback controller using the average sludge blankets for the different lines to control the distribution of the sludge. A control handle (gate/weir) is thus required downstream of the process tanks in order to carry out the right distribution of the flows to the clarifier lines. The controller selectively flushes the sludge to a specific clarifier line when the flow at the treatment plant increases due to rain. This procedure increases the hydraulic capacity of the WWTP almost instantly, and secures the controller does not need any lead time for handling a fast increasing flow.
Finally, in dry weather situations, the clarifiers are controlled to give a more stable performance, and thereby give a higher suspended solids concentration in the return sludge, by using the optimal and balanced return sludge flow $Q_{r,min}$.

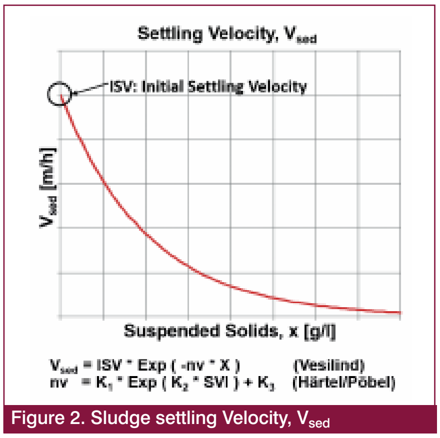


Figure 2. Sludge settling Velocity, V_{sed}

The controller is in operation on several WWTPs, including Marselisborg WWTP operated by Aarhus Water, Denmark, which is used in the examples below.

Sludge settling velocity

The relationship between the suspended solids concentration in the inlet to the clarifiers and the sludge settling velocity in the clarifiers can be represented by the well known Vesilind exponential equation (Vesilind, 1968) – see figure 2, with the exponent being equal to the suspended solids concentration multiplied by a factor, *nv*. The factor *nv* is a function of the Sludge Volume Index, *SVI*, which is a sludge characteristic, and therefore only changes slowly with the sludge age of the WWTP.

Several functions for the factor *nv* have been suggested. Here the function suggested by Härtel and Pöbel is used, as the determined constants (K_1, K_2 and K_3) do not change much from WWTP to WWTP.

The *SVI* can be determined in the laboratory as the sludge volume after 30 minutes, *SV30*, divided by the suspended sludge concentration in the sample. In the equation for the sludge settling velocity the exponential is multiplied by a factor known as the Initial Settling Velocity, *ISV*, which is, like *SVI*, a sludge characteristic. *ISV* can be determined in the laboratory from a measurement of V_{sed}, but it can also be estimated in real-time by a proper control of the clarifiers in dry weather.

Clarifier State Diagram

The operation of clarifiers can be described using a state diagram (figure 3) consisting of the functional relationship between fluxes of suspended solids in the clarifiers and the suspended solids concentration. The flux is given by the amount of sludge crossing a square meter of the clarifier per unit time. The settling flux, can be expressed as the suspended solids concentration multiplied by the settling velocity, where the settling velocity is described using the Vesilind equation.

In the Clarifier State Diagram the area below the settling flux curve describes the area for stable operation of the clarifier, i.e. the state point has to be located under the settling flux curve. The state point is defined as the point where the returned flux, equals the upward flux. The suspended solids concentration in the sludge arriving to the clarifiers (the same as the *SS* in the process tanks), can be read on the x-axis vertically under the state point.

Optimal return sludge rate

Usually values for the return sludge flow, Q_r, are calculated as a percentage of the inflow to the WWTP. Typically too high percentages are chosen, despite the fact that besides using too much energy for pumping, it also gives a varying and too low suspended solids concentration in the return sludge. This again can lead to an unnecessary use of polymer in the pre-dewatering of the surplus sludge taken from the return sludge.

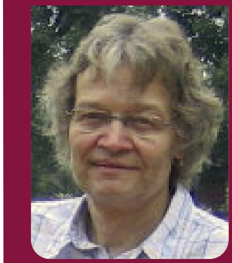
In the Clarifier State Diagram the returned flux is a straight line having the slope $-Q_r/A$, and it crosses the x-axis at the concentration of the suspended solids in the return sludge, SS_r. As the line is fixed to the state point, manipulating Q_r will make the line turning around the state point – increasing Q_r the line will become more vertical, and the SSr will decrease – decreasing the Q_r the line will become more horizontal and the SS_r will increase.

Increasing the Q_r too much will thus cause the clarifier to move towards a fully mixed tank and the sludge blanket will disappear. Decreasing the Q_r too much, making the returned flux line cross the settling flux curve, will cause the clarifier to function as a thickener, and the clarifier will fill up with sludge causing the sludge blanket to move towards zero.

The optimal Q_r (which also will be the minimal Q_r) will thus be obtained where the settling flux just equals the returned flux (figure 4) – in this point the two fluxes will also have the same slope, and therefore the first derivatives will also become equal. Solving the equations for the fluxes and their derivatives then gives the optimal value for Q_r, which then is used in the feed forward controller. Further, because the optimal Q_r balances the fluxes it also creates a steady sludge blanket.

Dynamic maximum hydraulic load

The upward flux is a straight line passing through the origin and having the slope Q_{bio}/A. Therefore, an increase in Q_{bio} will cause the line to become more vertical and move the state point upwards (still located vertically over the value for *SS* in the process tanks). When the state point reaches the curve for the settling flux, the upward velocity in the clarifier equals the settling velocity (figure 5), and the hydraulic load of the WWTP has reached its maximum, Qbiomax. The clarifier is overloaded and the sludge blanket will move upwards – no matter the size of Q_r - and eventually sludge will escape directly into the effluent or the next step of the WWTP (e.g. a sand filter, which will clog). However, if the sludge from the process tanks is allowed to flush to the clarifiers – keeping Q_r at its minimum – *SS* will decrease in the process tanks, as it will be stored in the clarifiers. Therefore, *SS* in the inlet to the clarifiers will decrease causing Vsed to increase. In the Clarifier State Diagram (figure 5) this will be reflected by a movement of the state point to the left – sliding down the line for the upward flux – also causing the controller to decrease Q_r, and giving the hydraulic load, Q_{bio}, the possibility to increase further. The result is that a controlled flush of sludge to the clarifiers and a subsequent controlled storage of the sludge in the clarifiers will increase the maximum hydraulic load, Q_{biomax}, during rain.



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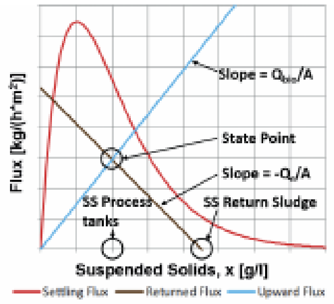
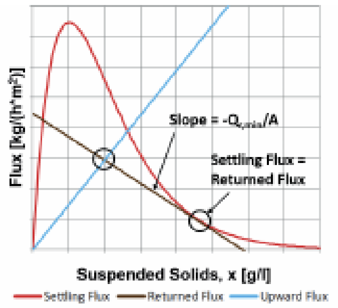
Distribution of return sludge rates between clarifiers

Most WWPTs have several secondary clarifiers or even more lines of clarifiers including several secondary clarifiers (figure 6). In practice it is a well-known problem that equal distribution of the load to the single clarifier (or line of clarifiers) sometimes through manually operated weirs in the distribution constructions is impossible to obtain – the weir positions (if any) are dependent on the hydraulic conditions in the distribution constructions. This in fact reduces the overall hydraulic capacity of the WWTP as such, because the clarifier with the highest load during



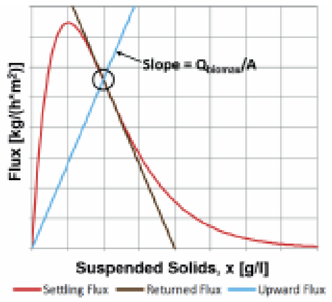
$$F_{settling}(X) = X * ISV * Exp(-nv * X)$$
$$F_{returned}(X) = ((Q_{bio} + Q_r) * SS - X * Q_r) / A$$
$$F_{upwards}(X) = X * Q_{bio} / A$$

Figure 3. Clarifier State Diagram



$$Q_r = ISV * A * (nv * X - 1) * Exp(-nv * X)$$

Figure 4. Clarifier State Diagram – $Q_{r,min}$



$$Q_{biomax} = V_{sed} * A \text{ or}$$
$$Q_{biomax} = ISV * Exp(-nv * SS) * A$$

Figure 5. Clarifier State Diagram – Q_{biomax}

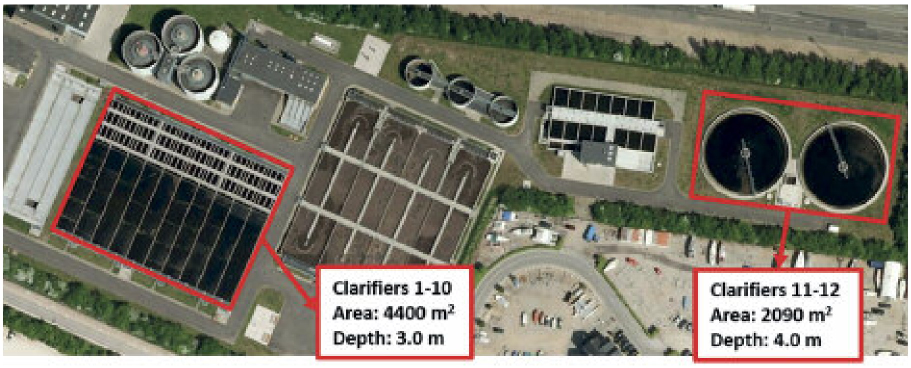


Figure 6. Marselisborg WWTP, Aarhus, Denmark is equipped with two clarifier lines

rain will produce the fastest growing sludge blanket level, and therefore set the limit to the inlet flow of the WWTP in order to avoid sludge washout.

In other words the operator experiences a too low value of Q_{biomax} compared to the dimensioned hydraulic load, and as this has nothing to do with V_{sed}, it can be compared to a loss of clarifier area, A, as the effective area is less than the built area. This can be quite a serious problem – an effective area as low as 2/3 of the built area has been observed. The straightforward solution could be real time control of all inlet weirs – if weirs exists, but on most treatment plants that will require investment in automatic weirs. Instead it is possible to compensate the skew distribution of the clarifiers using dynamic control of the distribution of the overall required return sludge flow, to the single clarifier based on each clarifier's sludge blanket level, SB, compared to the average value of the levels of all sludge blankets, SB_{Avg}.

The feedback controller aims at equalizing the sludge blankets in the clarifiers (having the same area and depth) to the same value in order to distribute and control the sludge storage capacity. The hydraulic load is not distributed, but the load variations, (measured as the variations in the sludge blankets) are compensated by higher or lower return sludge flow values from each of the clarifiers.

At the Marselisborg WWTP with 10 clarifiers in one line (figure 6), an equal distribution of the hydraulic load to the clarifiers in this line would require that the return sludge flow from each tank should be 10% of the calculated setpoint for Q_r, called Q_rSP. The controller adds or subtracts to this percentage for each clarifier keeping Q_rSP at the same value. The resulting return sludge flow values for each clarifier are sent to local control loops for the pumps or valves in each of the clarifiers.

The resulting movements of the sludge blankets are shown in figure 7 (left) together with the percentwise distribution of the return sludge pumping (right). The plots cover a period of two days, and the two peaks in the sludge blanket levels are caused by a small rain and a somewhat bigger rain respectively. It is clear that the distribution of the load to the 10 clarifiers is quite different in dry and wet weather, because the distribution of the return sludge pumping, which compensates for the skewness in the load distribution, is very different.

Distribution of load between secondary clarifier lines

Often more lines of secondary clarifiers at a wastewater treatment plant are a result of an investment in an extension of the WWTP in order to handle an increasing load. The extension of the secondary clarifier capacity is often done as an "add-on" exercise, and a proper distribution of the load between the old and the new clarifier line has to be done.

A control handle (gate/weir) is thus required downstream the process tanks, in order to control the flow to each of the clarifier lines. As the control handle is a part of the extension, it will typically work on the flow going to the new clarifier line (line 2), via a local control loop based on a measurement / set-point for the flow to the new clarifier line and divert the remaining part of the total flow to the old clarifier line (line 1).

It has to be remembered that the flow going to the clarifiers Q_{tot} is the sum of the inlet flow to the treatment plant and the return sludge flow, and as the control of the return sludge already is dependent on the inlet flow, Q_{tot} is as well. So any set-points applied to $Q_{tot,i}$ for each of the clarifier lines (i=1 and i=2) not only have to respect that $Q_{tot} = Q_{tot,1} + Q_{tot,2}$, but also have to respect the set-point to be calculated for the return sludge flow Q_r $(= Q_{r1} + Q_{r2})$.

In other words, the distribution of the flow to more clarifier lines has to be done in terms of the inlet flow, and the distribution shall reflect the ratio of the clarifier areas in the clarifier lines (as the possible load is dependent of the area).
In order to actively control the sludge distribution, the distribution according to clarifier areas is extended with a term including the sludge blanket averages: SB_{Avg1} and SB_{Avg2}, which then can be controlled to follow each other by compensating the area related return sludge flows with a percentage calculated from the distances of the sludge blanket average to the overall sludge blanket average for the WWTP. Calculating the overall sludge blanket average requires that the sludge blankets averages for each of the clarifier lines are comparable. For clarifiers of different depths the same sludge load per m^2 gives a comparable steady state sludge level, but as sludge blankets are measured from the top of the clarifier, they need to be compensated for the difference in clarifier depths. The clarifiers at the Marselisborg WWTP are 3 and 4 meters deep respectively, which requires an offset of 1 m on the sludge blanket average for clarifier line 2. This offset forms together with the measured sludge blanket average for clarifier line 2 a virtual sludge blanket, which can be directly compared to the sludge blanket average for clarifier line 1.

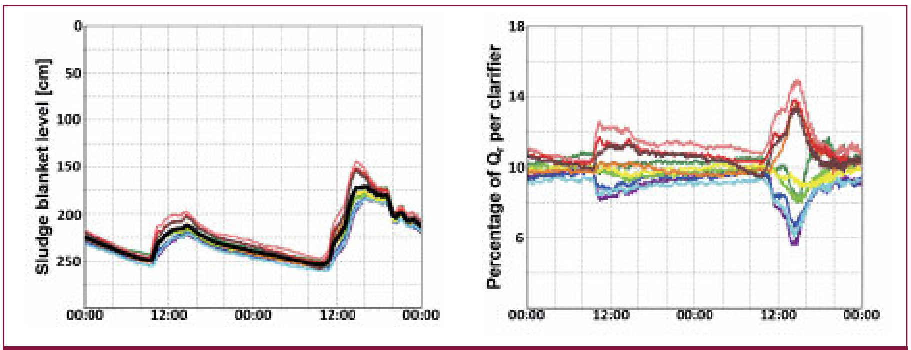


Figure 7. Marselisborg WWTP clarifier line 1 – Sludge blanket measurements resulting from the distributed return sludge pumping. Colors on plots follows the color spectrum – violet for clarifier 1 and dark red for clarifier 10. The average sludge blanket level is black

The controller is here described for two clarifier lines (at the Marselisborg WWTP), but obviously it can be extended to accommodate more clarifier lines. Sludge blanket offsets shall then be defined for each depth of clarifiers – the reference being the shallowest clarifiers.

Selective sludge storage control during rain

As the distribution of load between clarifier lines as described above is controlled by the average sludge blankets for each line, and as the average sludge blanket in the deeper clarifiers is virtual (measured sludge blanket level plus an offset), it is possible to force the load to a given line by manipulating the virtual sludge blanket (figure 8, bottom). When the inlet flow to the WWTP increases during the start of a rain, the offset can be set to zero.

When the offset is set to zero, the sludge blanket average in line 2 is suddenly increasing (note the inverted axis), which abruptly will increase the flow to the to the deeper clarifiers, as the controller will compensate a sudden increase in the average sludge blanket by a sudden increase in distribution percentage for line 2. As a result, sludge from the process tanks will be flushed to line 2, which will be heavily overloaded and therefore cause the average sludge blanket to decrease until the average sludge blankets (both being real) in the clarifier lines are balanced again. When it stops raining, the sludge blanket average in line 2 will again be virtual, and the average sludge blanket will suddenly decrease, which abruptly will decrease the flow the line 2, as the controller will compensate a sudden decrease in the average sludge blanket by a sudden decrease in the distribution percentage for line 2. As a result, the amount of sludge coming from the process tanks to the deeper tanks will be minimal, and the return sludge pumping will pump more sludge out of the clarifiers than arriving, and therefore cause the average sludge blanket to increase until the average sludge blankets (one real and one virtual) in the lines are balanced again. In figure 8 this is repeated at the next rain.

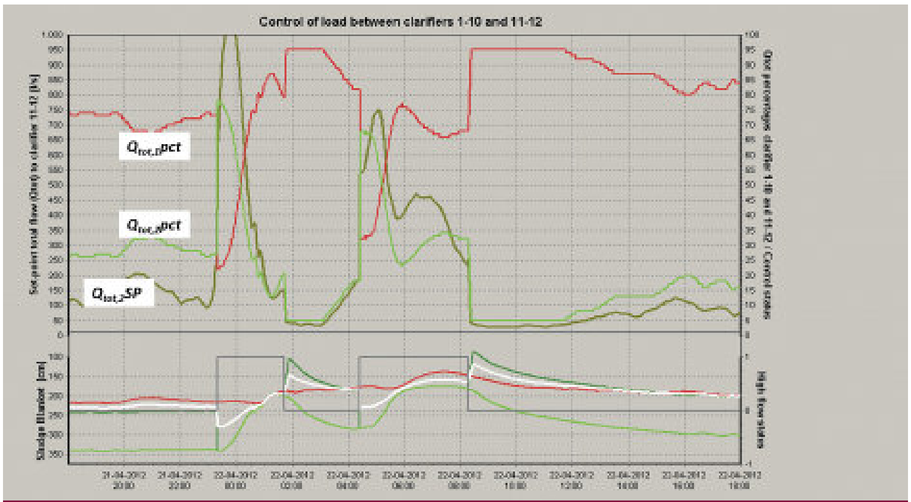


Figure 8. Marselisborg WWTP – sludge storage control using a virtual sludge blanket. Bottom: $SB_{Avg,1}$: red; $SB_{Avg,2}$: light green; $SB_{Avg,2\text{-}virtual}$: green; $SB_{Avg,WWTP:}$ white

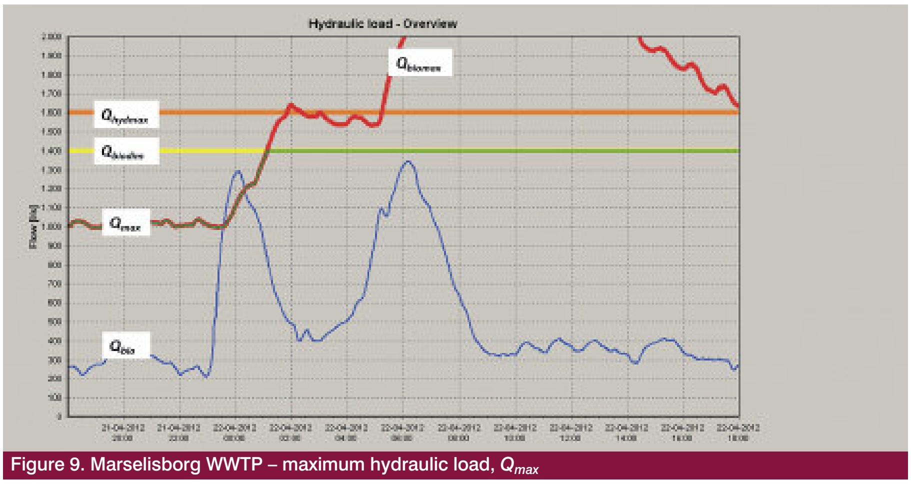


Figure 9. Marselisborg WWTP – maximum hydraulic load, Q_{max}

Combined value for max. hydraulic load

Figure 9 shows the same two rain events as in figure 8, and it can be seen that Q_{biomax} is increasing each time sludge is flushed to the clarifiers – from 1000 l/s to 1600 l/s and further on to 2800 l/s, which is far more than the WWTP can handle. The Qbiomax curve suggests that the settling velocity and the area are not the limiting factors.

Figure 9 shows how the maximum hydraulic capacity, Q_{max}, is calculated as a "safety wrapped" value:
If $Qbiomax <$ selected limit then $Q_{max} = Q_{biomax}$
If $Q_{biomax} >=$ selected limit then $Q_{max} =$ limit
where the selected limit can be either the dimensioned maximum inlet flow, Q_{biodim}, or the absolute maximum flow, Q_{hydmax}, that the WWTP can handle due to internal limitations. The limit can be selected by the WWTP plant manager. As the figure shows, Q_{biomax} can be less than the actual dimensioned capacity – especially during winter, where suspended solids concentrations in the process tanks need to be quite high, in order to be able to comply with the effluent standard for total-Nitrogen. The idea of Q_{max} is to protect the wastewater treatment plant when needed (low Q_{biomax}) and on the other hand to put more than the dimensioned capacity into service, if Q_{biomax} shows it is possible (selected limit = Q_{hydmax}).

Conclusion

A combined controller for real time control of secondary clarifiers has been developed and implemented on several WWTPs, and is here demonstrated by presenting the function of the controller at the Marselisborg WWTP. The results show:

- Efficient control of secondary clarifiers makes it possible to increase the hydraulic load during rain considerably above the dimensioned hydraulic load
- The presented controller does not have any lead time – which often is the case for this type of controller
- The controller does not affect the operation and control of the upstream biological process ■

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