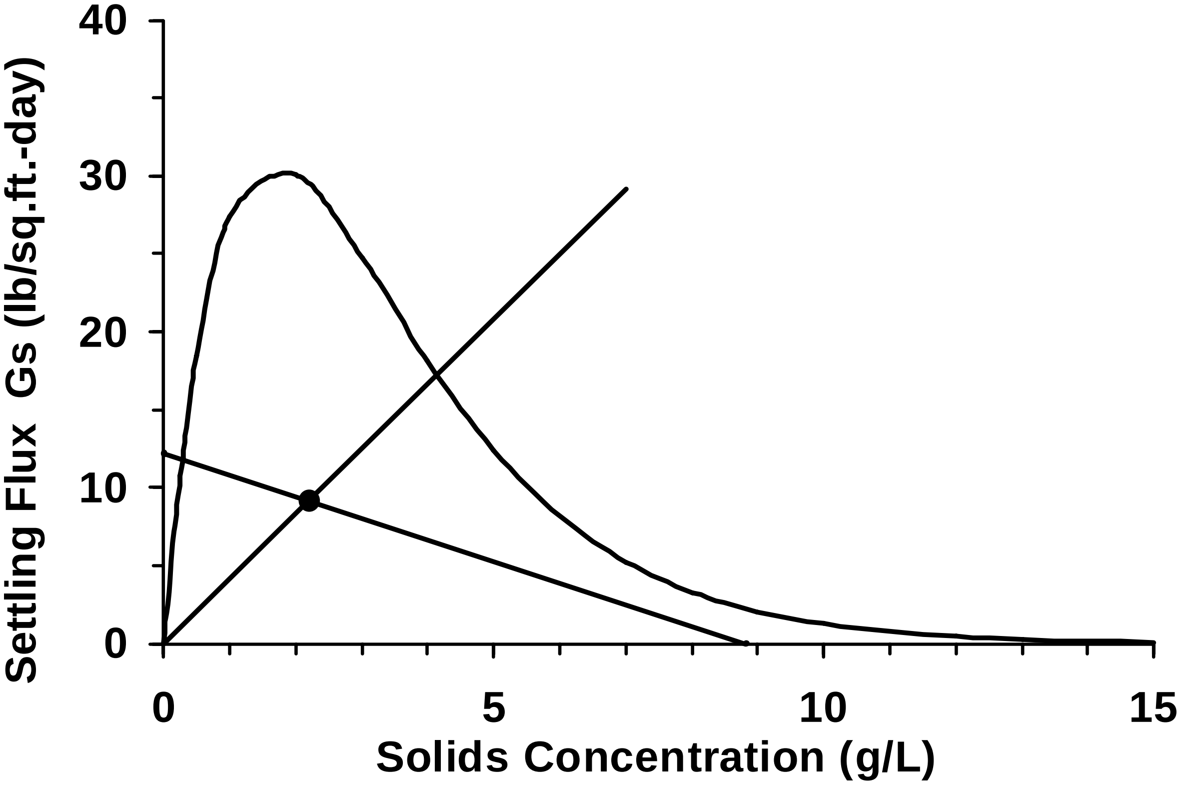
Using State Point Analysis to Maximize Secondary Clarifier Performance



Clarifier Performance

This document is a summary of a series of articles on secondary clarifier performance that appeared in the Maine DMR *O&M News* in 2003. The secondary clarifier is the most important part of the secondary treatment process. Unless the biological material in the mixed liquor can be separated from the clean water, it is likely that both the BOD and TSS limits will be violated. The purpose of this series of articles is to help you better understand how clarifiers work and how you, as the operator in control of the process, can adjust the operation of your clarifiers to make them as efficient as possible.

The first thing we need to understand about clarifiers is the principle of Mass Balance. Simply stated, whatever goes into a clarifier must come out, be that water or solids. In a clarifier, we want the solids to go out the bottom, to be returned or wasted, and the clean water to be discharged over the weirs carrying a few solids as possible. The mass of solids entering the clarifier is the product of the flow times the mixed liquor solids concentration (MLSS). The flow coming into the clarifier is the sum of the influent flow and the return flow (Q_I and Q_R). So we can write an equation for the mass of solids entering a clarifier as:

$$Solids\ Mass\ In = (Q_I + Q_R) \times MLSS$$

The mass of solids leaving the clarifier is the sum of three flow streams, the effluent, the return activated sludge (RAS) and the waste activated sludge (WAS).

$$Solids\ Mass\ Out = (Q_E \times Effluent\ TSS) + (Q_R \times RAS) + (Q_W \times WAS)$$

For most activated sludge systems the influent flow (QI) and the effluent flow (QE) are equal and we'll replace them in the equations above by Q. Since what comes into the clarifier must go out, the two equations are equal and thus:

$$(Q + Q_R) \times MLSS = (Q \times Effluent\ TSS) + (Q_R \times RAS) + (Q_W \times WAS)$$

Since the amount of sludge lost in the effluent is (we hope) very small and the amount of sludge wasted is small compared to the mass of sludge in the clarifier influent and return flows, we can remove those two terms from the right hand side of the equation leaving:

$$(Q + Q_R) \times MLSS \cong Q_R \times RAS)$$

If we do a little math, we can rearrange this equation to the following:

$$RAS \cong [(Q / Q_R + 1] \times MLSS$$

This equation tells us several important things:

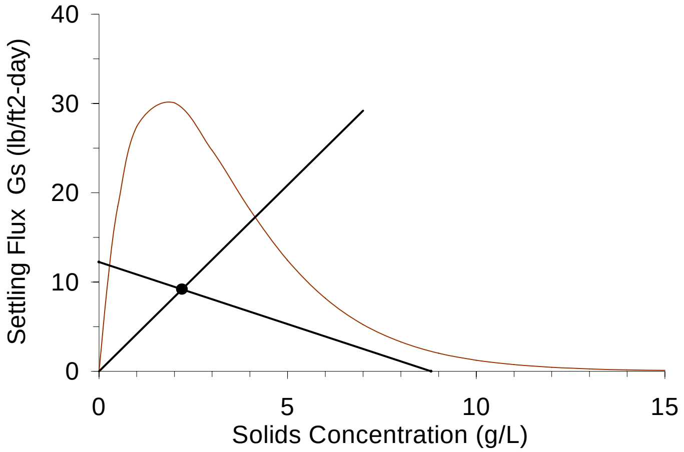
- Since $[Q/Q_R + 1]$ is always greater than 1, the return sludge (RAS) concentration will always be higher than the MLSS concentration.
- To get a concentration higher than the MLSS concentration, there must be some settling. This happens at or near the floor of the clarifier and regardless of the hydraulics of the tank, there will <u>always</u> be a sludge blanket.

- If you don't change the return flow, the RAS concentration will increase as the influent flow increases and decrease when the influent flow decreases.
- If you waste from your RAS line, the sludge will be thicker if you waste at a time when the flows are higher.
- Increasing RAS flows decreases the concentration of the RAS. Thus, while you may think that coning or "rat-holing" causes decreased RAS concentration, it is probably the result of the system maintaining the mass balance.
- The equation shows clearly that keeping the RAS flow at a constant percentage of the influent flow maintains the RAS concentration constant. That will, in turn, give a much more consistent operation.

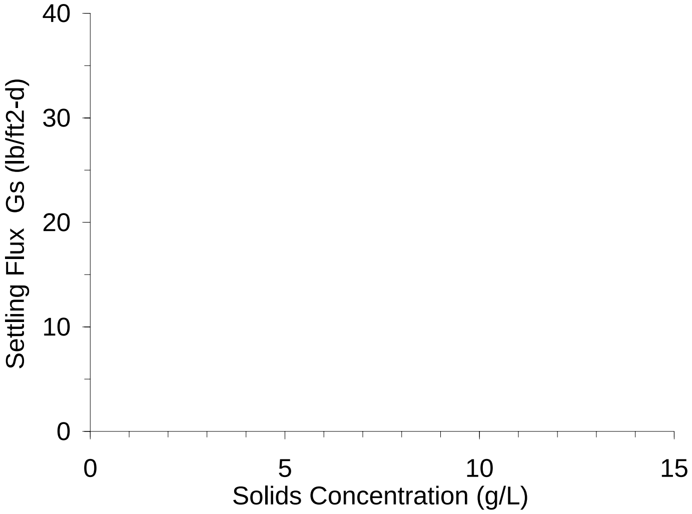
By looking the mass balance in the clarifier, we see that there is a clear relationship between the influent and return flows and the concentration of the RAS. Changing RAS flows to maintain a constant percentage of the influent flows helps provide a more constant environment for the bugs which will help them do their work better and help us look good.

Previously, we discussed the mass balance in the secondary clarifier. Again, mass balance means that whatever goes into a clarifier must come out, be that water or solids. If the clarifier is working correctly, the solids come out of the bottom of the clarifier as return activated sludge (RAS) or waste activated sludge (WAS) and the clean water flows out over the weirs carrying little or no solids. This month, we'll talk about something called "State Point Analysis", which is a tool you can use to help you find out what the mass balance looks like in your clarifiers and how that will change with flow and solids loading to the clarifier. The term "State Point" refers to the "State" of the mass balance in the clarifier. That is, what is the mass balance of the clarifier at a given point in time... what is going in and what is coming out?

The State Point Analysis is done using a graph that looks something like the one below. In this graph, we have two straight lines that cross each other at the State Point and a curved line that rises and falls as the solids concentration increases



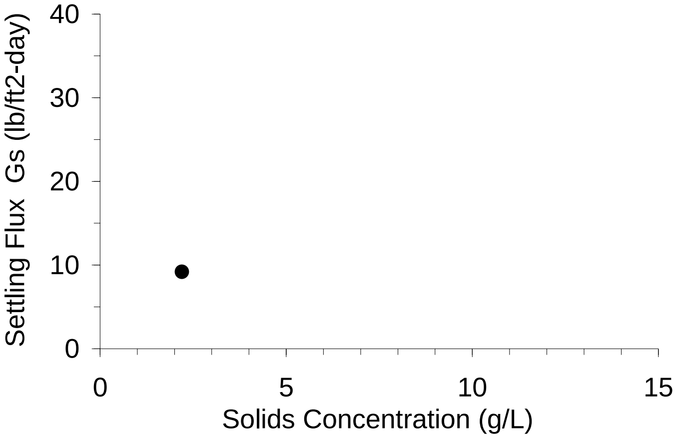
We begin the graph by setting up the axes. The y or vertical axis is the solids loading rate in pound per square foot per day (lb/ft^2-day). The x or horizontal axis is the solids concentration in grams/liter (g/L), which is milligrams/liter (mg/L) divided by 1,000. The "bare" graph is show below.



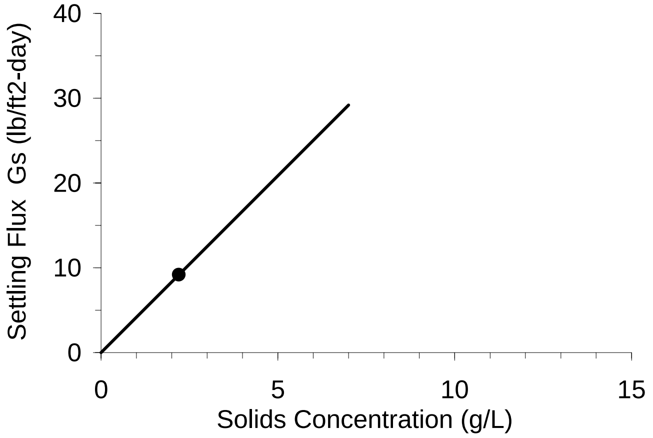
The solids loading rate (SLR) is, probably, the most important factor that will determine if your secondary clarifier works well. The design of many of the secondary clarifiers now being used in treatment facilities in Maine were based on the surface overflow rate (SOR) only. The SOR measures only the amount of water flowing through the clarifier. Since we are concerned with the mass balance of the solids in the clarifier, the SLR is really what we should be looking at. You calculate the SLR by multiplying the total flow coming into the clarifier, the influent flow plus the return flow ($Q + Q_{RAS}$) by the mixed liquor settleable solids concentration (X_{ML}) and dividing that quantity by the surface area of the clarifier (A). A little rearranging of the math gives us the formula for the SLR.

Equation 1 – $SLR = (Q/A)X_{ML} + (Q_{RAS}/A)X_{ML}$

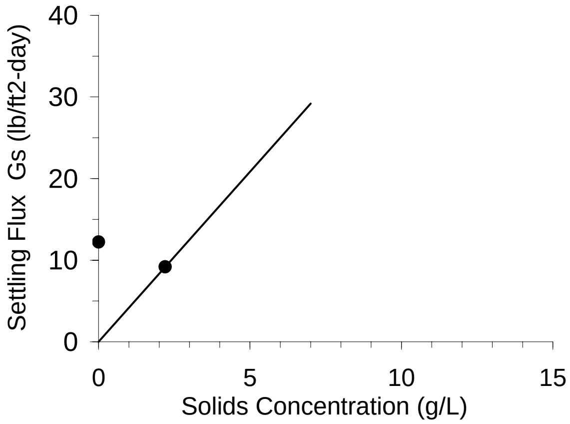
The first term in the equation above is used to plot the State Point. The y-coordinate of the point is $(Q/A)\ X_{ML}$ and the x-coordinate is X_{ML}. The graph is shown below.



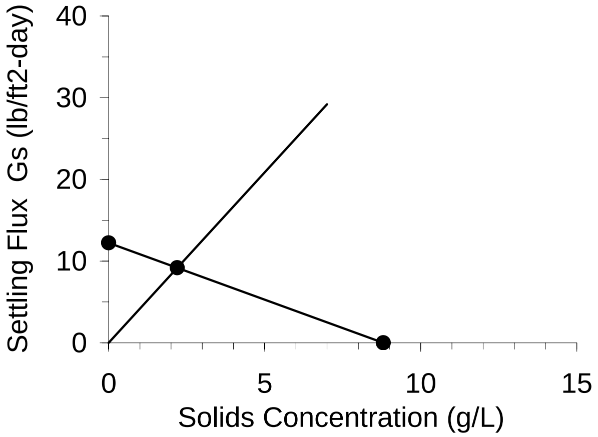
Next, we draw a straight line through the State Point and the Origin (0,0). The slope of this line is the surface overflow rate (SOR). The line is called the Overflow Rate Operating Line.



The total solids loading rate (SLR) is then computed using Equation 1 and plotted on the y-axis.



Now, we will draw a straight line from the SLR point through the State Point down to the x-axis. The slope of this line is the underflow rate, which is represented by $-Q_{RAS}/A$. The minus sign means that flow is leaving the clarifier. This line is called the Underflow Rate Operating Line.



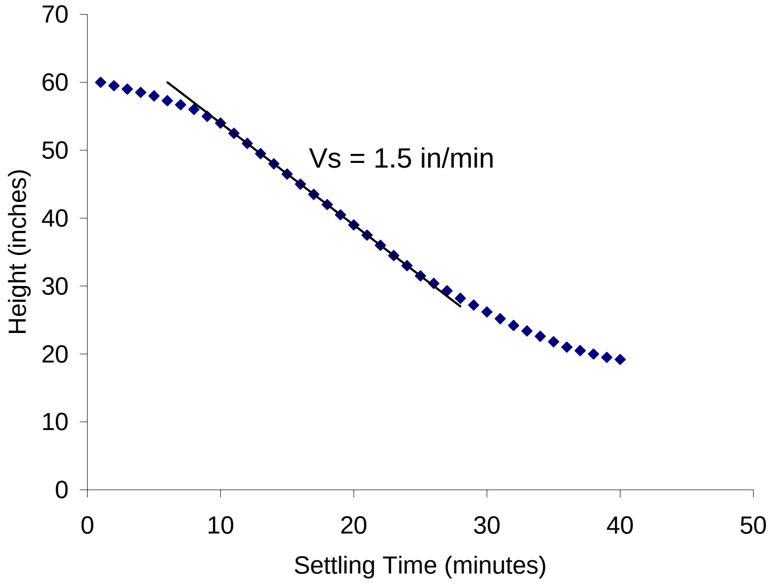
We’ve almost finished the graph that was shown at the beginning of this discussion. All we’re missing is the curved line that goes up and down. The lines and points we’ve plotted so far relate to five of the six factors that determine secondary clarifier performance.

- Clarifier Surface Area
  [Q/A & -Q_{RAS}/A]
- Mixed Liquor Solids Concentration
  [(Q/A) X_{ML} & (-Q_{RAS}/A) X_{ML}]
- Influent Flow
  [Q/A]
- RAS Flow
  [-Q_{RAS}/A]
- Sludge Settling Characteristics

Clarifier Hydraulics

All the things checked off in the previous list (the size of the clarifier, the amount of flow, and the solids concentration) all depend on physical parameters. These parameters can be measured and, to some extent, controlled. Most operators know, however, that the quality of the secondary sludge determines whether we can hold solids in the system. The curved line on the State Point Analysis chart is determined by the sludge settling characteristics and to have that chart be useful for any purpose, we need to figure out the shape of that curved line.

If you take a large sample of mixed liquor with a MLSS of 2480 mg/L, put it in a six foot tall settling column, and measure the height of the top of the sludge blanket as the sludge settles, you will see a curve shaped something like the one below.

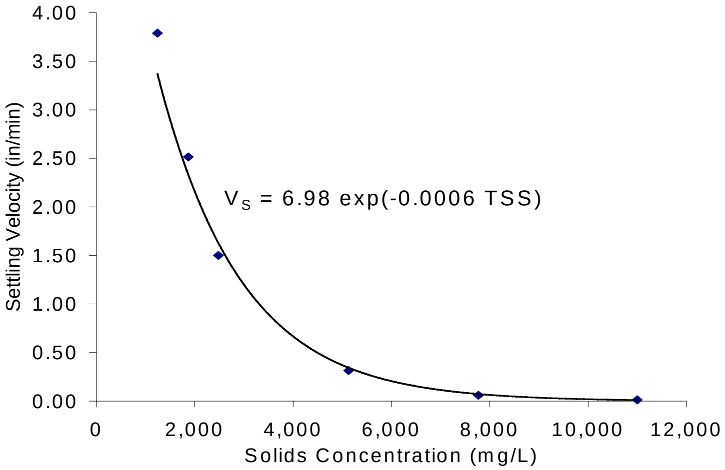


When we look at the curve, there is a section of the curve that is very close to being a straight line. If you draw a line through that section of the curve, the slope of the line gives you the settling velocity, as shown above.

You then repeat the test using various concentrations of mixed liquor and RAS as described in the following list.

Sludge Description	**MLSS Concentration (X_{ML})**	**Settling Velocity (V_S)**
Straight Mixed Liquor	2,480 mg/L	1.500 in/min
Straight RAS	7,770 mg/L	0.060 in/min
50/50 blend Mixed liquor and unchlorinated effluent	1,240 mg/L	3.790 in/min
50/50 blend of mixed liquor and RAS	5,130 mg/L	0.315 in/min
Concentrated RAS	11,000 mg/L	0.013 in/min
75/25 blend of mixed liquor and unchlorinated effluent	1,870 mg/L	2.515 in/min

If we plot the data from the various settling column runs, we get a graph that looks like the example on the top of the next page.



The equation of the curve is in the form: $V_S = V_O e^{-kx}$

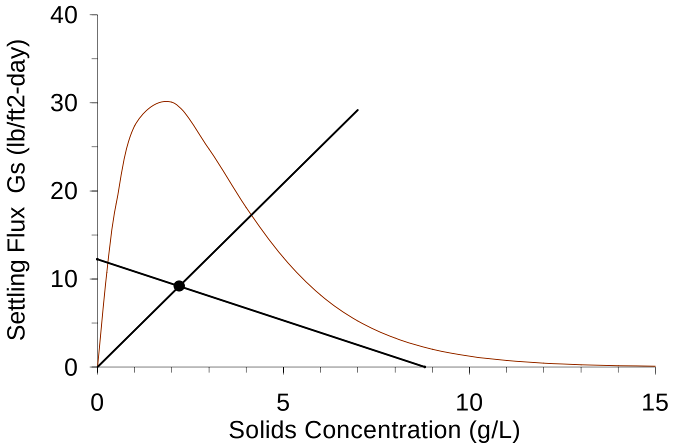
Where: V_S is the settling velocity and x is the TSS concentration of the sludge.
V_O (the initial settling velocity) and k (the settling rate) are defined by the settling characteristics of the sludge.

In the example above, the values of V_O and k are 6.98 in/min and –0.0006 L/g, respectively.

Once we have determined V_O and k, we can determine the Solids Flux (G). The Solids Flux is just like the solids loading rate. It is the amount or mass of solids that pass through a give area in a certain amount of time. Thus, it has the same units as the SLR, lb/ft^2-day. The Solids Flux is found by multiplying the settling velocity (V_S) by the solids concentration X_{ML}.

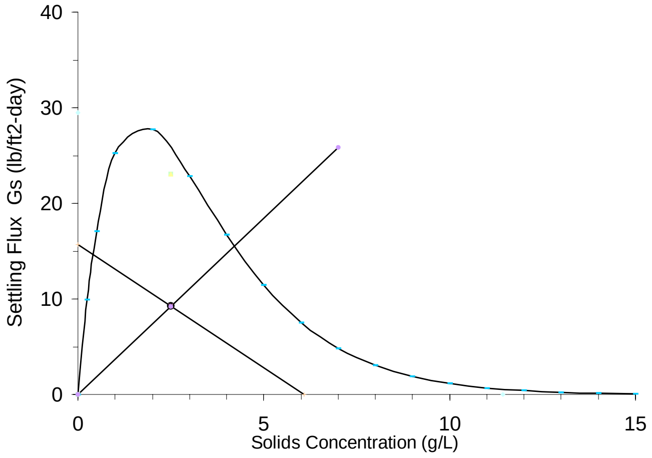
This gives the formula $G = X_{ML} \cdot V_S$ or $G = X_{ML} \cdot V_O e\text{-}^{kx}$

By computing the values for V_O and k, we can add the final piece of the State Point Analysis curve.

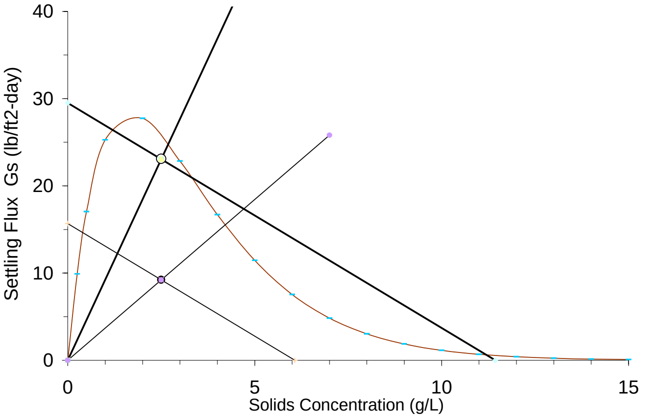


We have shown how the State Point Analysis curve is developed. We use the concept of mass balance, whatever goes into a clarifier must come out, to draw some lines and determine the shape of a curve that reflects the quality of the sludge. In this article, we'll look at how the different lines and curves change as the operation of the clarifier changes and how you can use the State Point Analysis chart to learn some things about how your clarifiers work and put that knowledge to use in your facility.

We'll start with a simple example. In this facility, the flow equals 1.0 MGD, there are two (2) circular secondary clarifiers each 34 feet in diameter and the RAS flow rate is 0.7 MGD. The operator is running with 2,500 mg/Ll of mixed liquor suspended solids with an initial settling velocity (V_o) of 738 ft/d and a k factor of 0.6 L/g. Plotting the various lines, curves and points we discussed last month gives a graph that looks like the one below.

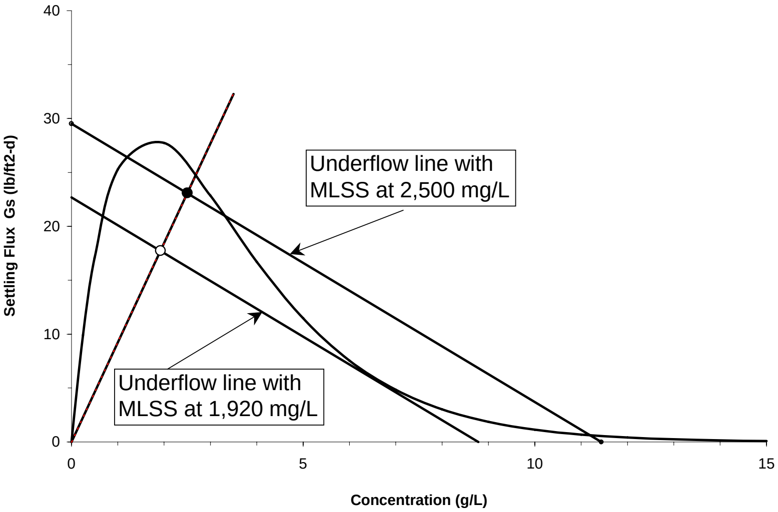


If the flow increases to 2.5 MGD and the return rate is not changed, we can add a second set of lines to the graph to show the effects of the additional flow. This graph is shown on the next page. It shows us some interesting (and not very good) things that will happen to the system.



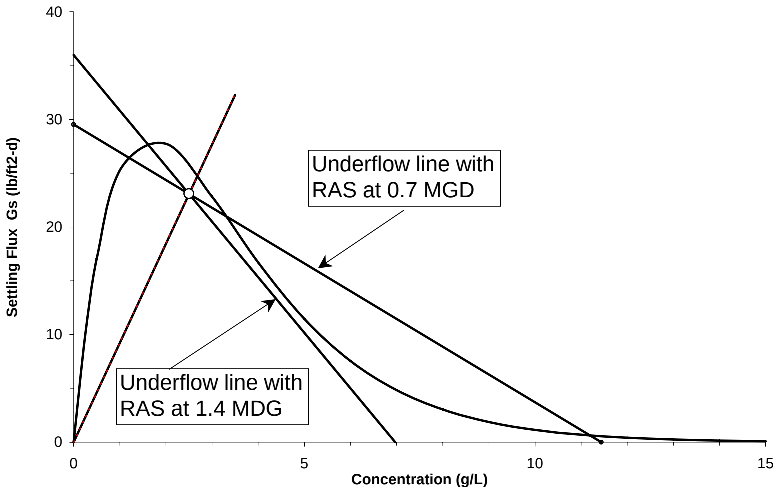
The increased flow causes the slope of the overflow rate operating line to get steeper. Since the mixed liquor concentration is still 2,500 mg/L, the state point on the new overflow operating line remains at that concentration (as shown by the open circle point). Since the underflow (RAS) rate is the same, the underflow operating line must be parallel to the original line and must go through the new state point. Notice that the point where the underflow rate line (the line that slopes down to the right) crosses the Settling Flux axis move from about 15.7 lb/ft^2-day to almost 30 lb/ft^2-day. Notice also that the underflow operating line is to the right of the settling flux curve. This means that the clarifiers are overloaded and they are receiving more solids than can successfully be transferred to the bottom, collected and removed. This sounds like a disaster in the making.

Luckily, the activated sludge process is forgiving, to a point. Because the clarifiers are overloaded, a sludge blanket will form. As the sludge blanket gets thicker, more of the solids in the system are transferred to the clarifiers and the MLSS in the aeration tank decreases. When the MLSS in the aeration tank decreases, the state point “slides” to the left and as it moves, the underflow rate line also moves until it just touches the settling flux curve. At that point, the clarifiers are “critically” loaded, which means that mass balance has been restored. But, almost one-quarter of the sludge in the system is now in the clarifiers. This is not an ideal situation, but if the blanket doesn't go over the weirs, the system will maintain good treatment.

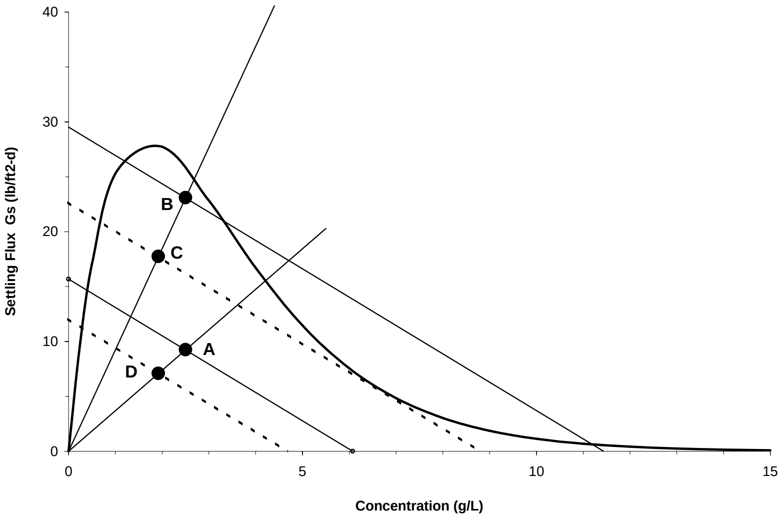


If, instead of letting the system correct itself, the operator increases the RAS rate as the influent rate increases, what happens? As you can see in the chart below, the slope of the underflow rate line gets steeper and the underflow line is now all under the settling flux curve. The clarifier is underloaded and a blanket should not form or, if there is a blanket, it should not increase.

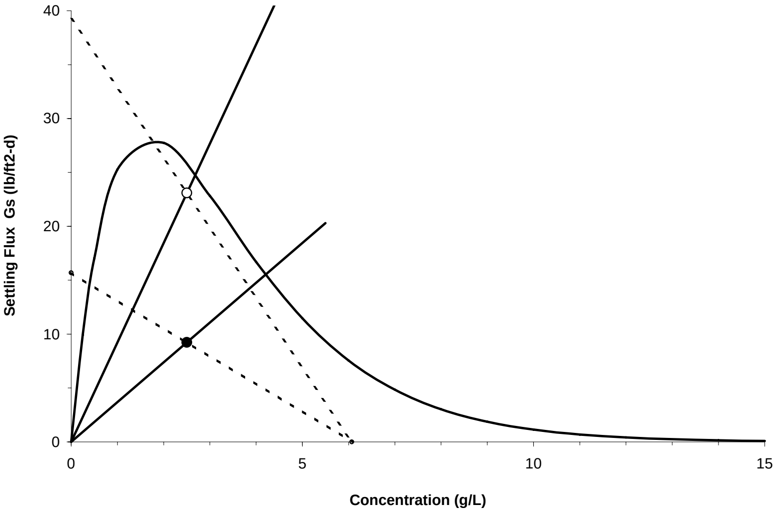
Many operators are concerned about raising the return rates because thy think the solids loading rate to the clarifiers will be too great and washout will happen. As this chart shows, even though the solids loading rate does increase, as long as the underflow rate line is under the settling flux curve, the sludge will stay in the clarifier.



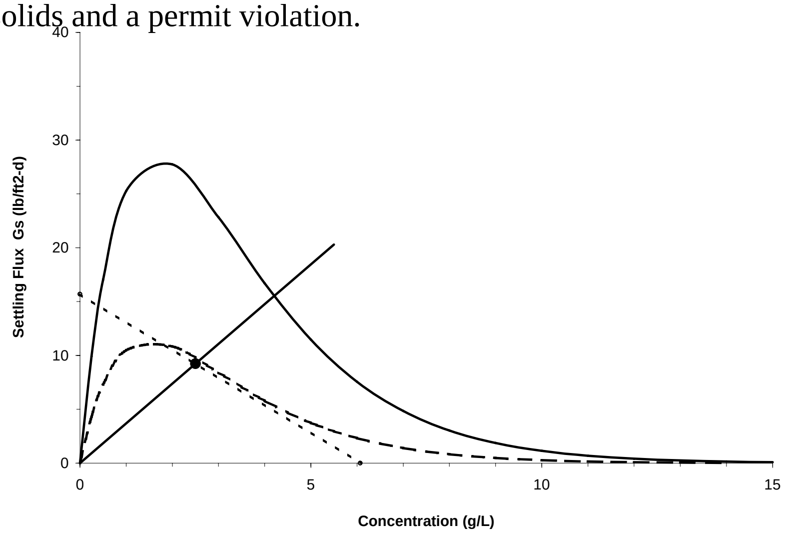
We can use the state point analysis chart to look at what happens in a system when the flow varies during the day. Let’s assume that the facility has two flow rates during the day: a normal flow of 1.0 MGD and a high flow of 2.5 MGD. This may seem funny, but the system will react the same, regardless of how the flows change within these bounds. Let’s start with the flow at 1.0 MGD, the RAS rate is 0.7 MGD, and the MLSS at 2,500 mg/L. That gives us a state point at **A** and everything is good. If the influent flow suddenly increases to 2.5 MGD and the RAS flow remains constant at 0.7 MGD, we move to state point **B** and the clarifiers are overloaded. A sludge blanket will form (or increase in depth if a blanket is already there) and solids will start to build up in the clarifier. As the MLSS in the aeration tanks become more dilute, we move to state point **C**, where the clarifiers are no longer overloaded and things are back to steady state. If the influent flow now drops quickly to 1.0 MGD, we move to state point **D** and the sludge will slowly move back to the aeration tanks until we reach the state point **A**, where we began.



Some facilities run with a fixed RAS rate, regardless of the influent flow. This is the situation we just looked at and you can see, if there was a significant sludge blanket in the clarifiers before the influent flow increased, you could have a washout of solids and a permit violation. If the RAS rate is set as a percentage of the influent flow, the solids loading to the clarifier will change but the underflow rate line should stay below the settling flux curve and the sludge should stay in the clarifiers. Let's look at the previous example but we'll set the RAS rate at 70% of the influent. When the flow is at 1.0 MGD and the RAS rate is at 0.7 MGD we have our original state point at **A**. When the flow increases to 2.5 MGD, the RAS rate increases to 1.75 MGD and the state point moves to **B**. Notice that the underflow rate line stays below the settling flux curve and the clarifiers remain under critical loading. This means that the sludge blanket, if any, should not increase even though the solids loading rate has increased.

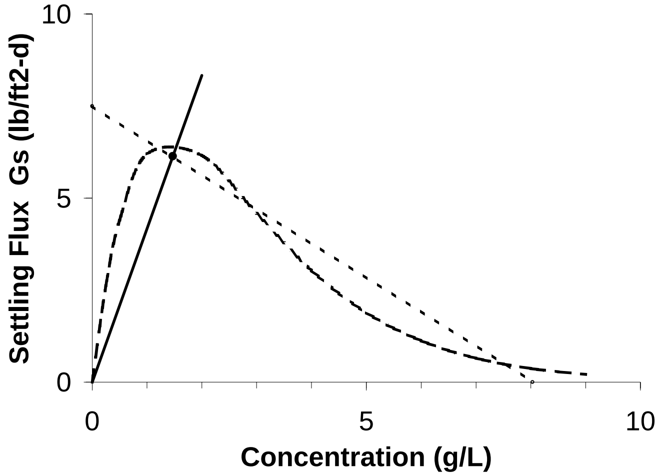


Finally, we'll look at what happens if the sludge quality deteriorates. Assume we have filamentous bacteria that "bloom" in the system. The sludge quality changes from an initial settling velocity (V_o) of 738 ft/d and a k factor of 0.6 L/g to with an initial settling velocity (V_o) of 325 ft/d and a k factor of 0.66 L/g. Now, the settling flux line is very much different than our original situation with influent flow of 1.0 MGD, RAS of 0.7 MGD and MLSS at 2,500 mg/L is right on the edge. Any increase of flow will probably mean a loss of solids and a permit violation.

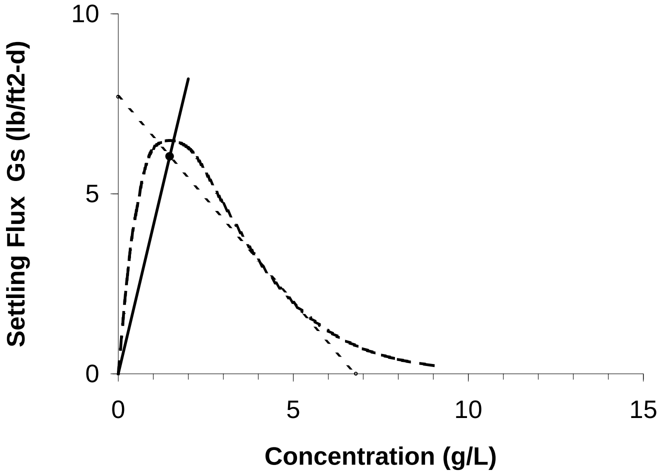


In our article last month, we showed how the different lines and curves of the State Point Analysis curve change as the operation of the clarifier changes. We also showed you how you can use the State Point Analysis chart to learn some things about how your clarifiers work and put that knowledge to use in your facility. This month we'll give a concrete example of how State Point Analysis was used to diagnose and solve a "Real-World" clarifier problem. We'll also discuss some models that have been developed to plot the Veslind curve (the up-down curved part of the State Point Analysis chart) based on sludge Volume index (SVI).

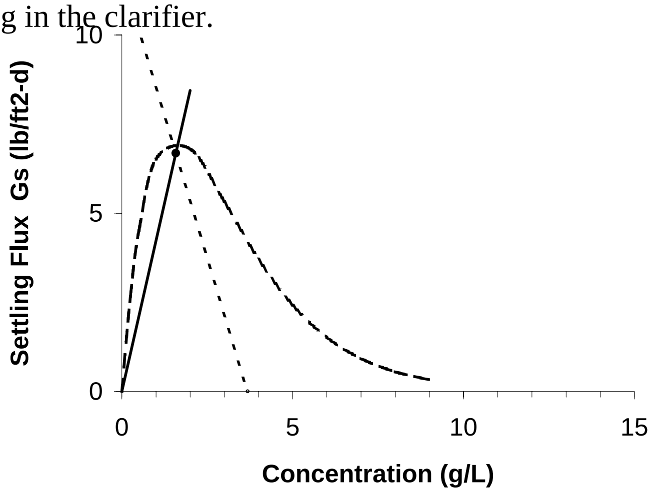
We'll start our "Real-World" example by describing the situation at the facility. This is a large municipal facility with a daily flow of between 53 and 55 MGD. The facility had three 215-ft. diameter, 16-ft. deep circular clarifiers. Technical assistance was requested when the system began loosing solids. At that time, the flow was 54.4 MGD, the SVI was 375 mL/g, the RAS flow was 12.2 MGD and the MLSS was 1470 mg/L. As the curve below shows, the clarifiers were overloaded with the Solids Underflow line clearly to the right of the Veslind curve.



The technical assistance troubleshooter immediately advised the operator to increase the RAS flow. Reluctantly, the operator turned the RAS flow up to 14.8 MGD while influent flow decreases to 53.5 MGD. RAS flow increased from 22% to 28% of influent flow. At the same time, the SVI improved slightly to 369 mL/g and the loss of solids lowered the MLSS to 1354 mg/L. As the graph below shows, the system is now in equilibrium and no more solids were being lost.

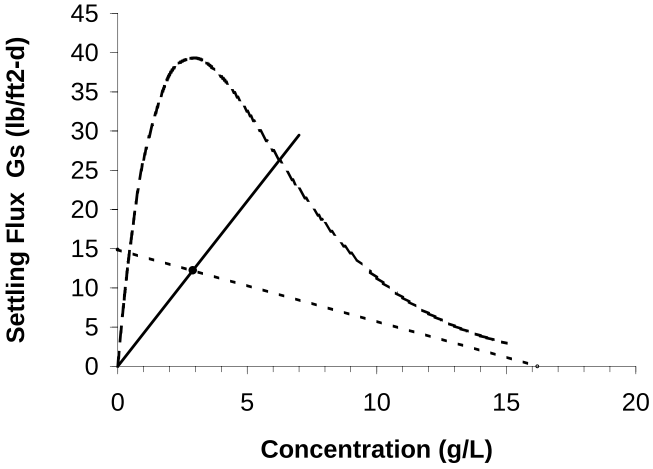


The technical assistance troubleshooter finally convinced the operator to increase the RAS flow even more. The operator turned the RAS flow up to 41.5 MGD while influent flow increased to 55.1 MGD. RAS flow increased from 28% to 75% of influent flow. At the same time, the SVI got slightly worse at 380mL/g while the MLSS increased to 1580 mg/L because more solids were being returned to the aeration tanks. The operators also increased wasting to remove solids from the clarifier. As the graph below shows, the blankets are staying in the clarifier.



Once the solids were staying in the clarifier, the technical assistance troubleshooter worked with the operator to improve the sludge quality and get the SVI under control. Over the course of a few weeks, through a combination of wasting, dissolved oxygen control and RAS control, the plant was brought to the following condition: Flow at 55 MGD with a RAS rate of 12 MGD (the original 22% RAS rate); MLSS at 2900 mg/L (with better BOD removal); and, SVI at 122 mL/g.

The graph for this operating state is shown below. The system is obviously running much better.



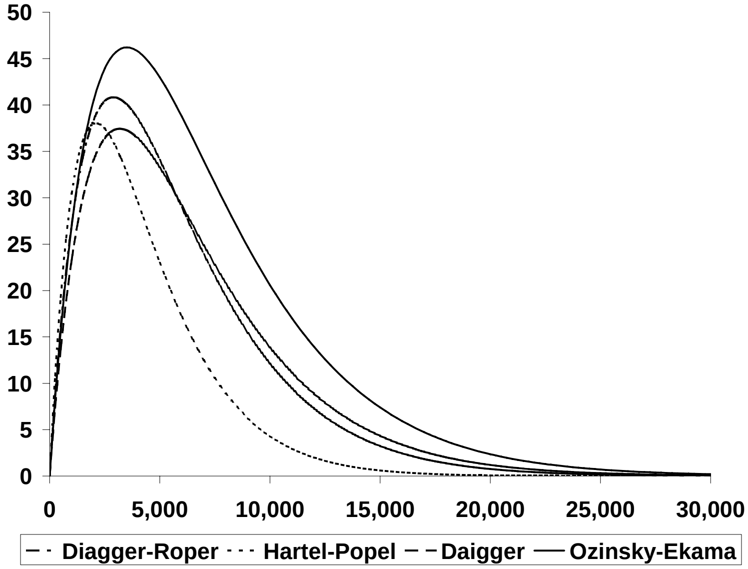
In this particular "Real World" example, the technical assistance troubleshooter did not have the settling velocity data necessary to develop the Veslind curve. In this case, he used one of several models developed by researchers that allow you to draw the Veslind curve as a function of SVI. Two of these models were developed by Dr. Glen Diagger and others while the other two were developed by Drs. Hartel and Popel in 1992 and by Drs. Ozinsky and Ekama in 1995. The equations developed by these researchers rely on data taken at several wastewater treatment facilities over some period of time. These data were "fit" to give the V_o and k factors needed to plot the Veslind curve

In Dr. Diagger's first equation, V_o is 7.8 m/hr (614.173 ft/day) and k is 0.148 + 0.00210 x SVI.

In Dr. Diagger's second equation, V_o is 6.495 m/hr (511.417 ft/day) and 0.1646 + 0.001586 x SVI. In the equation developed by Drs. Hartel and Popel, $V_o = 17.4 \text{ x } e^{[(-0.0113 \text{ x SVI}) + 3.931]}$ and

$k = 1.043 - 0.9834 \text{ x } e^{[-0.00581 \text{ x SVI})]}$. The fourth equation, developed by Drs. Ozinsky and Ekama, gives $V_o = 8.53094 \text{ x } e^{[-0.00165 \text{ x SVI}]}$ and k = 0.20036 - 0.00091 x SVI.

The graph below shows a comparison of the Veslind curves generated by the four methods.



While the curves shown on the last page are very similar, they may or may not compare well with Veslind curves developed by using actual settling date. One reason for this may be that the SVI data that forms the basis for these curves was collected using the recommended procedure in “Standard Methods”, which specifies using a l liter graduated cylinder rather than a one or two liter settleometer. Most operators in Maine and other northeast states use settleometers to determine the 30-minute settling volume and thus, the data may be somewhat different.

For troubleshooting purposes, use of one of the models will probably give a Veslind curve that is “close enough” and that will tell the troubleshooter what process change to recommend and what effect that change will have on the performance of the clarifiers. However, for day-to-day process control, actual settling data is far superior to using any of the Models.

Staff members from the Facility Operations Assistance Section (FOAS) of the New York Department of Environmental Conservation (NYDEC) have developed a fairly simple methodology for operators to perform the settling tests and develop the Veslind curves under various operating conditions. With enough of this settling data and corresponding SVI data, an operator could develop an equation to fit his/her facility’s characteristics. That equation would probably be somewhat different than any of the curves described before, but it would be a better tool for the operator to predict the performance of his/her facility.

If you want more information about the SVI models or the methodology developed by the NYDEC FOAS staff, contact Dick Darling at 287-7806 or by e-mail at dick.darling@maine.gov.