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1 Introduction

The stirred sludge volume index (SSVI) is one of the most widely used tests for determining the settling properties of an activated sludge. It is a very simple and rapid test that provides a lot of information, which can be used in the routine operation and control of an activated sludge plant. Perhaps the majority of plant operators use the SSVI test simply to assess whether an activated sludge settles well or whether it is experiencing sludge bulking. However, it can provide a lot more useful information than this:

- indicate potential problems with the airation basin
- ensure efficient operation of the final sedimentation tank

The aim of this manual not only to outline how the apparatus is used in the laboratory, but also to provide the theoretical background to the SSVI test. It will describe how the SSVI is employed in the design of a final sedimentation tank and how it is used in the routine operation and control of these tanks.

The following section is a brief discussion of sludge settlement in general; section 3 and onward detail the SSVI technique - for both plant operation and initial plant design.

2 The Role of Final Settlement Tank

2.1 Introduction

A final sedimentation tank has two roles.

To clarify and remove suspended solids from the effluent
The process of clarification is essential to produce a clear effluent that meets its discharge consents. In addition the removal of suspended solids from the effluent determines the overall process efficiency, as suspended solids are a major contributor to the

effluent BOD.

To store and thicken these solids in the tank

Sludge thickening is important to ensure that solids are removed from the tank faster than they are added. Some of these solids are returned to the aeration basin in the sludge recycle line, some of them are wasted from the system as surplus sludge. Thickening the sludge improves the efficiency of both these processes, and reduces the pumping requirements.

The thickening function of a final sedimentation tank is normally the rate limiting process. When a final sedimentation tank suffers operating problems it is nearly always because solids are being added to the tank faster than the ability of the tank to thicken and remove them. Consequently the sludge blanket in the tank starts to rise and as it nears the outlet launder, the clarification function is compromised, and suspended solids leave in the effluent.

In order to ensure efficient operation, a sedimentation tank is designed with a number of engineered features aimed at promoting good clarification and thickening. These are:

1. An inlet zone to dissipate the incoming flow velocity and distribute the flow evenly in a radial and vertical direction

2. An outlet weir to collect the settled sewage without excessive local flow velocities

3. A settlement zone within the tank to allow the solids to settle and thicken under gravity

4. A collection device which allows the thickened sludge to be removed efficiently from the tank

Typical circular sedimentation tank is illustrated in figure 1, and this highlights the four features described above.

2.2 Clarification

The clarification process is relatively simple and its efficiency depends on the available surface area of the clarifier. This is expressed in terms of the upward flow velocity and is given by:

Where: $$Q_A = \frac{Q}{A} \qquad \textbf{1}$$

Q_A =upward flow velocity (m/h)

Q = influent flow rate to tank (m^3/d)

A = tank surface area (m^2)

Good clarification requires that the upward flow velocity is <1.0 m/h at peak flow and the clarification efficiency of the final sedimentation tank determines the efficiency of the whole treatment process. This is because the biological stage of a wastewater treatment process involves the breakdown of biodegradable organic material (measured as BOD) by microorganisms in the presence of oxygen. This breakdown generates energy that is then used to synthesise new microorganisms. Thus the soluble BOD in the wastewater is converted into particulate BOD in the form of microorganisms. In order to ensure the maximum removal of BOD from the wastewater, it is essential that all the microorganisms are removed by sedimentation in the final sedimentation tank. This is illustrated in figure 2 which shows the contribution of solids in the effluent to the final effluent BOD.

2.3 Thickening

The mixed liquor entering a final sedimentation tank will typically have a solids concentration in the range 2,500 to 6,000 mg/L (0.25 to 0.6% dry solids). In other words they are up to 99.75% water!

A final sedimentation tank should store and thicken these solids such that the solids concentration in the underflow from the tank is in the range 12,000 to 15,000 mg/L. The ability of a sedimentation tank to thicken solids depends on three factors, namely:

i) The rate at which solids are introduced into the tank, which is known as the solids loading rate, with units of kg/m^2 d.

ii) The rate at which solids are withdrawn from the base of the tank in the underflow (m^3/d)

iii) The ability of the solids to settle in the final sedimentation tank.

The inter-relationship of the three factors is discussed in detail in section 5 (p.).

It is easy to calculate the first of these factors, the applied solids loading rate, and with reference to figure 1, this is given by:

$$G_a = \frac{X(Q+Q_r)}{A} \qquad \mathbf{2}$$

Any given final sedimentation tank will have a maximum solids loading rate which can be applied to it. If this value is exceeded the tank will be overloaded and it will experience thickening failure. However for a given tank the maximum applied solids loading depends on the other two factors, and in particular the ability of the solids to settle in the tank. The maximum applied solids loading can be determined directly by increasing the solids loading to a clarifier until it experiences failure. However this procedure is cumbersome and time consuming. In addition it may result in the final effluent failing its discharge consent. It is far more practical to calculate the maximum applied solids loading based on laboratory tests of sludge settleability.

Unfortunately it is difficult to assess the ability of the solids to settle within the tank. A lot of research effort has thus been directed towards developing improved laboratory methods for determining sludge settleability. One such test, the stirred sludge volume index (SSVI), has gained widespread acceptance both in the UK and throughout the world.

3 The Stirred Sludge Volume Index (SSVI)

3.1 Introduction

The SSVI was derived by the Water Research Centre (WRc) in 1975. The test was intended to simulate the conditions occurring in a final sedimentation tank and it involves gently stirring activated sludge at 1 rpm during its settlement in a column, over a 30 min. period. The height of the sludge in the column is measured at the end of this period and this is used to calculate the volume occupied by 1g of sludge; hence the SSVI has units of mL/g. Stirring the sludge plays an important role in that it helps to improve flocculation and reduce short-circuiting. It also generates a linear relationship between the settled volume of sludge after 30 min. and the sludge concentration. However the value of the SSVI is not independent of the initial sludge concentration, and consequently it is important to report the value of the SSVI at a standard concentration of 3.5 g/L. It is thus referred to as the $SSVI_{3.5}$. In the UK the $SSVI_{3.5}$ is the routine sludge settleability measure and used extensively for the design and control of secondary sedimentation tanks.

3.2 Using the SSVI Test Apparatus

It is very easy to measure the $SSVI_{3.5}$ of a sludge using the Triton-WRc settling apparatus (figure 3). A sample of sludge (~5L) is taken from the aeration basin close to the point where the mixed liquor exits the basin. The sample is returned to the laboratory and the $SSVI_{3.5}$ test carried out within 2h of sampling. In the laboratory the sludge sample is mixed vigorously to ensure that all the sludge is resuspended. A portion of this sludge is removed for the determination of its suspended solids concentration. The remainder is used for the $SSVI_{3.5}$ test.

The **perspex tube** of the settling apparatus is filled to the **top graduation** (marked 50 cm) with the well-mixed sludge. The **low-speed stirrer unit** is connected to the cylinder and the timer started. After 30 min. of settling the sludge will have formed a clear interface with the clarified effluent. The height of this **sludge interface** is measured against the **graduated scale** on the side of the perspex tube. The remainder of the well-mixed sludge is now diluted with either final effluent (which is the preferred dilutant) or with tap water, at a 1:1 dilution. The perspex tube is filled with this diluted sludge, and the SSVI test repeated.

In order to determine the suspended solids concentration of the sludge sample, a 70 mm filter paper (Whatman GF/C), is placed on a dish and dried at 105°C for 1h. The filter and dish is then cooled in a dessicator and the combined weight determined (X_1). The filter paper is placed in the filter apparatus and the paper wetted by drawing a small amount of water through it by suction. The sludge sample is well mixed and 25 mL of this sample is transferred to the filter. The water is drawn off the sludge by suction, and the residue remaining on the filter is washed well with 25 mL of distilled water. The paper is now folded and carefully removed from the filter apparatus. Any sludge adhering to the funnel is wiped off onto the filter paper and the paper placed on a dish. The dish and paper are dried at 105°C for 1h, cooled in a dessicator and the combined weight determined (X_2). The suspended solids concentration is then calculated from the equation:

$$\text{Suspended solids} = \frac{(X_2 - X_1)\ \text{mg} \times 40}{1000} \quad (\text{g/L}) \qquad \mathbf{3}$$

Only one test is required to determine the suspended solids concentration, as obviously the suspended solids concentration of the diluted sludge sample is half that of the undiluted sample.

The SSVI for the two tests can now calculated from the equation:

$$\text{SSVI (mL/g)} = \frac{\text{Volume occupied by sludge after 30min settling (mL/L)}}{\text{Suspended solids concentration of sludge (g/L)}} \quad \mathbf{4}$$

These two SSVI values are converted into an $SSVI_{3.5}$ from a graph of SSVI vs MLSS (figure 4). The two values for SSVI determined in the test procedure, are marked on the graph and then joined with a straight line. The value of the SSVI at a MLSS of 3.5 g/L is then read off from this line and reported as the $SSVI_{3.5}$.

4 Interpretation of Test Results

A well settling activated sludge will have a value for the $SSVI_{3.5}$ of less than 90 mL/g, and this is a good target to aim for in plant operation. Providing that the plant operating conditions remain relatively constant, then the SSVI should not vary widely (±15 mL/g). However for most treatment plants (particularly in the industrial sector), operating conditions are not constant, and the influent flow and load in particular will vary widely. It is important therefore to monitor a range of parameters that are likely to influence the value of the $SSVI_{3.5}$. These are:

- Sludge age
- Food/Microoganism ratio
- Influent flow
- Influent BOD/COD
- Nutrient concentration in influent (ammonia and phosphate)

- Aeration basin temperature
- Aeration basin dissolved oxygen
- Sulphate and sulphide in the influent (if appropriate)

All of these values should be entered into a spreadsheet and the trends plotted and displayed regularly. There is generally a range of plant operation conditions that are associated with a good settling sludge with a low $SSVI_{3.5}$. Conversely certain plant operating conditions will be found to be detrimental to sludge settleability, and should be avoided.

If the $SSVI_{3.5}$ increases significantly to values in excess of 120 mL/g, then this is indicative of sludge bulking. This is a condition in which a group of microorganisms known as filaments, proliferate within the mixed liquor and extends from the floc into the bulk liquor. They interfere with the compaction, settling and thickening of the sludge in the final settlement tank and are a major problem at many activated sludge plants. The presence of filaments can be confirmed by microscopic analysis of the sludge (plate 1). A useful poster is available free of charge, which outlines the steps to be taken to deal with a bulking sludge (Activated Sludge Troubleshooting Chart, HydroCare Ltd., Immingham, NE Lincolnshire DN40 2NS).

In addition to determining the value for the $SSVI_{3.5}$, the SSVI apparatus also gives usual visual information that can be helpful in diagnosing problems with the activated sludge process. Sludge from a well operated treatment plant will settle rapidly in the perspex column, giving a distinct solids interface and a clear supernatant, free from suspended or floating material. Often however this does not take place and Table 1 outlines some of many problems which can be diagnosed using the SSVI test apparatus.

Table 1 Typical problems encountered with sludges settling in the Triton Settling Apparatus

Observation	$SSVI_{3.5}$ (mL/g)	Problem
Sludge settles well with a distinct interface and clear supernatant	< 90	Well operated treatment plant
Sludge settles poorly but with a distinct interface and a clear supernatant	> 120	Filamentous bulking - confirm by microscopic analysis
Sludge settles poorly, no distinct interface, supernatant cloudy, large amounts of scum/foam on surface	Difficult to measure / > 120	Foaming - confirm by microscopic analysis of foam for presence of Nocardia spp. and M. parvicella
Some sludge settlement but with no distinct interface. Supernatant very turbid containing a lot of small flocs. No foam or scum on surface.	Difficult to measure	Toxic compounds may be present in influent, causing some inhibition and toxicity, particularly of ciliated protozoa - confirm by microscopy.
Very little or no sludge settlement. Sludge does not form flocs and comprises dispersed, small clumps	Can't be measured	Severe toxic shock due to toxic compounds in influent
Sludge settles well with a distinct interface, but towards the end of the test (or later) the sludge rises to the surface of the apparatus. Small gas bubbles observed attached to sludge flocs.	60 -100	Nitrification occurring in the aeration basin, leading to denitrification of nitrate to nitrogen gas in the final clarifier.

5. The Application of SSVI in Design of Final Sedimentation Tanks

There are a number of different procedures used within North America and Europe for the design of secondary sedimentation tanks. These can be classified into four main approaches, namely:

i Solid flux theory

ii WRc (Water Research Centre, UK) Method

iii ATV (Abwasser Technik Verband, Germany)

iv STORA (Stichting Toesgepast Onderzoek Reiniging Afvalwater, Holland)

Although apparently different in concept, they are all based on solids flux theory and they can be unified by adoption of the SSVI as a measure of sludge settleability.

Solids flux theory is a generally accepted approach for describing the thickening function of a sedimentation tank. It is based on the observation that there is a maximum quantity of solids that can be applied to a sedimentation tank at a given underflow rate, without affecting performance. In a sedimentation tank operating at a steady state, there is a constant flux of solids moving downwards. This is brought about by gravity and by the fact that solids are being withdrawn from the bottom of the tank in the underflow (or sludge return line). Thus the total flux of solids is described as:

$$G = G_S + G_b \qquad \mathbf{5}$$

Where:

G = Total rate at which solids of a given concentration travel downwards (total solids flux)

G_S = Solids flux due to gravity (or settling flux)

G_b = Solids flux due to solids removal (bulk flux)

The settling flux is a function of how quickly the sludge settles and it can be described by equation 6.

$$G_s = X_i . V_i \qquad \textbf{6}$$

Where:

G_S = solids flux due to gravity (kg/m^2 h)
X_i = solids concentration (g/m^3)
V_i = zone settling velocity of solids at concentration X (m/h)

It is apparent from equation 6, that the total solids flux in equation 5 will be dependent upon the solids concentration of the sludge entering the final sedimentation tank. Solid flux theory thus requires a relationship to be established between the zone settling velocity and the solids concentration. Perhaps the best model of this relationship is that described by Vesilind, which takes the form:

$$V_s = V_o e^{-nX} \qquad \textbf{7}$$

In this equation V_o (m/h) and n (L/g) are coefficients which describe the settling behaviour of the sludge.

Having defined a relationship between the zone settling velocity and the solids concentration, the mass balance for the solids flux is completed by considering the movement of solids due to sludge withdrawal, as described by equation 8.

$$G_b = U_b X_i \qquad \textbf{8}$$

Where:

G_b = solids flux due to underflow (kg/m^2 h)
U_b = bulk downward velocity (m/h)

The bulk downward velocity can also be expressed in terms of the clarifier area as:

$$U_b = X_i \frac{Q_u}{A} \qquad \mathbf{9}$$

Where:

Q_u = underflow flowrate (m^3/d)

A = required sedimentation tank area (m)

Thus the total mass flux of solids can be determined from equation 5 after substituting the values calculated in equations 6, 7, 8 and 9, and this is given by:

$$G = X_i V_o e^{-nX} + \left(\frac{Q_u}{A}\right) X \qquad \mathbf{10}$$

As the required tank area is governed by the minimum solids flux (which represents the minimum solids handling capacity of the tank), this equation can now be differentiated twice to determine with respect to X, in order to determine the point of inflexion (equation 11). This represents the minimum area of tank required at a given underflow velocity.

$$\left(\frac{Q_u}{A}\right) = 0.13\ V_o \qquad \mathbf{11}$$

In order to use solids flux analysis the constant V_O for the Vesilind equation must be determined, and this requires that a number (6 to 10) of batch settlement test are carried out over a range of solids concentrations (typically 2 to 12 g/L). Thus although the Vesilind equation is probably the most rationale design model for secondary sedimentation tanks, it is not widely applied because of the need for a large number of tests to determine the relationship of the zone settling velocity with the solids concentration. Consequently a number of other measures of sludge settleability have been developed. These include the diluted sludge volume index (DSVI) and the stirred sludge volume index (SSVI).

When the $SSVI_{3.5}$ is used in place of the zone settling velocity, design of sedimentation tanks can take two forms. One approach is to use the Vesilind equation (5) and estimate the values of Vo and n from the SSVI. Empirical relationships have been derived which relate the values of these parameters, namely:

$$n = 0.16 + 0.0027\ SSVI3.5 \qquad \mathbf{12}$$

and

$$Vo = (10.9 + 0.18\ SSVI_{3.5})e\text{-}^{0.016\ SSVI_{3.5}} \qquad \mathbf{13}$$

Thus having selected a value for the SSVI, the settling parameters V_o and n are calculated. These can be substituted in equation 11 to determine the required tank area.

In the UK a more widely used approach is to use an equation developed by the WRc which allows the area of the sedimentation tank to be calculated directly based on an assumed value of the $SSVI_{3.5}$.:

$$A = \frac{MLSS^{3.125}\ SSVI^{2.41}\,(Q_u^{\,0.32} + {}^{Q_s}\!/\!_{Q_U^{\,0.68}})^{3.125}}{306.86^{3.125}} \qquad \mathbf{14}$$

Where:

A = Horizontal surface area of sedimentation tank (m^2)

MLSS = Operating mixed liquor suspended solids (mg/L)

Q_u = Return sludge flow rate (m^3/d)

Q_s = Flow rate of sewage into aeration basin (m^3/d)

This equation has been verified by full-scale design and performance of a large number of tanks in the UK where it predicted the maximum solids loading within ±20%.

In order to use this equation a designer is required to select a value for the SSVI of the sludge. Where a large amount of historical data is available, selection of this value can be based on previous performance (with the application of a suitable margin of safety). Where no such information is available a design value of 120 mL/g is usually selected. The value of SSVI chosen has a large impact on the area of sedimentation tank, as illustrated in table 2, and it is worth spending some time to ensure that a representative value is selected.

Equation 14 has also been expressed in the form of a nomograph which is widely used by plant operators in order to avoid a solids overload to the final sedimentation tank (fig. 5). This is discussed in more detail in section 6.0.

6 Using the SSVI Test for Plant Operation and Control

6.1 Introduction

The $SSVI_{3.5}$ provides an excellent tool for controlling the operation of a final clarifier. Section 5.0 has described how a final sedimentation tank has a maximum solids loading at which it can operate. If the tank is operated within this limit, it will perform well. However the value of the maximum solids loading is not constant and it will vary as the sludge settling properties change. As the $SSVI_{3.5}$ of the sludge increases (ie the settling properties deteriorate), the maximum solids loading of the tank will also decrease. Equation 14 summarises the nature of this relationship. It shows that for a final sedimentation tank of a given area, if the $SSVI_{3.5}$ changes, then the maximum solids loading of the tank can be maintained constant either by: changing the recycle rate; changing the reactor MLSS; or changing the influent flow rate to the aeration basin. As it is generally not an option to change the influent flow rate this leaves just two parameters available for controlling a final sedimentation tank, namely the recycle rate and the reactor MLSS. Equation 14 is very cumbersome to use routinely (although it can be applied to a spreadsheet with ease), but fortunately it can be expressed in the form of a nomograph (figure 5). This nomograph is a tried and tested technique for operating a final sedimentation tank under optimum conditions and its routine use is recommended. In order to use the nomograph:

1. Measure the $SSVI_{3.5}$ of the sludge in the Triton Settling apparatus and mark this value on the left-hand axis (**a**).

2. Measure the return activated sludge flow rate from the final sedimentation tank in m^3/h. Divide this value by the tank surface area in m^2 to give the underflow rate per unit area (m/h). Mark this value on the second axis on the left (**b**).

3. Mark a line to join the value of the SSVI$_{3.5}$ with the underflow rate per unit area. Continue this line to the centre axis (**c**). This value represents the predicted maximum solids loading rate. The tank should be operated at about 20% of its maximum solids loading rate, so mark the operating solids loading rate on the central axis (**c**).

4. Measure the total flow rate into the final sedimentation tank (both the influent and the return flow rate) in m^3/h. Divide this value by the tank area to give the total flow rate per unit area (m/h). Mark this value on the right hand axis (**d**).

5. Mark a line to join the operating solids loading rate (**c**) with the total flow rate per unit area (**d**). Continue this line to the far right axis (**e**).

6. This is the value of mixed liquor solids that must be maintained in the aeration basin in order to operate the final sedimentation tank at its optimum.

6.2 What do I do if my final sedimentation tank is performing badly?

If after using the WRc nomograph as described above, and the MLSS in the aeration basin is higher than that suggested by the nomograph, then it will be necessary to waste solids from the final sedimentation tank in order to maintain the required value for MLSS. Wasting solids in this way will cause the sludge age of the aeration basin to decrease. Often the sludge settleability is very poor (ie the SSVI$_{3.5}$ has increased significantly) and there is not a lot of spare sedimentation tank capacity available. Under these circumstances the amount of sludge that must be wasted may cause the sludge age to drop so low that the ability of the system to treat the waste is prejudiced. Another way to increase the maximum solids loading of the tank is change return sludge rate. Inspection of the nomograph (figure 5), shows that for a given value of SSVI$_{3.5}$

(**a**), the predicted maximum solids loading (**c**) will increase as the underflow rate per unit area (**b**) is increased. However the underflow rate per unit area must not be increased above a value of 1.2 m/h.

Thus if it is not possible to reduce the MLSS to the required value without prejudicing treatment, then increase the sludge recycle rate to give an underflow rate of 1.2 m/h. Repeat steps 3 to 6 above in order to determine the new operating concentration of MLSS and waste sludge in order to achieve this concentration.

The above procedure should only be seen as a temporary measure and every effort must be made to reduce the $SSVI_{3.5}$ of the sludge in the aeration basin. Once the $SSVI_{3.5}$ has returned to an acceptable value, the sludge recycle rate should be reduced to as low a value as possible.

6.3 What can I do in an emergency, if the sludge blanket is rising rapidly?

There are occasions when a period of very high flow coincides with a period when the $SSVI_{3.5}$ of the sludge is very high. Under these conditions the sludge blanket may rise rapidly and be in danger of overflowing from the final sedimentation tank. Should this happen the discharge consent would be breached. In addition, the loss of solids would reduce the sludge age in the aeration basin and may make it difficult to treat the wastewater. Finally if the solids loss was high enough it may lead to a major pollution incidence in the receiving watercourse. The options for dealing with this are very limited! In order to prevent the sludge blanket from rising further, it is necessary to turn off all aeration in the aeration basin and let the sludge settle in the basin. By doing so the aeration basin is effectively being used as a sedimentation tank and solids are no longer being applied to the final sedimentation tank. The blanket is thus very rapidly lowered by the action of the sludge return line. Aeration can be left off for up to 1 hour without compromising effluent quality. This cycle can be repeated indefinitely until the period of high flow subsides or the sludge settlement improves. However, if this approach is undertaken it requires very careful monitoring of the sludge blanket height and of the final effluent quality.

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7 Further Reading

Albertson, OE (1992) Clarifier design, In: Design and Retrofit of Wastewater Treatment Plants for Biological Nutrient Removal, Water Quality Management Library Vol 5, Technomic Publishing Co. 185-255.

Catunda, PFC and van Haandel, AC (1992) Acivated Sludge Settling Part 1: Experimental determination of activated sludge settleability. Water SA 18 165-172.

Ekama, GA and Marais GvR (1986) Sludge settleability and secondary settling tank design procedures. Water Pollution Control, 85, 101 –113.

Davies, P. (1996) Designing solids removal systems to aid in compliance with the requirements of the EC Urban Waste Water Treatment Directive. In: Environmental Waste Management: A European Perspective, Ed. NJ Horan, Publ. Wiley. 47 – 72.

Horan, NJ (1990) Biological Wastewater Treatment Systems: Theory and Operation Publ. Wiley.

Vesilind, PA (1968) Theoretical considerations: Design of prototype thickeners from batch settling tests. Water and Sewage

Works, 115, 302-307.

White MJD (1975) Settling of Activated Sludge, WRc Technical Report TR11

WPCF (1981) Clarifier Design Water Pollution Control Federation Manual of Practice FD-8

List of Figures

Figure 1a - A circluar secondary sedimentation tank.

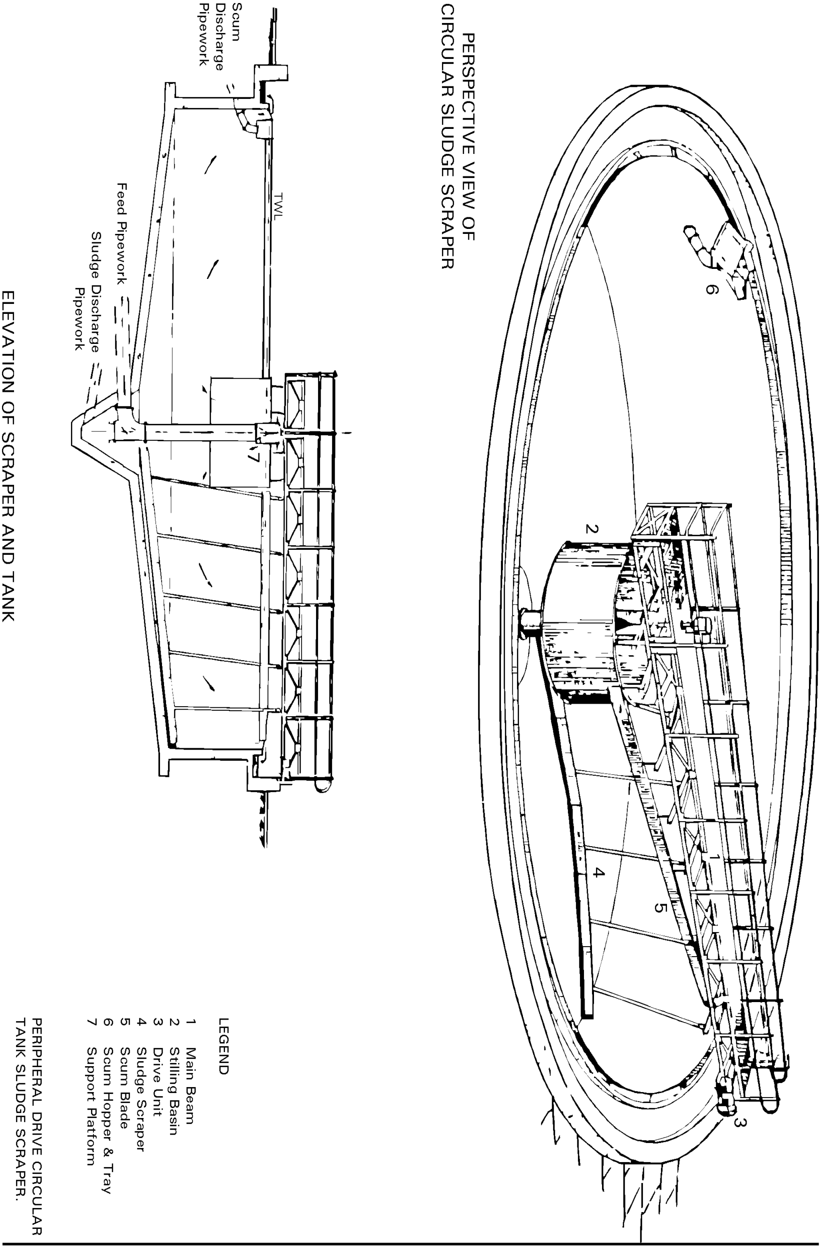

Figure 1b - Schematic diagram of a sedimentation tank.

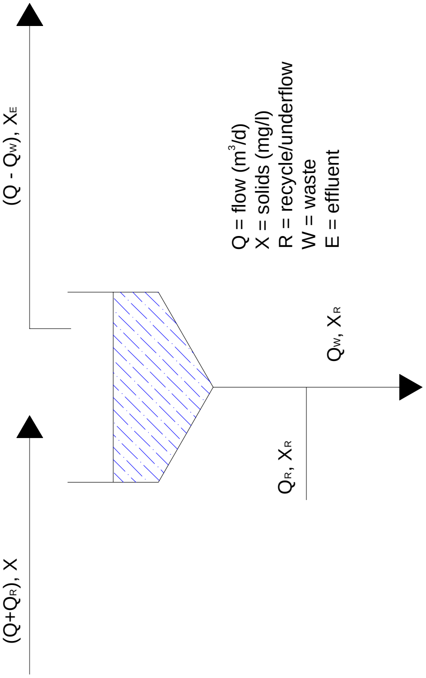

Figure 2 -The impact of effluent suspended solids on the final effluent BOD, showing that 1 mg of suspended solids contributes 0.6 mg BOD

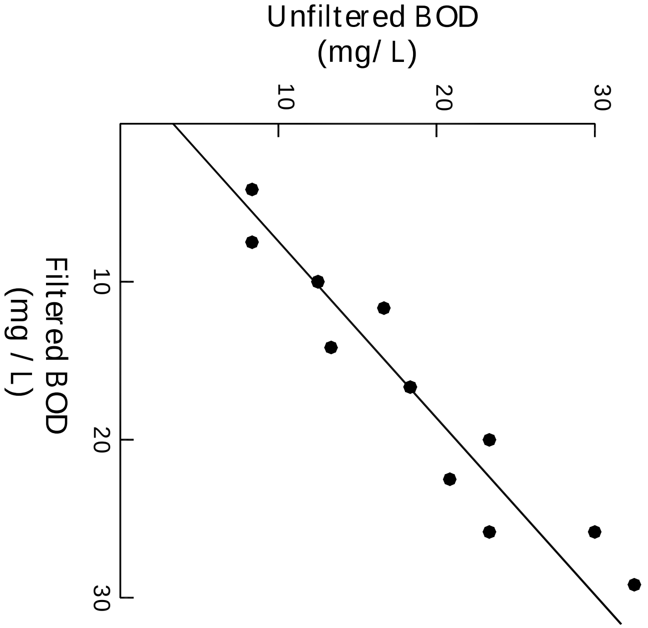

Figure 3 - The Triton-WRc settling apparatus

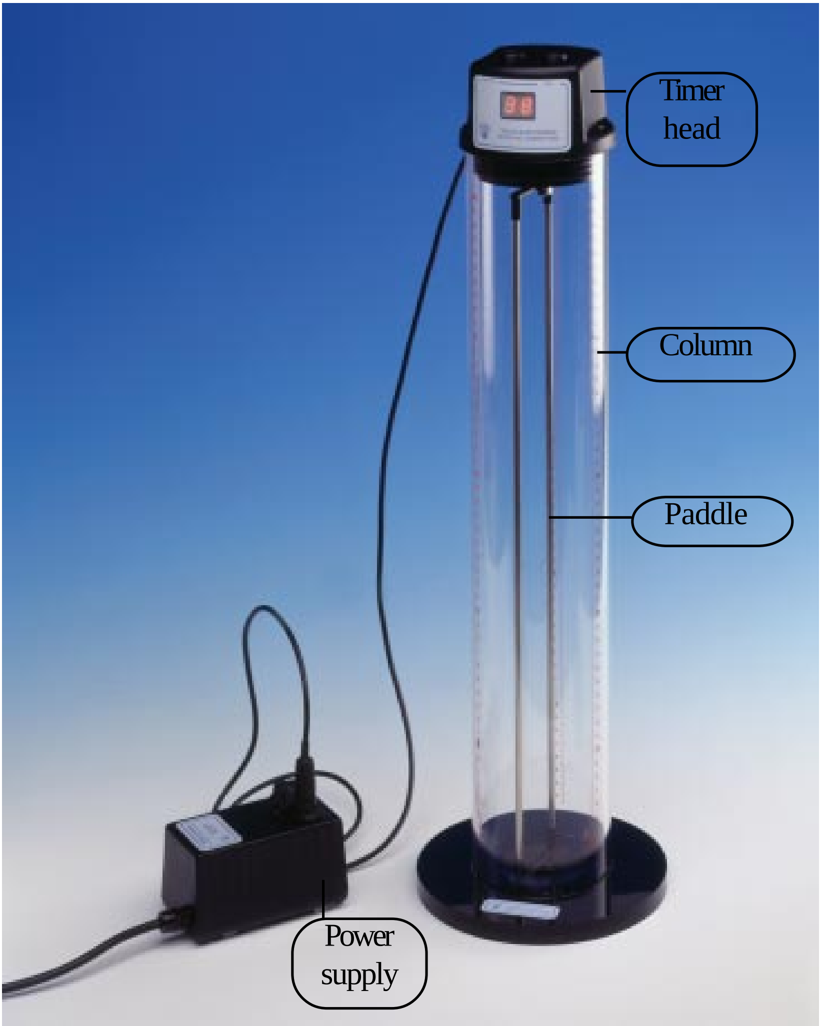

Figure 4 - Determination of the SSVI$_{3.5}$ from a graph of the laboratory determined SSVI

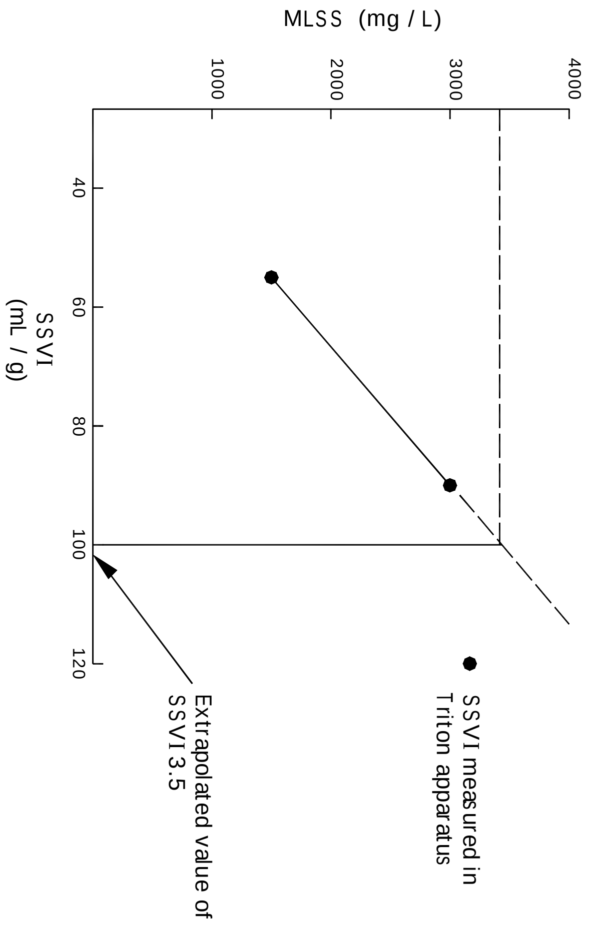

Figure 5 - Numograph for the calculation of predicted & applied solids loading.

$$\text{SSD\%} = \frac{\text{INITIAL HEIGHT OF SLUDGE IN COLUMN} \times \text{INITIAL CONCENTRATION OF SS (\%)}}{\text{HEIGHT OF SLUDGE IN COLUMN AFTER 30 MIN}}$$

$$\text{SSVI} = \frac{100}{\text{SSD}}$$

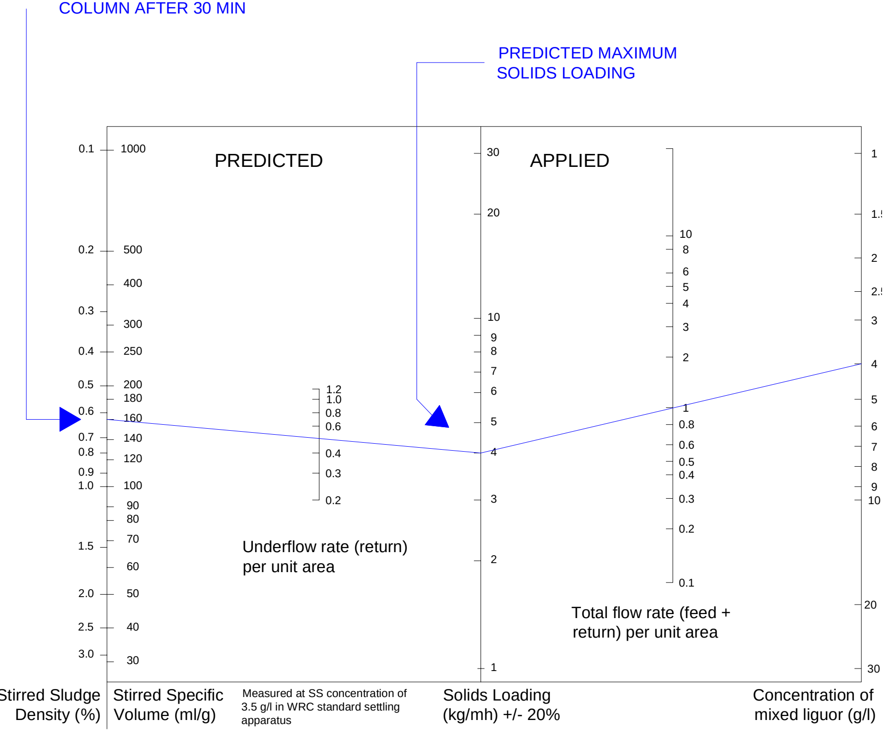

Plate 1a - Photomicrograph of a high quality ecosystem

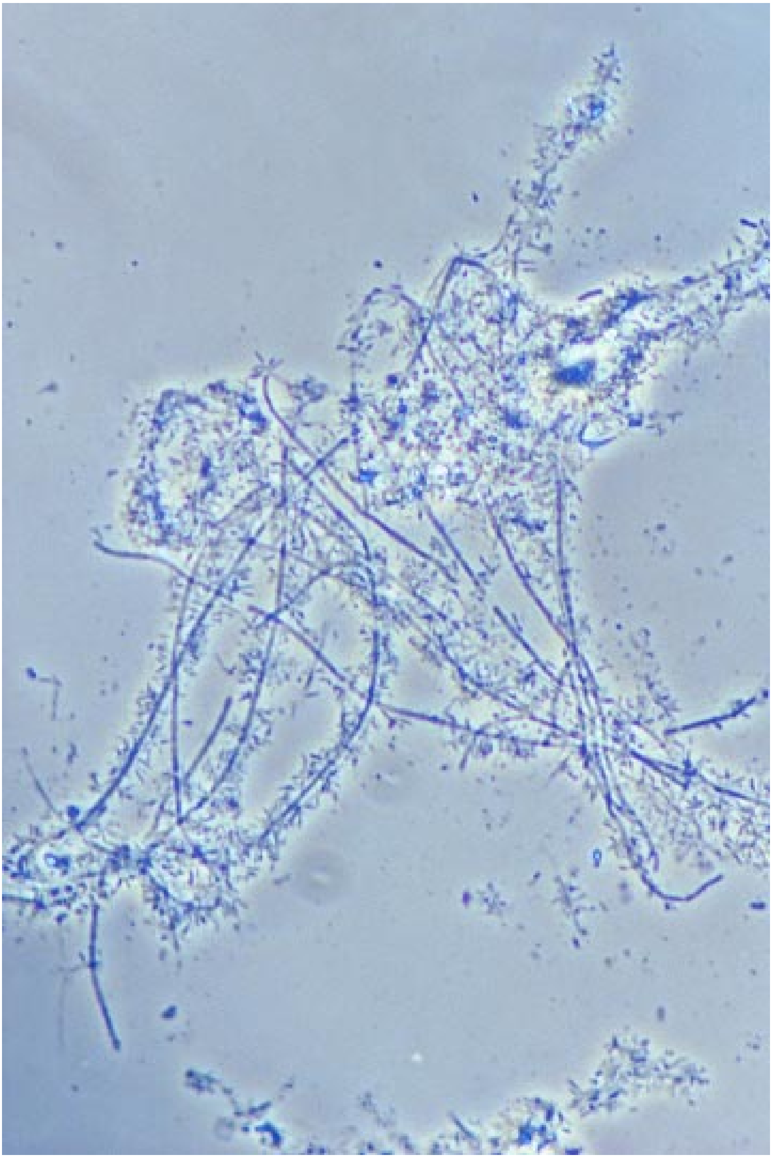

Plate 1b - Photomicrograph of a bulking sludge showing the excessive outgrowth of filamentous bacteria from the sludge flocs