Effects of Sludge Settleability in Final Sedimentation Tank

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Abstract—The study investigates the validity of Pitman and White correlation on sedimentation efficiency of a ferric dosed sludge using the sludge volume index (SVI) and stirred specific volume index (SSVI) settleability tests. This was conducted using a 2000ml graduated cylinder, mixed liquor suspended solid (MLSS) concentration and mean sludge volume of 3 replicate samples after 30 minutes analysis, based on the Water Research Council (WRC) method. The SSVI and SVI parameters were analysed to determine the most suitable approach to be adopted in examining the operating state of the clarifier using the Pitman and White solid flux correlation. The SVI test yielded a better sludge settling characteristics with an SVI of 240 ml/g while the SSVI test produced a poor sludge settling characteristics with an SSVI of 316.6 ml/g, anticipated to be due to the stirring and non-stirring variations. After a series of simulation, the Pitman and White model was found to be suitable for ferric dosed sludge settling at boundary conditions of MLSS≤3000mg/l, SSVI≤120ml/g, particle settling velocity 7.78m/h≤v_0≤8.16m/h, tank diameter of 28.5m≤d≤29.2m and a reduced number of tanks. For increased MLSS (3000mg/l<MLSS≤3300mg/l), the Pitman and White model predicts a suitable settling boundary condition at SSVI ≤100ml/g, particle settling velocity of 7.78m/h≤ ≤9.37m/h, allowable tank diameter of 26.6m<d≤29.2m and a reduced number of tanks. Therefore, the Pitman and White model shows that the existing tank was overdesigned and could accommodate additional Full flow for treatment up to 2.54% and could save 16.5% cost of design

Index Terms—Final Sedimentation Tank, Pitman and White correlation, Sedimentation, Sewage Treatment, Sludges, SSVI, SVI.

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1 INTRODUCTION

"The bottle neck limiting the capacity of the wastewater treatment plant (WWTP)", the most sensitive and complicated process in an activated sludge treatment plant, "almost invariably the reason for poor performance of an activated sludge system" [1], [2]; these are just a few examples of expressions emphasizing the role of the final sedimentation tank (FST) in the overall performance of the activated sludge system.

The biological treatment of municipal wastewater predominantly depends on the activated sludge process. Basically, the activated sludge system comprises of the biological reactor and the secondary settling tank (SST) [3]. The biological reactor serves as an aeration tank where biological reaction occurs to eliminate carbon and nitrogen, provides oxygen and mixing while the SST separates free falling particles that are denser than water by mechanism of gravity. The sludge mass and suspended solids (SS) concentration in the biological reactor is estimated by the hydraulic load of the WWTP primarily by the efficiency of the SST.

In the UK, the Activated sludge plants (ASPs) are primarily used to treat approximately 50% of all treated sewage [4]. These plants have the tendency to produce effluents in compliance with the existing legal regulations to meet consents. However, the European legislation has demanded improvements in effluent quality and the prerequisite to manage bigger volumes in our residential and industrial area. This has mounted pressure on the existing sewage treatment works facilities. In 2012, Ledbury reporters have shown that Severn Trent Water had been fined the sum of £18,000 following the discharge of untreated sewage into the River Leadon at Ledbury causing the death of thousands of fish. According to ICE (2010), Sewage Treatment Works in the West Midlands are facing a 20% efficiency challenge and intend to cut spending from £2.6 billion to £2.2 billion due to the shortfall in plant capacity efficiency [5].

Proper collection, treatment and disposal of wastewater have heightened the need to enhance the quality of water in the UK. The waste water produced daily would have consequences on aquatic animals, environment and cost without proper treatment [6]. Metcalf and Eddy [7]conducted research which show that thickening remains a significant method in the conveyance of sewage particles to the bottom layer of the secondary settling tank which results in return activated sludge (RAS) and concentrated underflow.

Subsequently, there is growing interest in the upgrade and development of the efficiency of the secondary clarifier of the ASP. For, it is the efficiency of the final clarifier that defines effluent quality of an ASP [4]

The process of sludge thickening mainly occurs in the thickener and bottom portion of the sedimentation tanks [8]. There are basically some forms of deviation that takes place in the sludge settling within the thickeners and final sedimentation tank which made their designs to be based on a continuous flow process instead of batch flow process. Furthermore, a variety of parameters designed to achieve a quantitative estimation for settleability of sludges was based on laboratory test involved two methods. The main method uses the sludge volume involved after a set time for sedimentation i.e. allowing the sludge to thicken by either stirring or gravity settling in a two litre graduated cylinder and recording the position of the water sludge interface. The subsequent method involves the use of settling column of 0.5m deep, 0.1 m diameter and a wire stirrer rotating at 1 rev/min [9]. The sludge settleability have various measuring parameters; Sludge Volume Index (SVI), Stirred specific volume index (SSVI), Diluted Sludge Volume Index (DSVI) and Sludge density index (SDI).

2 METHODOLOGY

2.1 Settleability Analysis

The SSVI value was calculated from the settleability test carried out using two different sludge samples; a conventional sludge from Wanlip Sewage Treatment Works (WSTW) and a ferric dosed sludge from Finham Sewage Treatment Works (FSTW). For settleability analysis and justification of the most suitable boundary conditions, the measured SSVI and SVI were justified by comparison with ideal SSVI and SVI values used as benchmark from secondary resources such as textbook; Biology of wastewater treatment [9].

In order to predict the sludge settling behaviour using the Pitman and White model which adopts the solid flux theory, the settling tests for the determination of settling properties of the sludge (e.g. SSVI and SVI) were performed using a 2 litre graduated cylinder as described below in accordance with Water research council standards. The resulting SSVI test values were obtained using the SSVI formula, given as:

$$SSVI\ (ml/g) = SV \times 1000\ (mg/g)/MLSS \qquad (1)$$

Where,

SV=Sludge volume (ml)
MLSS= Mixed liquor suspended solids (mg/l)

Step 1

A volume of collected sample was properly mixed before poured into a 2ml dry graduated cylinder (Both stirred and unstirred test) up to the top mark.

Step 2

The stirrer was started for the stirring test to ensure suspension of the sludge.

Step 3

The stopwatch was started for a span of 30 minutes and the suspension was allowed to settle.

Step 4

The measurements of suspended sludge volume were recorded at intervals of 5 minutes for 30 minutes on 3 replicates. The rate and behaviour of sludge settling for each sample replicate was carefully observed during the test.

Step 5

The measured sludge volume at 30 minutes for replicates of each sludge sample was recorded, and the average value was evaluated and used to compute the SSVI.

The SSVI test procedure was repeated for the SVI (non-stirring) test procedure, though there was no stirring mechanism as stated in Step 2.

2.2 Final Stage Validation of Pitman and White Equation on Unconventional Sludges

The Pitman and White model is commonly known in describing the sedimentation and thickening state of conventional sludges in clarifiers using the solid flux curve, influent concentration, number of FST, FST diameter and SSVI.

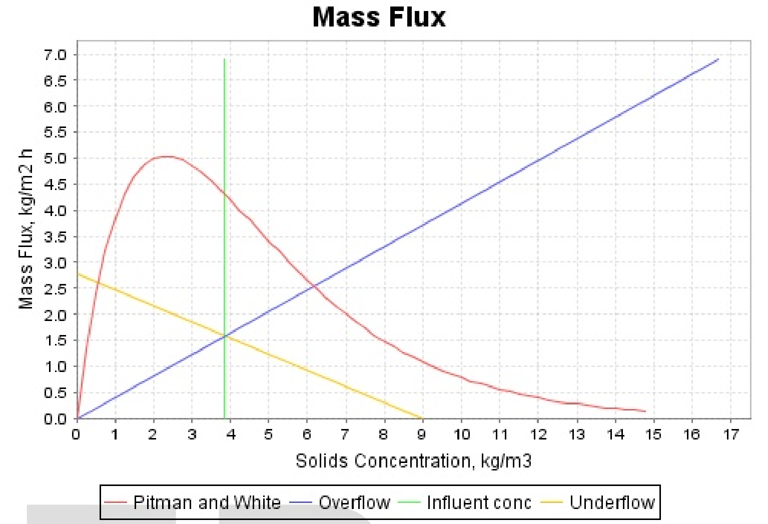


Fig 1. Pitman and White Solid Flux Curve

The state point analysis used to predict the solid behaviour in the tank was examined based on the four criterions applied to settling clarifiers. As described by the Water Research council, criteria I (a) and II are the most common and criterion III and IV by the German ATV guidelines.

a) Criterion I (a): Solids mass loading rate

This criterion states that the solid flux applied to a tank must not exceed the permissible flux in a clarifier. Mathematically,

$$J_{QF} < J_L \qquad (2)$$

Where,

J_{QF} = Actual solid flux applied to tank

J_L = Flux limit

But,

$$J_{QF} = X\,(Q_i+Q_r)/A \qquad (3)$$

And

$$J_L = 8.85\,(100/SSVI_{3.5})^{0.77}(Q_r/A)^{0.68} \qquad (4)$$

Where X is the solids concentration, Q_i is the influent rate, Q_r is rate of RAS, A is the FST surface area and $SSVI_{3.5}$ is the stirred sludge volume index

b) Criterion I (b): Critical underflow velocity

According to (Ekama *et al*., 1997), Criterion I (a) is only binding on critical underflow velocity, q_R[m/h].

c) Criterion II: Hydraulic loading
This states that the upward velocity within a clarifier must not exceed the settling velocity in clarification.

$$Qi/A \leq v_o \exp(-nX) \qquad (5)$$

Where,

Qi = Influent rate, m^3/h
v_o = Vesilind settling velocity
n = Free settling parameter or coefficient

d) Criterion III: Volumetric loading rate
This states that the product of solid mass loading rate and the SSVI should not exceed 500 $L/m^2.h$.

$$VLR = Q_{sv} / A \qquad (6)$$

But

$$Q_{sv} / A = X.Qi/A\ (4/3SSVI_{3.5}) \qquad (7)$$

Where
Q_{sv} = VLR, m^3/h (8)

e) Criterion IV: Weir loading rate
This describes effluent flow rate per length of overflow weir and flow velocities within the height of the weir. Basically, the WLR is maintained under $10m^3/h.m$ but is reduced to $5m^3/h.m$ for light sludges. (Ekama *et al*., 1997).

$$Q_e = Q_i/L \qquad (9)$$

Where,

L = Total weir length, m
Qe = WLR, $m^3/h.m$

3 RESULTS

TABLE 1

SUMMARY OF RESULTS OBTAINED FROM SSVI AND SVI TESTS FOR FINHAM SLUDGE SAMPLES USING A 2000ML GRADUATED CYLINDER

S/No	Type of Test	MLSS (mg/l)	Mean (ml)	SV_{30}	Mean SSVI (ml/g)
1	SVI Analysis	3000	720		240
2	SSVI Analysis	3000	950		316.6

Where SV_{30} is the suspended sludge volume after 30 minutes settling.

TABLE 2

SSVI TEST RESULTS FOR FINHAM SLUDGE REPLICATE SAMPLES (STIRRING)

Time (min)	0	5	10	15	20	25	30
Replicate 1(ml)	2000	1200	1180	1000	940	920	900
Replicate2 (ml)	2000	1220	1100	1080	1060	1020	1000
Replicate3 (ml)	2000	1260	1140	110	1040	980	950
MeanSSV (ml)	2000	1227	1140	1060	1013	973	950
MLSS(mg/l)	3000	3000	3000	3000	3000	3000	3000
MeanSSVI (ml/g)							316.6

TABLE 3
SSVI TEST RESULTS FOR FINHAM SLUDGE REPLICATE SAMPLES (NON-STIRRING)

Time (min)	0	5	10	15	20	25	30
Replicate 1 (ml)	2000	1580	1200	980	840	740	680
Replicate 2 (ml)	2000	1720	1420	1160	980	850	760
Replicate 3 (ml)	2000	1640	1320	1080	920	800	720
Mean SSV (ml)	2000	1647	1313	1073	913	797	720
MLSS (mg/l)	3000	3000	3000	3000	3000	3000	3000
Mean SVI (ml/g)							240

The settleability analysis results, as shown in Table 1, indicate that the SSVI (stirring method) and SVI (non-stirring) values for the Finham sludge were 316.6 ml/g and 240 ml/g respectively. The results depicts that SVI analysis showed more settling tendencies than the SSVI analysis. However, the SSVI had a poor settleability because the SSVI value was greater than 240 ml/g (> 120 ml/g in a 1L graduated cylinder) while the SVI showed a fairly good settling (120 ml/g). The lack of uniformity in the results (As shown in Table 1 and Table 2) is probably seen as a result of problems observed with wall effects due to the gentle stirring effect, equipment geometry and frictional effects in the SSVI analysis [10]. According to Ekama and Marais [11], their research showed that the SSVI is slightly insensitive to column geometry, probably due to the gentle stirring. Biological organisms infect sludges thereby leading to bulking problems in the sludges which results into poor settling. There are, however, other possible explanations.

Zhang and Hyninnen [12] conducted a research study on settleability test for a ferric dosed sludge at different MLSS and SVI values using a 1L graduated cylinder. The result proved that settleability improves with increase in iron concentration resulting to a decrease in SVI value. This further showed that addition of ferric salts decreases bulking problems and thus enhances metabolic activities in the process. In comparison with SVI results (240 ml/g) obtained from this research using a 2L graduated cylinder, it clearly shows that the SVI values are within same range considering the fact that the SVI would be about 120 ml/g if it was obtained from a 1L graduated cylinder. This is slightly higher than SVI value (95 ml/g) obtained by Zhang and Hyninnen [12] which may be due to the differences in MLSS concentrations between the two results.

After a series of comparison between the SSVI and SVI analysis, the result was a positive one and was able to identify the suitability of the SVI analysis and limitation of SSVI. Hence, the SVI was found to be the most suitable for this research.

3.1 DESCRIPTION OF THE EXISTING SETTLEABILITY CONDITION OF FINHAM SEWAGE WORKS USING THE PITMAN AND WHITE SOLID FLUX CURVE

In conformity with the Pitman and White model, considered to be the most widely accepted set standard for sludge settleability analysis in the UK, Figure 2 presents the operating state of the clarifier sedimentation and thickening based on experimental results found to be 120 ml/g and 3000 mg/l for SVI and MLSS values respectively. It is apparent from Figure 2 that state point in the solid flux curve (SFC) is below the falling curve line and the underflow line (UFL) passes through the solid curve at least once, thus predicting the tank is not overloaded in solids bulk. This suggests that there is a considerate solid accumulation. The outcome of this graph which is in accordance with the graphical method approach of the Pitman and White, confirms that it is in conformity with the defined criteria for state point analysis by Metcalf and Eddy [7]. However, this tank results shows fairly good settling tendencies due to the fact that the state point lies at an area below the solid flux curve, thereby providing allowance for adjustment within the SFC. It can therefore be assumed that the graphical method depicts a fairly good settling sludge.

In addition to the graphical method, another possible alternative explanation for the settleability analysis is the hand method, governed by the three solid flux. Accordingly, the Severn Trent operation handbook suggests that two of these criterions must at least be met and maintained for optimal tank sizing, operation and effective performance.

It is interesting to note that between the SSVI and SVI analysis undertaken, it is somewhat surprising that the SSVI analysis is contrary to expectations as an insignificant settleability was observed (Table 2 and Table 3). It seems possible that these poor SSVI values are due to the non-conformity of the stirrer speed, varying between ranges of 1-3 rpm and the stirrer blade. The result was however insignificant as compared with criterions I and II as set by the Water Research Council. Therefore, this yields an unrealistic SSVI value.

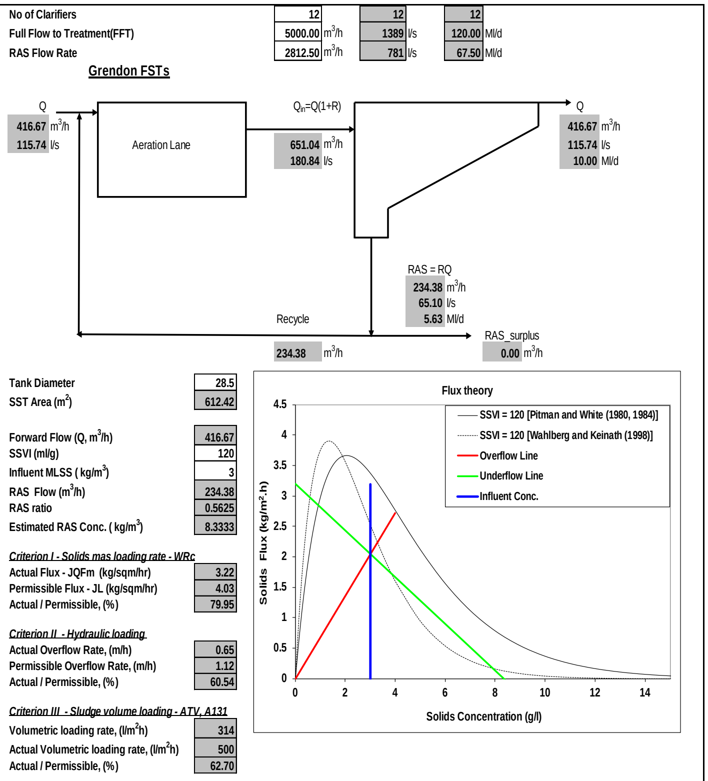
In addition to this, the SVI analysis as shown in Figure 2 demonstrates a result with a solids loading rate (SLR) of 78.72%, hydraulic loading rate (HLR) of 57.67% and volumetric loading rate (VLR) of 299 l/m^{2}h. In comparison with the STW set standards, the SLR, HLR and VLR are in compliant with the set limits of <80%, <100% and <500 l/m^{2}h respectively (Ekama and Marais 2004).

3.2 OPTIMIZATION OF FINHAM SEWAGE TREATMENT WORKS

After a series of solid flux analysis, the results was a successful one as it was able to predict the behaviour of the sludge performance in the Finham sewage clarifier in accordance with the Pitman and White equation. In conformity with Pitman and White model, the following operating conditions were identified:

- The state point was situated below the solid flux curve.
- The underflow line cuts through the SFC once.
- The solid mass loading rate (criterion I) was obtained to be 78.2%.
- The hydraulic loading rate (criterion II) was obtained to be 57.67%.
- The volumetric loading rate (criterion III) was found to be 299 l/m^{2}h.

Criterions I and II analysis produced results which corroborates the findings set by Water Research Council (<80% and <100% respectively) while criterion III is in compliance with set limits (<500 l/m2h) by Severn Trent process manual (2011). Based on this analysis, the plant is seen to be over capacitated as it could operate optimally at operating conditions below the existing one. A number of 10 tanks instead 12 tanks is capable to accommodate sludge sedimentation which could have saved approximately £3,800,000 as estimated below. The over design probably provides allowance within the tanks to accommodate additional ferric dosing in the tanks.



No of Clarifiers	12		12		12	
Full Flow to Treatment(FFT)	5000.00	m³/h	1389	l/s	120.00	Ml/d
RAS Flow Rate	2812.50	m³/h	781	l/s	67.50	Ml/d

Tank Diameter	28.5
SST Area (m²)	612.42
Forward Flow (Q, m³/h)	416.67
SSVI (ml/g)	120
Influent MLSS (kg/m³)	3
RAS Flow (m³/h)	234.38
RAS ratio	0.5625
Estimated RAS Conc. (kg/m³)	8.3333
Criterion I - Solids mas loading rate - WRc	
Actual Flux - JQFm (kg/sqm/hr)	3.22
Permissible Flux - JL (kg/sqm/hr)	4.03
Actual / Permissible, (%)	79.95
Criterion II - Hydraulic loading	
Actual Overflow Rate, (m/h)	0.65
Permissible Overflow Rate, (m/h)	1.12
Actual / Permissible, (%)	60.54
Criterion III - Sludge volume loading - ATV, A131	
Volumetric loading rate, (l/m²h)	314
Actual Volumetric loading rate, (l/m²h)	500
Actual / Permissible, (%)	62.70

Fig 2. Optimized State of Finham secondary sedimentation tank

$$\%FFTcapacity = \frac{allowableFFT - existingFFT}{existingFFT} \times 100\%$$

Existing FFT=120000 m³/hr

Allowable FFT=123050 m³/hr

$$\%FFTcapacity = \frac{123050 - 120000}{120000} \times 100\%$$

$= 2.54\%$

As reported by Ojo (2011), the cost of a tank is £ 1.872 million. Using the consumer price index (CPI), with an average annual inflation rate of 2.8% in 2012 (ONS 2013), a tank will cost as follows:

Cost of tank = £1,872,000 + (2.8% X 1,872,000)
= £1,924,000

Therefore total cost of tanks before optimization:
= £1,924,000 X 12
= £23,040,000

Cost of tanks after optimization:
= £1,924,000 X 10
= £19,240,000

Cost of savings:
= Cost of tanks before optimization – Cost of tanks after optimization
= £23,040,000 – £19,240,000
= £3,800,000

Percentage of cost savings:

$$= \frac{\text{Cost of savings}}{\text{Cost of tanks before optimization}} \times 100\%$$

$$= \frac{3800000}{23040000} \times 100\% = 16.5\%$$

5 CONCLUSION

The SVI analysis showed showed a more significant impact in the settleability analysis for ferric dosed sludges at SVI =120ml/g. The analysis has also shown that footprints could be reduced when the SVI analysis is adopted for settleability test. Therefore, the SVI settleability test is seen as an ideal method for ferric dosed sludge analysis.

The Pitman and White model was found to be suitable for ferric dosed sludges at operating boundary conditions of MLSS≤3000mg/l, SSVI≤120mg/l and particle settling velocity 7.78m/h≤ V_o ≤8.16m/h based on the existing overdesigned tank diameter 28.5m≤d≤29.2m. At increasing MLSS 3000mg/l<MLSS≤3300mg/l, the operating conditions are SSVI≤100ml/g and particle settling velocities 7.78m/h≤ V_o ≤9.37m/h based on the existing overdesigned tank diameter 26.6m<d≤29.2m. An allowable 2.54% of the FFT could also be accommodated in the FST tanks (123050 m³/day instead of 120000 m³/day) and an estimated £3,800,000 could also be saved, which is 16.5% cost of design.

REFERENCES

[1] G.A. Ekama and P. Marais, "Hydrodynamic Modelling of Secondary Settling Tanks," *Water Resources Group*. 2002.

[2] E. J. Wahlberg, T. M. Keinath, and D. S. Parker, "Influence of activated sludge flocculation time on secondary clarification," *Water Environment search*, http://www.jstor.org/discover/10.2307/25044481?uid=3738032&uid=2&uid=4&sid=21102798046161. 1994.

[3] M. Patziger, H. Kainz, M. Hunze and J. Jozsa, "Influence of secondary settling tank performance on suspended solids mass balance in activated sludge systems," *Water search*, http://www.sciencedirect.com/science/article/pii/S0043135412000954. 2012.

[4] D. J. Burt and J. Ganeshalingam, "Design and Optimisation of Final Clarifier Performance with CFD Modelling," *The CIWEM / Aqua Enviro joint conference on Design and Operation of Activated Sludge Plants*, http://www.clarisim.net/consultancy_files/ciwempaper_davidjburt-rev2.pdf. 2005.

[5] Institution of Civil Engineers (ICE), "*State of The Nations Briefing: WESTMIDLANDS INFRASTRUCTURE 2010,*" http://www.ice.org.uk/getattachment/7be0b911-3690-4764-a075-f0dc506c1b3f/State-of-the-Nation--Infrastructure-2010-briefing-

.aspx. 2010.

[6] Department for Environment, Food and Rural Affairs (DEFRA), “Sewage Treatment in the UK,” *UK Implementation of the EC Urban Waste Water Treatment Direcrective,* http://archive.defra.gov.uk/environment/quality/water/waterquality/sewage/uwwtd/documents/uwwtreport2.pdf. 2002.

[7] Metcalf and Eddy, Wastewater Engineering. Treatment and Reuse, New York.: McGraw-Hill, pp. 247-258, 2004.

[8] N.F. Gray, Biology of waste water treatment: series on environmental volume 4 science and management. London: Imperial College Press, 2004.

[9] N.F. Gray, Water Technology-An Introduction for Environmental Scientists and Engineers. London: Elsevier, 2010.

[10] A. R. Pitman, “Operation of biological nutrient removal plants. In Theory, Design and Operation of Nutrient Removal Activated Sludge Processes,” 1984.

[11] G. A. Ekama and G.V.R. Marais, “Sludge settlability and secondary settling and design procedures,” *Journal of Water Pollution Control 87,* 1986.

[12] Y. Zhang and P.T. Hynninen, “The Effect of Iron Ion on Activated Sludge,” *Helsinki University of gy,* http://www.tappi.org/Downloads/unsorted/UNTITLED-ENV00213pdf.aspx. 2013.

[13] G.A. Ekama and P. Marais, “Assessing the applicability of the 1D flux theory to full-scale secondary settling tank design with a 2D hydrodynamic model,” *Water search,* http://www.sciencedirect.com/science/article/pii/S0043135403005797. 2004.