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SAFEGUARDING ACTIVATED SLUDGE SYSTEM -SLUDGE REDUCTION AND EFFICIENCY-

Hasan Hamouda[1] and Nadine Abu-Shaaban[2]
Department of Civil Engineering, Faculty of Applied Engineering and Urban Planning, University of Palestine

ABSTRAT: *Activated sludge system is the most widely used biological process for the treatment of wastewater. One problem associated with this process is related to the amount of excessive sludge produced which requires further treatment and disposal. Current methods for dealing with this sludge include disposing to landfills, recycling as a soil fertilizer and incineration. All of which considered to be costly options due to advanced treatment requirements related to tightened regulations and environmental measures placed on the outlets. In this essence, estimation of sludge production amounts has come to the forefront. The current practice in performing the mass balance around the Activated Sludge system only considers the steady state scenario and neglects the Secondary Clarifier (SC) dynamic state. In particular, the determination of sludge height is not accurate as it is predicted based on the visible depth measurements. Under such condition, the solids accumulation in the SC is usually not accounted for in the mass balance calculations. This paper will address the impact of actual sludge height rather than visible depth on the activated sludge mass balance. Further, this study suggests a scenario of reducing the wasted activated sludge in an attempt to improve the SC functioning, reduce the disposal cost while, safely operating the SC. The required data were collected from a Wastewater Treatment Plant over a seven months period, representing sludge height measurements using both manual and automatic sludge depth detector. Results presented in this paper provide a better understanding of the SC performance; as mass balance can be accurately drawn and the SC safety margin can be exactly determined. In addition, the laid out scenario will enhance the SC performance in terms of settling properties, reducing the excessive sludge while, maintaining almost the same effluent characteristics.*

KEYWORDS: Activated sludge, Sludge reduction, Sludge height, Wastewater treatment plant

INTRODUCTION

Wastewater treatment generally consists of a combination of physical, chemical and biological methods where each is typically designed for a specific function (Naidoo and Olaniran, 2014). Depending upon the characteristics of the sewage and the degree of treatment provided in each operation, the overall efficiency of the wastewater treatment plant can be monitored and controlled. As the quality of the effluent is largely dependent on the efficiency of the biological treatment, this study focuses on the secondary clarifier (SC) as a key player in the activated sludge process. SC has three main functions including clarification to meet the specified discharge limits, thickening to produce thickened bio-mass to be returned to the aeration tank and as storage to accumulated sludge to be wasted as excessive sludge. Due to time-varying change in flow rate and constituents of the wastewater, the SC is usually operated under the influence of hydrodynamic state with respect to hydraulic and organic loadings ((Zhang, 2011), (Bakiri and Nacef, 2012).

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In this essence, controlling the level of sludge is of great importance to the effective operation of the SC. From one side, although SC is stable under normal operating conditions, its behaviour is largely affected by sudden excessive hydraulic loading which ultimately could lead to hydraulic shock failure. This can be readily offset by a high sludge level resulting in sludge wash-out over the final effluent weirs. In turn, causing serious deterioration in the effluent quality, thus, having a direct bearing on the amount of activated sludge in the system and the return/waste rate. From the other side, maintaining a high sludge level in the SC will allow sludge accumulation and gradually increases the concentration of the wasted sludge ((Cheng, 2008), (Wang, et al. 2014)

This will have an implication on the WWTP disposal cost; as the denser the wasted sludge, the less disposal cost incurred. In addition, the disposal cost is influenced by the amount of excessive sludge produced; therefore accurate predictions of sludge solid production are critical for WWTPs planning. Against this background, a well controlled activated sludge system should determine the exact sludge amounts accumulated while having an accurate monitoring procedure to avoid the risk of sludge flotation.

The utilization of mass balance approach is the common method of detecting the performance of activated sludge system ((Rieger, 2010), (Durai and Rajasimman, 2011), (Korostynska, *et al*. 2012), (Trojanowicz and Koc, 2013)). However, these studies were developed under the assumption of SC operating at steady state; not accounting for the variation in sludge depth and suspended solids within different layers.

The main contribution of this study is related to a more reliable predication of SC performance by examining a full scale dynamic data including the exact sludge depth and concentration measurements within different layers. In particular, the aim of this research is to address the effect of encountering the exact sludge height, rather than the conventional method where the sludge level is predicted based on the measurements of visual depth on the mass balance. Furthermore, in connection with this aim, a scenario of reducing the wasted activated sludge will be assessed in terms safety and effluent characteristics.

THE ACTIVATED SLUDGE PROCESS

Typically, after the primary treatment, the wastewater moves on to secondary treatment where the biological treatment takes place. The main objective of the biological treatment is to reduce the concentration of organic and inorganic contents resulting in a high quality effluent. In particular, Activated Sludge (AS) is the most popular biological waste water treatment systems consisting of three basic interrelated components; Aeration Tank, Secondary Clarifier and a sludge recycling system. Firstly, in the Aeration tank wastewater is aerated with oxygen allowing microorganisms to breakdown organic matter and other nutrients for their survival and growth and converts it into carbon dioxide, new cell mass and biomass. Likewise the Nitrification process, the ammonia (NH_4) is also oxidized to nitrate (NO_3) for which pumped oxygen is required. Then, under anoxic conditions, nitrate (NO_3) is further converted into nitrogen (N_2) and oxygen (O_2) through Denitrification. Concurrently, phosphate elimination is achieved through bio-P process by adding iron or aluminium salts as flocculants.

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The bacteria exhibit four phases of growth that are representative by a typical growth curve shown in Figure (1). The lag phase represents a period of slow growth as organisms require time to adapt to the new environment. Then, the population enters the exponential phase, in which bacteria are multiplying at a maximum rate.

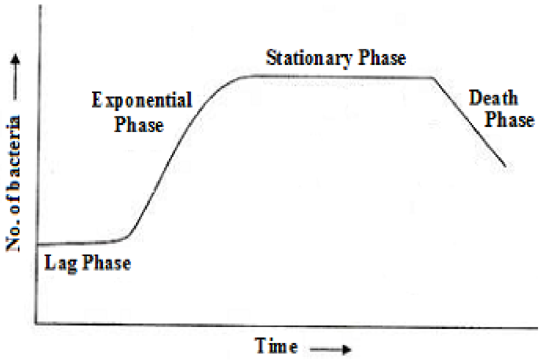

Figure (1): Phases of bacterial population growth

The exponential phase of bacterial growth is followed by a stationary phase, where the rate of cell growth is balanced by the rate of cell death. This phase continues until the nutrients are biologically degraded and bacterial reproduction rate slows down considerably. Ultimately, in the death phase, the rate of cell death becomes greater than cell division causing dead cells to accumulate.

Following the aeration stage, the activated sludge is separated from liquid by gravity sedimentation and the clarified liquid is discharged from the system. As shown in Figure (2), depending on the concentration of the suspended solids, four distinct zones can be identified in the secondary clarifier: clear water zone (h_1), separation zone (h_2), storage zone (h_3), and a thickening/ sludge removal zone (h_4). Finally, a recirculation line from the bottom of the clarifier tank return a portion of the concentrated microorganisms, returned activated sludge (RAS), to the aeration tank so that a constant concentration can always be maintained. Meanwhile, the excess activated sludge is then permanently removed from the system and conditioned for ultimate disposal (waste activated sludge, WAS).

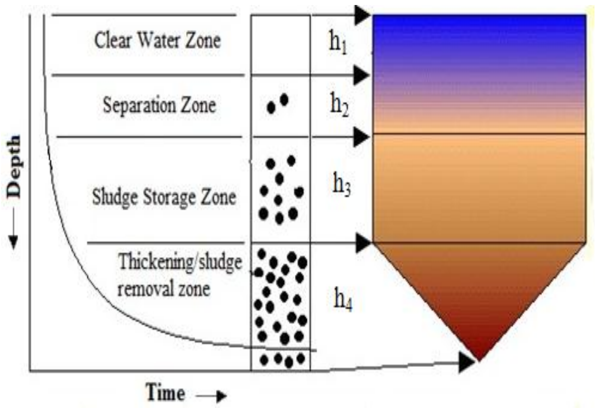

Figure (2): The SC Solids Concentration Profile

MASS BALANCE AROUND THE AERATION TANK AND THE SECONDARY CLARIFIER:

In conducting mass balance on the biological treatment component of a WWTP, both the aeration tank and the secondary clarifier are considered as one unit and generally represented as shown in Figure (3).

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Figure (3): Biomass accumulation around the Biological Treatment Component

Mass in Input = Mass in Output + System Mass Accumulation

Performing solids mass balances across the interconnected components of the WWTP allow tracking key operating parameters from one unit of operation to a downstream one ensuring overall stability. In this context, Figure (4) presents a diagram illustrating key parameters required to conduct a solids mass balance around the biological treatment components of a WWTP.

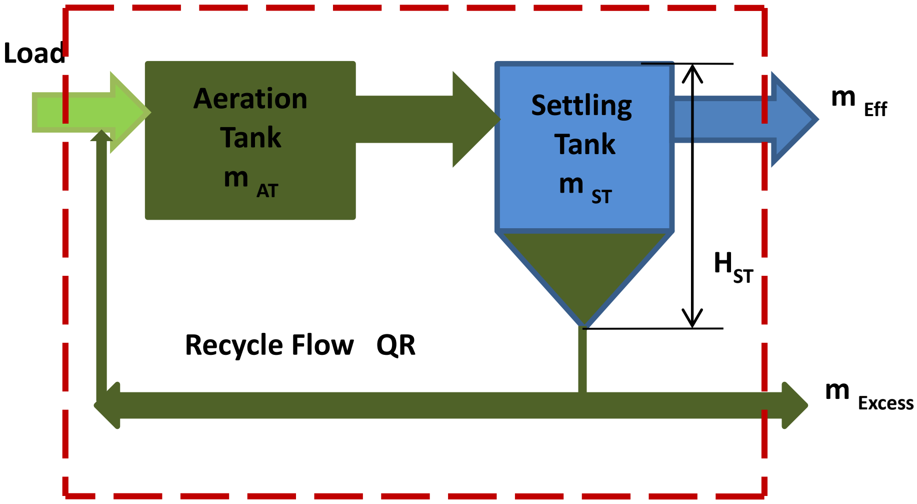

Figure (4): Solids Mass Balance around the Biological Treatment Component

In this case, solids mass balance around the biological treatment component is mathematically expressed as:

$$BOD - load = m_{Inf\ ,total} = \sum (m_{AT} + m_{ST} + m_{Excess} + m_{Eff}) ....(1)$$

Where;

$C_{BOD} = C_{SS}$ Using concentration levels for medium domestic wastewater, table (1) shows typical concentration levels of the constituents of strong, medium and weak domestic wastewater.

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Parameter	Concentration in mg/l		
	Strong	**Medium**	**Week**
BOD	400	220	110
COD	1000	500	250
Org.- N	35	15	8
NH3-N	50	25	12
Total N	85	40	20
Total P	15	8	4
Total Solid	1200	720	350
Suspended Solid	350	220	100

Table (1): Concentration Levels of Typical Domestic Wastewater (Metcalf and Eddy, 2013)

$$BOD_5 - Load = m_{Infleunt} = Q_{Infleunt} \cdot c_{BOD_5} \text{..............(2)}$$

At normal operating conditions of WWTP, considering steady state condition prevailing in the system, both the solids lost each day equal the solids generated by biological reproduction. Consequently, sludge level is constant and the accumulation of biomass in the system is considered to be zero. Meanwhile, under dynamic (non-steady) state, the accumulation in the SC is reflected by variation in the sludge level. However, a critical situation could present under shock loads as the mass will accumulate in the SC and the sludge level will begin to rise and may eventually flow over the weir. Therefore, to better control the process, the safety margin must be determined taking into account both the mass accumulated in the SC and the exact sludge height.

To illustrate the impact of the accumulation term in mass balance, the following examples illustrate data for an Aeration Tank with a volume of 3800 m^3. Suppose that the total solid concentration in the aeration tank is 3.5g/l and 4.1 g/l at the beginning of March and April respectively (see Table (2)). Based on equation (3), the accumulation in the aeration tank is estimated to be 2.3 tonne.

Accumulation in the aeration basin: $m_{SS,AT} = V_{AT} \cdot (c_{SS,AT,End} - c_{SS,AT,Begin})$...........(3)

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Parameter	Data
$C_{SS,\ AT,\ begin\ (1.3.2014)}$	3.5 g/l
$C_{SS\ AT,\ end\ (1.4.2014)}$	4.1 g/l
$\Delta C_{SS,AT}$	0.6 g/l
V_{AT}	3800 m^3
Δm_{AT}	2.3 t

Table (2): Accumulation in the Aeration Tank

In addition, accumulation in the SC can be calculated using equation (4) taking into account the exact sludge height. Table (3) represents data for SC including reliable measurement of sludge height using SONATAX. The accumulation in the SC clarifier is found to be 3 tonne.

Accumulation in the sedimentation tank: $$m_{ST} = A_{ST} \cdot (h_{ST,End} - h_{ST,begin}) \cdot C_{SS,ST} \quad (4)$$

Where, h_{ST} = 4m.

Parameter	Data
$h_{ST,\ begin\ (1.3.2014)}$	0.50
$h_{ST,\ end\ (1.4.2014)}$	1.70
Δh	1.20
$C_{SS,ST}$	8.0 g/l
A_{ST}	315.0 g/l
Δm, TS	3.0 t

Table (3): Accumulation in the Secondary Clarifier

Sonatax allows establishing the profile of the sludge concentration versus depth in the SC. Figure (5) shows that there is no suspension in the effluence region (first meter) and the TS concentration increase gradually as the depth increases till compression phase. In addition, the average TS at the SC can be set to be 8 g/l, by taking the average from Figure (5) and as indicated in Table (3).

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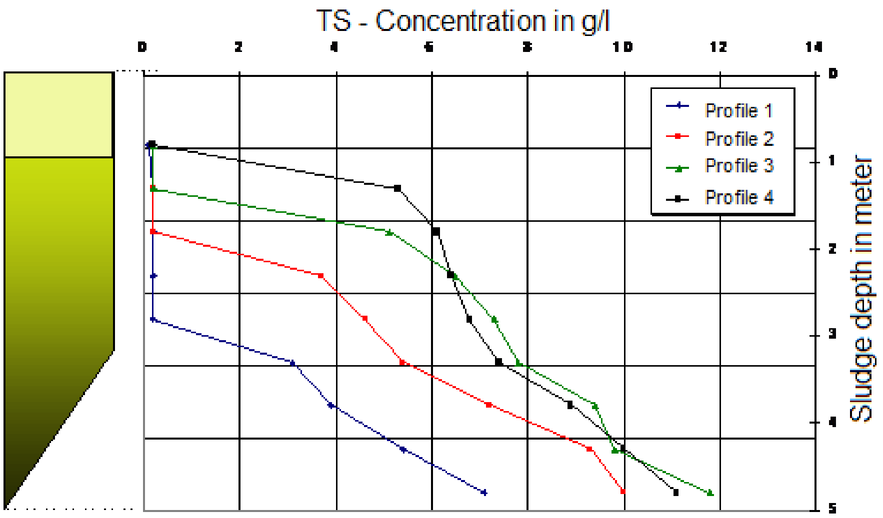

Figure (5): SS-Concentration Profile as a Function Sludge Depth

In addition, the excessive sludge is calculated according to equation (5):

Excessive sludge:

$$m_{Excess} = Q_{Excess} \cdot c_{SS,_{Excess}} \quad (5)$$

Although, the solid mass in the effluent can be estimated using equation (6), the effluent solids concentration is considered to be negligible as it is commonly less than 10 mg/l.

Solid mass in the Effluence:

$$m_{Eff} = Q_{Eff} \cdot c_{SS,Eff} \quad (6)$$

Thus, the excess sludge production is found to be:

$$m_{Excess,Total} = \sum (m_{AT} + m_{ST} + m_{Excess} - m_{Eff}) \quad (7)$$

Therefore, in order to control the operation of the activated sludge systems, the TS concentration in the AT must be determined as well as the exact amount of produced sludge in the SC must be estimated.

OPERATIONAL PARAMETERS OF THE SECONDARY CLARIFIER:

Wasted Sludge Rate (WSR) is an important parameter in controlling the activated sludge process, as it maintains a relatively constant concentration of microorganisms in the system.

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The three main methods of controlling sludge wasting include the F/M ratio, the sludge age method and the sludge retention time.

Food-to-Microorganism Ratio (F/M Ratio)

Food –to-Microorganism ratio (F/M) is one of the most important parameter of an activated sludge system. As the growth rate of bacteria depends on how much food is available and the bacterial population held under aeration measured by the food to microorganism ratio (F/M), see equation (8).

$$F/M = \frac{Food}{Microoganism} = \frac{Load}{V_{Areation} * TS_{Areation}} = \frac{kgBOD}{kgTS * d} \qquad (8)$$

The F/M ratio at which the plant is designed and operated play a key role in achieving the desired plants treatment efficiency as it directly related to the degree of BOD removal. Typically, WWTP operates at a specific F/M ratio between 0.01-0.1 (kg BOD/kg TS.d). On average, this range result in 95% BOD removal efficiency, see Figure (6). Different implications can be encountered in operating the plant at different F/M ratio as too many or too few organisms can cause operational problems. From one hand, running the WWTP at high F/M ratio causes bacteria to be active and dispersed, consequently, multiplying at rapid rate and not developing well into floc causing settling problems. Under these conditions, frequent sludge waste is required to maintain a young sludge age. On the other hand, promoting low F/M ratio limit the food available for bacteria to grow yielding an old sludge age. In essence, less sludge to be wasted but poor quality effluent is produced.

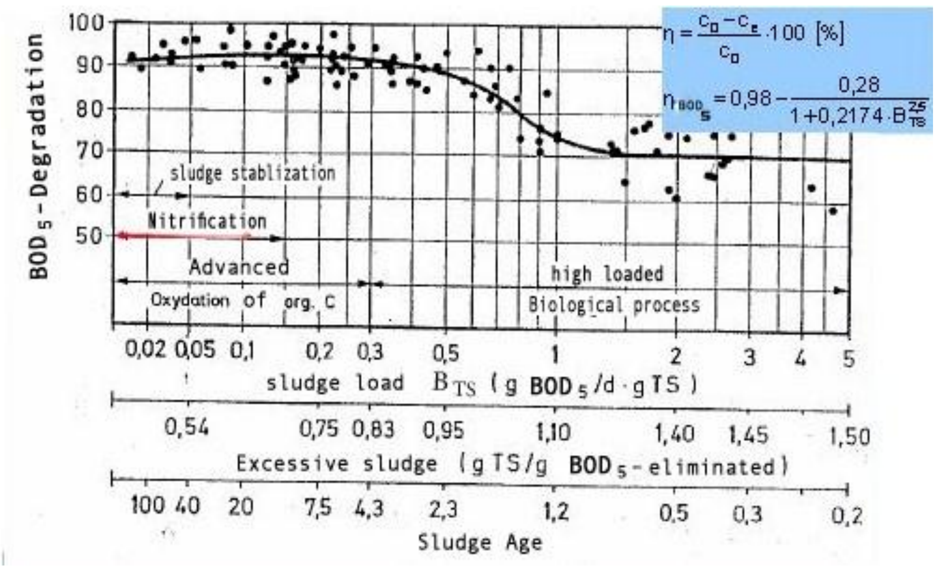

Figure (6): F/M ratio as function of BOD-Degradation

The F/M ratio is controlled by the amount of wasted sludge; an increase in wasted sludge mass decreases the F/M ratio, and vice versa. The best performance of activated sludge is only achieved when F/M is maintained at an optimum, constant value.

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Sludge Age (SA)

It is a measure of the length of time a particle of suspended solid retains in the activated sludge system. As shown in equation (9), the volume used for calculation of sludge age includes volume of the aeration tank only. Sludge age is an important parameter, because the amount of time that the microorganisms are given to breakdown the waste products has a significant effect on effluent quality.

$$\text{SA (days)} = \frac{\text{Mass of Sludge in Aertation Tank}}{\text{Mass of excessiveSludge Wasted per day}} \quad (9)$$

In addition, being able to measure the sludge age and correlate it to the F/M ratio allows monitoring the process and adjusting the F/M ratio to the designed value. As the higher the F/M ratio, the shorter the sludge age and vice versa. The common range for sludge age for a conventional activated sludge plant is between 3 and 15 days. Meanwhile, for extended aeration activated sludge plants the range is between about 15 and 40 days.

Sludge Retention Time (SRT)

This parameter is a refinement of the sludge age and takes into consideration the total solids mass in the SC, see equation (10). Control of Solids Retention Time (SRT) in the activated sludge process is critical for ensuring effective wastewater treatment as SRT sets the growth rate of microorganisms in the activated sludge process and the effluent characteristics.

$$\text{SR}\mathbf{T}\text{ (days)} = \frac{\text{Mass of Sludge in Aertation Tank} + \text{Mass of Sludge in Settling tank}}{\text{Mass of exessive Sludge Wasted per day}} \quad (10)$$

Yet, determining the exact retention time is related to being able to calculate the exact amounts of sludge in the settling tank.

DATA COLLECTION & RESULTS

This work presents raw data collected from a Wastewater Treatment Plant, with a capacity of 15000 capita, over the period of seven months, from May to November, representing sludge height measurements using both manual and automatic sludge depth detector. During the course of study, the activated sludge system was operated under normal conditions and the following average characteristics were recorded including the flow rate and effluent characteristics such as; BOD, COD, NH_4, NO_3, NO_2, N_{total} and P_{total}

The sludge depths were measured manually by observing the clear water zone depth using a flat disc; where the disc is gradually lowered into the SC until it is just barely visible. The depth of the disc at this point is recorded as the clear water zone depth and the sludge height was estimated accordingly. While, the SONATAX automatic sludge depth detector provided a

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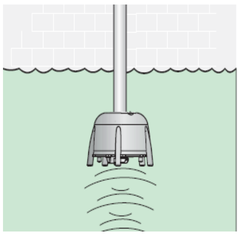
vertical profile of the suspended solids concentration in the secondary clarifiers with the exact sludge depth.



SONATAX accurately measures the exact sludge depth using an ultrasonic echo, where an ultrasonic signal is sent from a specially designed probe towards the sludge blanket in the SC (see Figure 7). Based on the time taken for the ultrasonic echo to return to the probe, the sludge depth is displayed on the ultrasonic transducer.

Figure (7): SONATAX

Figure (8) shows a typical profile of a sludge level measurement with both graphical and digital display. The sludge depth was recorded as a function of time and a plot generated from the depth-time sets of data, see Figure (9).

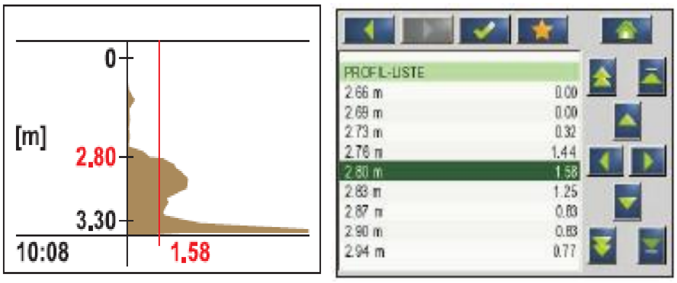


Figure (8): Graphic & List Profile

Figure (9) shows that the average depth for manual and automatic readings is 1.8m and 3m respectively; giving a difference of 1.2m (which forms 30% of the total SC height).

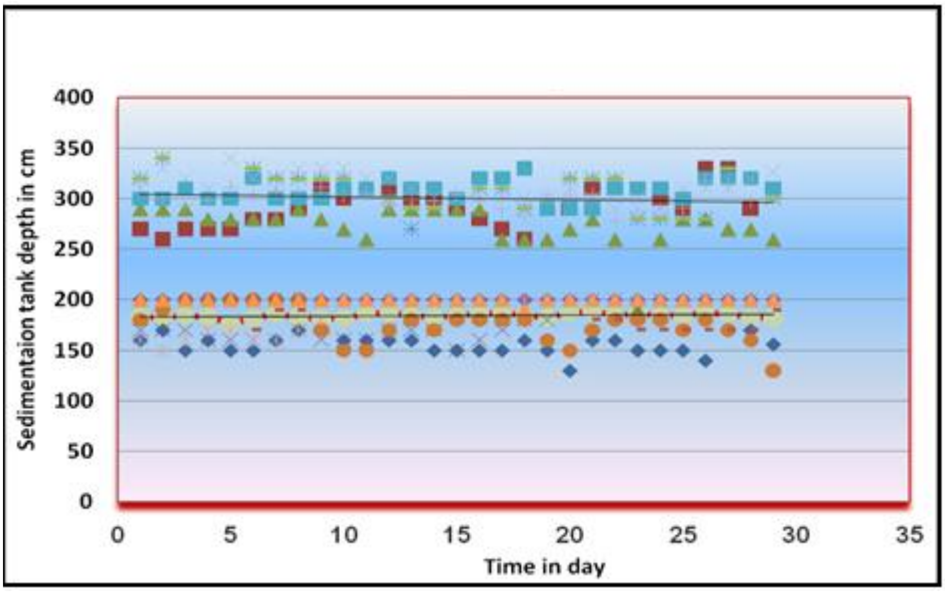


Figure (9): Visible Depth and Clear Water Depth in the Secondary Clarifier.

Proposed Scenario:

Wasted Sludge Rate (WSR) is an important parameter in controlling the activated sludge process. As by wasting sludge on a consistent rate, the biomass within the aeration tank will remain healthy. To determine the effect of reducing the WAS on the functioning of SC, data were further examined by proposing a scenario of reducing the Wasted Sludge Rate (WSR) by

30%. This scenario was based primarily upon the results obtained for the average sludge height in the SC.

The Sludge Volume Index (SVI) was calculated to assess the activated sludge settling properties in the SC; where the SVI is the volume in millilitres occupied by 1 g of a suspension after 30 minutes settling. It is governed by the following equation:

$$SVI = \frac{\text{Settled sludge volume (ml/l) X 1000}}{\text{Suspended solids (mg/l)}} \text{ in ml/g} \qquad (11)$$

Variations in the value of the SVI indicate changes in the sludge settling characteristics and quality. In practice, the SVI can vary from 40 to 300 ml/g and a well settling sludge does not exceed the value 150 ml/g; indicating good settling properties of the sludge.

The SVI was determined for the period of 160 days taking into account the automatic sludge depth measurements as shown in Figure (10). It was observed that the value of the SVI was substantially decreased in the SC; from an average initial value of 100 ml/g to 50 ml/g. This indicates an improvement in the sludge settling properties, as reducing the WSR allows heavier sludge particles to be formed causing an increase in the sludge density. In addition, calculations also show an increase in the sludge mass with no variation in the sludge storage volume, see Figure (11).

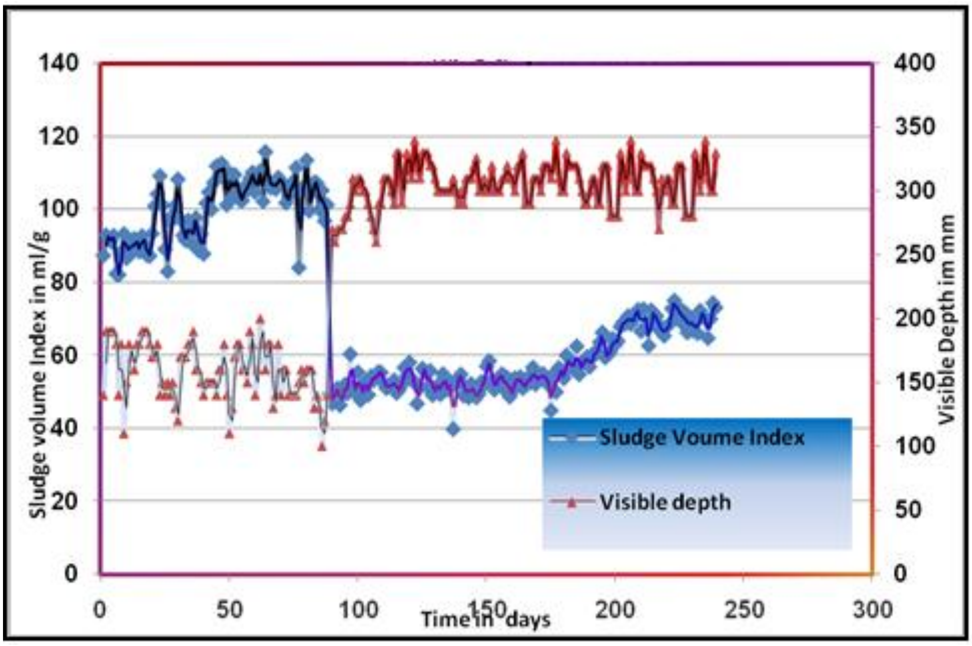


Figure (10): Sludge Volume Index in the Secondary Clarifier.

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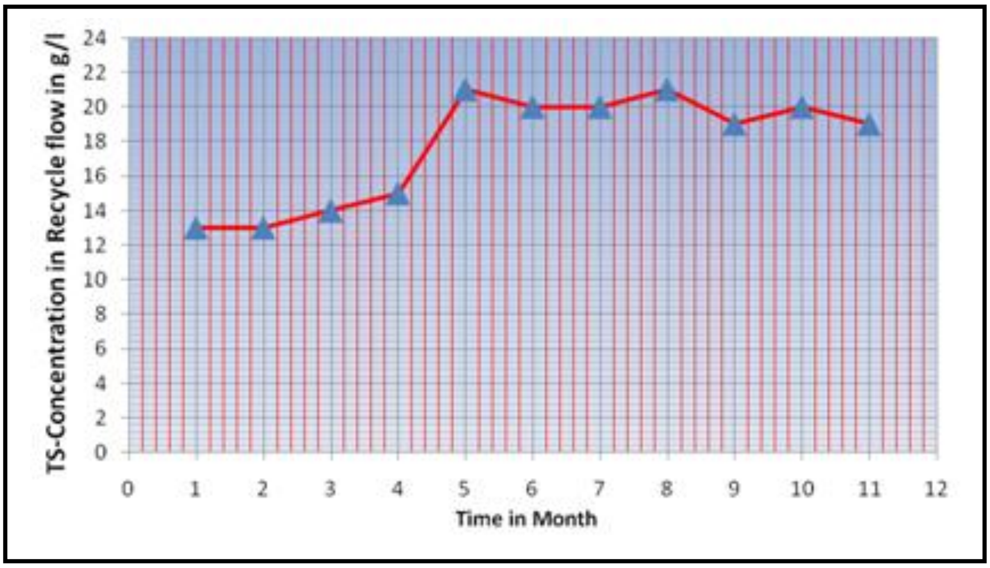

Figure (11): TS-Concentration in the Recycle Flow

In conclusion, despite lower SVI, there is no threat of hydraulic shocks caused by fluctuations in the sludge height as reducing the WSR had more or less no impact on the sludge depth. In addition, the concentration of WAS has a direct bearing on the amount to be wasted; as high WAS concentration requires less amount of wasting than a low WAS concentration which in turn will have an impact on disposal cost.

Effluent Characteristics:

To monitor the effect of reducing the WSR and the associated increase in the sludge storage volume on the SC functioning, different effluent characteristics were thoroughly examined. Table (2) and Figure (12) show the monthly average of various SC effluent parameters including: BOD, COD, NH_4, NO_3, NO_2, N_{total} and PO_4.Throughout the period of study, results indicate more the less no variation in the characteristics of the relevant examined parameters leading to the conclusion that reducing the WAS has no influence on the quality of the SC effluent.

Month	COD [mg/L]	BOD [mg/L]	NH_4-N [mg/L]	NO_3-N [mg/L]	NO_2-N [mg/L]	N_{total} [mg/L]	PO_4 [mg/L]
May	18	1.6	0.8	1.7	0.1	2.6	1
June	18.5	2.0	0.9	0.9	0.2	2.0	1.2
July	17.2	1.1	0.4	1.8	0.2	2.4	1.2
August	18.0	1.4	0.7	1.3	0.2	2.2	1.1
September	20.0	2.0	0.9	0.6	0.1	1.6	1.0
October	20.0	2.0	0.9	0.6	0.1	1.6	1.0
November	18.3	1.9	1.0	1.1	0.1	2.2	0.9

Table (2): Secondary Clarifier Effluent Characteristics

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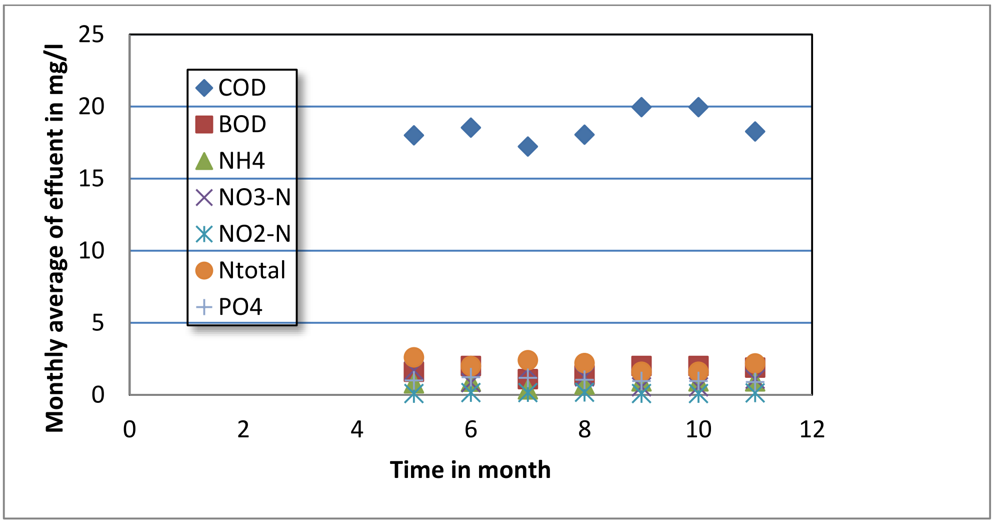

Figure (12): Average Effluent Characteristics from the Secondary Clarifier

CONCLUSION

Secondary Clarifier plays a key role in biological treatment processes where activated sludge is utilized. In this paper, the dynamic behaviour of the SC was described using the mass balance technique. Results indicated that detecting the sludge height using the automatic method rather than the manual technique enables the exact amount of excessive sludge produced. In turn, the disposal method and cost can be determined. In addition, The Sludge Retention Time (SRT) can be calculated as the mass of solids in the SC can be calculated.

In the light of the presented scenario of reducing the WAS by 30%, findings proved an improvement in the sludge settling properties with no effect on the effluent characteristics and the safety margin.

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