Journal of Energy, Environmental & Chemical Engineering
2023; 8(1): 18-25
http://www.sciencepublishinggroup.com/j/jeece
doi: 10.11648/j.jeece.20230801.13
ISSN: 2637-4331 (Print); ISSN: 2637-434X (Online)

Analysis of the Sludge Settling Behavior of the Kibendera Waste Stabilization Ponds in Ruiru, Kenya

George Kirumba[1], George Thumbi[2], John Mwangi[3], John Mbugua[4]

[1]School of Chemical and Biological Systems Engineering, Technical University of Kenya, Nairobi, Kenya

[2]School of Civil and Resource Engineering, Technical University of Kenya, Nairobi, Kenya

[3]School of Civil, Environmental and Geospatial Engineering, Jomo Kenyatta University of Agriculture and Technology, Nairobi, Kenya

[4]School of Chemistry and Material Science, Technical University of Kenya, Nairobi, Kenya

Email address:

georgefxchira@gmail.com (George Kirumba), georgechira@tukenya.ac.ke (George Kirumba)

To cite this article:

George Kirumba, George Thumbi, John Mwangi, John Mbugua. Analysis of the Sludge Settling Behavior of the Kibendera Waste Stabilization Ponds in Ruiru, Kenya. *Journal of Energy, Environmental & Chemical Engineering*. Vol. 8, No. 1, 2023, pp. 18-25. doi: 10.11648/j.jeece.20230801.13

Received: March 6, 2023; **Accepted**: April 10, 2023; **Published**: April 20, 2023

Abstract: Waste Stabilization Ponds (WSP) provide both cost-effective and high-performance wastewater treatment benefits in the tropical regions. The 3-month sludge settling behavior in the Kibendera WSP in Ruiru, Kenya, was studied between July and September 2022. The study aimed at determining the sludge volume index (SVI) and hindered settling velocity during the dry weather flow regime. Based on these experimental data, Vesilind Model was used to characterize the settling behavior in the anaerobic and primary facultative ponds. Whereas Standard Methods for the examination of water and wastewater were used to determine the total suspended solids (TSS) concentrations in the ponds, batch column settling tests were used to generate the batch settling curves for each pond. Generally, good settling behavior characterized by SVI values of less than 150 mL/g was observed during the study period. Highest settling velocities of 1.16 m/hr and 1.22 m/hr were recorded in the anaerobic and primary facultative ponds respectively for TSS concentrations of 0.6 g/L and 0.416 g/L. Optimal maximum velocity (V_{max}) values of 3.42 m/hr and 1.78 m/hr were observed in the anaerobic and primary facultative ponds respectively. The corresponding optimal model parameters (n) describing the measured data accurately were 0.47 L/g and 0.51 L/g respectively. The model parameters so obtained may be useful in characterizing the sedimentation behavior in the WSP during the dry weather flow regimes.

Keywords: Sedimentation, Settling Velocity, Sludge Volume Index, Total Suspended Solids, Waste Stabilization Ponds

1. Introduction

Waste Stabilization Ponds (WSP) provide a cost-effective, high-performance and least-mechanized sewage treatment alternative in developing countries within the tropics. The tropical climate has played a vital role in enhancing microbial processes of nitrification-denitrification, enhanced biological phosphorus removal, autotrophic and heterotrophic bacterial activities and algal photosynthesis. Findings from a previous study carried out in 2018 revealed that WSP constituted about 55% of the available wastewater treatment plants in Kenya [1]. In addition, several other studies investigating the performance of some WSP in wastewater treatment in Kenya have also been conducted [2-5]. Although high removal efficiencies were observed in these studies, the effluent failed to meet the local sewage effluent guidelines as stipulated by the National Environmental Management Authority (NEMA). A recent study to investigate the performance of the Kibendera WSP in Ruiru revealed increasing total suspended solids (TSS) in the effluent coupled with non-compliance with the NEMA guidelines [6].

Sedimentation plays a crucial role in wastewater treatment in WSP and more particularly in TSS removal. In addition, there has no been significant changes over time in regards to the current design principles, which are primarily based upon empirically derived surface loading rates [7]. It has been observed that particle diameter, water temperature, overflow rate and suspended matter loading influence the sedimentation process in WSP [8]. In a typical configuration of conventional WSP, anaerobic, facultative and maturation ponds all contribute to partial elimination of suspended matter. Whereas highest levels of sedimentation occur in the anaerobic ponds, the least is observed in maturation ponds. In view of this, the hydraulic retention time (HRT) in each pond is therefore important for the settling process [9]. Whereas good sludge settling is a precursor for high TSS removal through the sedimentation process, poor sludge settling is detrimental to the overall sewage treatment process. The latter is associated with excessive propagation of filamentous bacteria, foaming caused by the growth of certain microorganisms and poor sludge flocculation properties [10]. Sewage concentration and flocculation tendency play a crucial role in determining the settling behavior of solids therein [11].

Despite the WSP technology being an active research area over the last three decades, literature describing and quantifying the various processes taking place in WSP is limited. Consequently, modelling has been adopted as a low-cost tool to describe and characterize these processes [12, 13]. Although several models describing sludge settling in activated sludge systems have been developed previously [11, 14], studies on sludge settling behavior in WSP are unavailable both globally and nationally hence the need for simple one-dimensional models.

In Kenya, the frequency for desludging operations in WSP is low, posing a great risk of resuspension of sludge under high flow regimes. Consequently, the effluents from majority of the WSP in Kenya are NEMA non-compliant in terms of TSS removal. The high TSS effluent observed is an indicator of hindered/incomplete sedimentation process. Understanding and characterizing the sludge settling behavior through batch settling experiments is vital. The tests would eliminate the hydraulic influences caused by inflows and outflows from such systems. The sludge settling data would provide the basis for modelling of sludge settling behavior in the ponds thus enhancing the optimization of the process. This study aimed at:

1) Determining the sludge volume index (SVI), sludge blanket height and hindered settling velocity of the sludge in the anaerobic and primary facultative ponds of the Kibendera WSP.
2) Modelling the sludge settling behavior using the Vesilind model.

2. Materials and Methods

2.1. Description of Waste Stabilization Ponds

Kibendera WSP located in Ruiru Sub-county of Kiambu County (0.5°N latitude and 37°E longitude lines) is premised on a 12.6 hectare-land. It is composed of a design of four trains of ponds with a capacity of 10,500m^3 /day [6]. A single train carrying 2,625m^3/day, consists of 5 ponds namely Anaerobic, Primary Facultative (PF), Secondary Facultative (SF), First Maturation (FM) and Second Maturation (SM) ponds (Figure 1). Due to previous storm intrusion events that resulted to significant TSS sedimentation and ongoing desludging operations at the plant, one train (Train A) of fully functional ponds was considered for this study (Figure 1). Table 1 summarizes the depth and hydraulic retention time (HRT) data for the ponds.

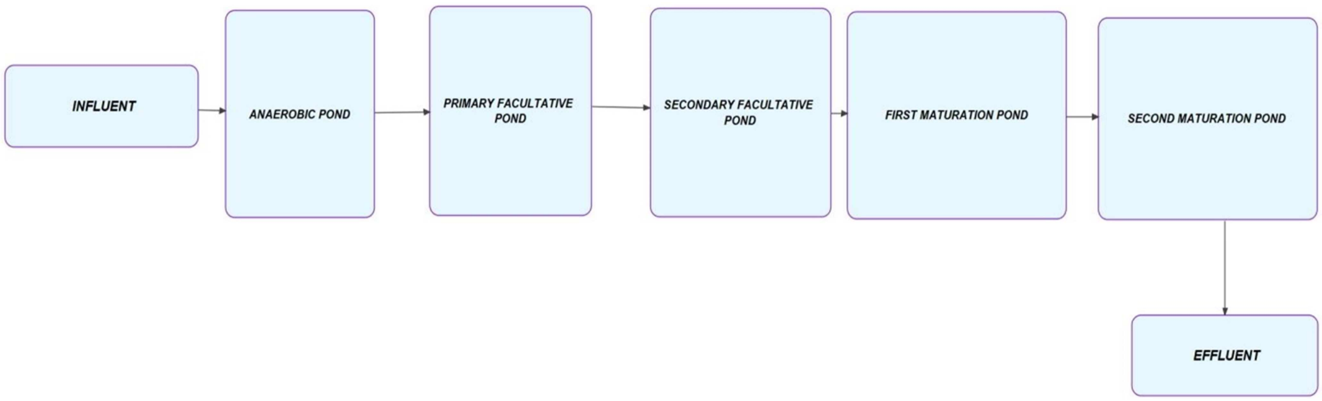

Figure 1. *Train A of the Kibendera Waste Stabilization Ponds.*

Table 1. *Hydraulic parameters for the Kibendera WSP.*

Pond	Depth (m)	HRT (Days)
Anaerobic Ponds (A.P)	4	1
Primary Facultative Ponds (P.F)	1.75	5
Secondary Facultative Ponds (S.F)	1.75	5
First Maturation Ponds (F.M)	1.50	5
Second Maturation Ponds (S.M)	1.50	5

2.2. Sedimentation Experiments

Liquid sludge samples from the anaerobic (AP) and primary facultative (PF) ponds were collected at a depth of 1.5 meters during the dry weather flow months of July (1ST, 10TH, 20TH and 30TH), August (10TH, 20TH and 30TH) and September 2022 (10TH, 20TH and 30TH). Grab samples were collected during these dates at 8 a.m., 12 noon and 4 p.m.

inorder to incorporate the daily sewage load variations and averages obtained for analysis and modelling. The Total Suspended Solids (TSS) concentration of the sludge sample was determined in accordance with the Standard Methods [15]. A 1 L graduated cylinder with the sludge sample was allowed to settle for 30 minutes after which the volume occupied by the sludge was read from the graduated cylinder (SV_{30} in mL/ L). The sludge volume index (SVI) was calculated by use of Equation 1.

$$SVI = \frac{SV30}{XTSS} \quad (1)$$

Where SV_{30} and X_{TSS} are the sludge volume after 30 minutes (ml/L) and the measured Total Suspended Solids concentration (mg/L) respectively.

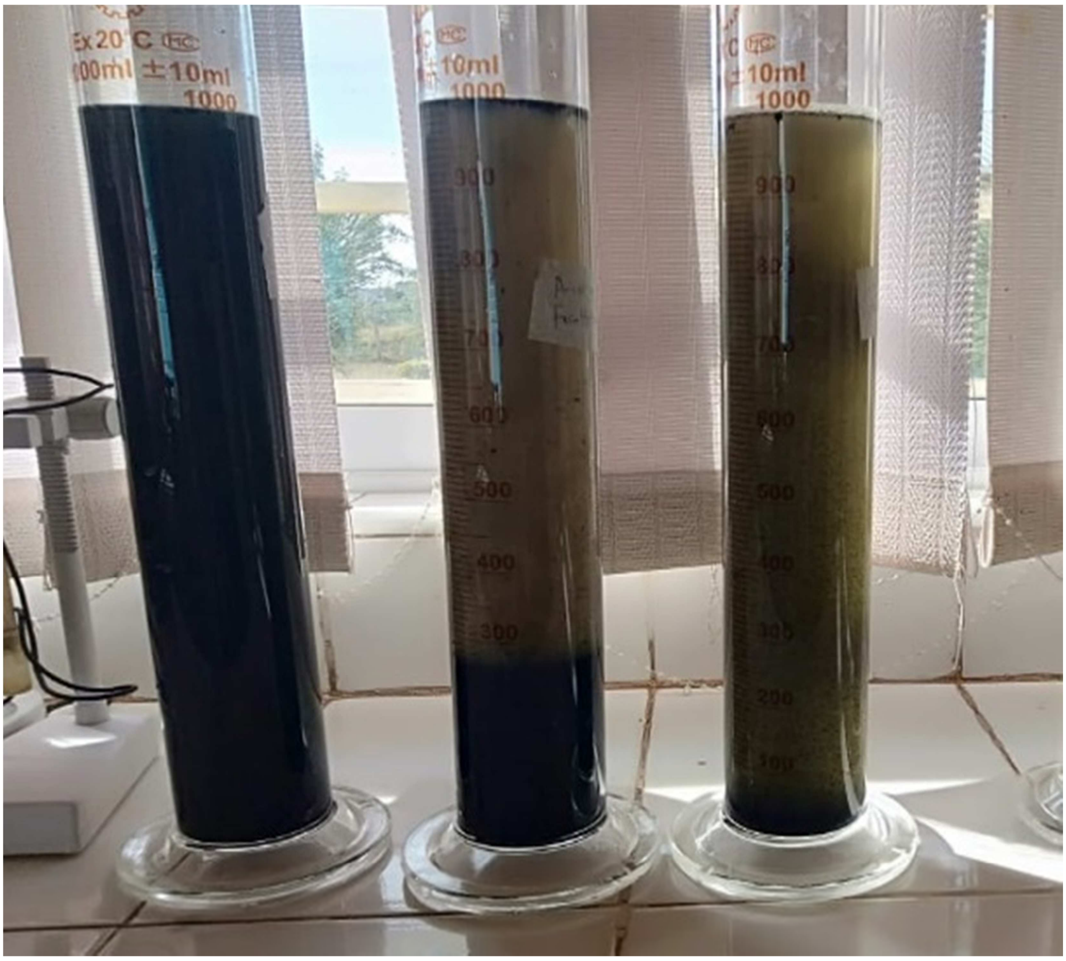

Figure 2. *Experimental set-up for batch column tests.*

The characterization of settling properties of sludge samples and determination of zone settling velocity as a function of sludge concentration were carried out through a series of batch settling tests. Batch settling tests provide good estimation of the sedimentation model parameters as the obtained results depend only on the physical properties of the settling column (which are constant for a given set-up) and the settling properties of the sludge [16]. Batch settling tests were performed in triplicate sets at room temperature in unstirred settling columns with a height of 30 cm (Figure 2). This was achieved by pouring a well-mixed sample from the A.P and P.F ponds into the columns and recording the corresponding height of sludge blanket for a period of 0–45 minutes at 5 minutes time interval, (0, 5, 10, 15, 20, 30 and 45 min). A timer was started and monitored to keep track of the duration of the experiment. The position of the suspension-liquid interface was then measured at the different time intervals to obtain the sludge blanket height. The hindered settling velocities in the ponds were computed by determining the steepest slope between three consecutive data points on the sludge blanket height against time curve.

2.3. Modelling the Settling Behavior

The Vesilind sedimentation model summarized by Equation 2 was used to link the velocity of settling flocs to the TSS concentration:

$$\mathrm{V(X)} = V_{max} e^{-nX} \quad (2)$$

where X (g/L) is the TSS concentration; V is the settling velocity (m/hr); V_{max} (m/hr) and n (L/g) are maximum settling velocity and model parameter respectively. Batch settling curves for the anaerobic and primary facultative ponds were used for the estimation of the Vesilind model parameters. The Vesilind settling constants, V_{max} and n, are determined by conducting batch hindered settling velocity tests of different concentrations of the particular sludge [17]. Whereas the constant, n, defines the slope of the line thus indicating how fast the velocity will decrease per unit increase of sludge concentration, the n will be low for a well-settling sludge even under high velocity and high sludge concentrations conditions. Therefore, V_{max} & n plays a superior role over conventional SVI parameters in giving an accurate reflection of the sludge settling velocity behavior [17]. Previous research report successful fitting of one-dimensional settling models to single batch settling curves [18, 19]. Therefore, batch settling curve based parameter estimation offers the best means of obtaining information on sludge settling characteristics for use in the solid flux theory [16].

In this study, the obtained relationship between settling velocity and sludge concentration was used to estimate Vesilind sedimentation model parameters. Model calibration was empirically achieved as summarized by Equations 3 and 4 [20].

$$V_{max} = 17.4\, e^{-0.0113SVI} \quad (3)$$

$$n = -0.9834e^{-0.00581SVI} \quad (4)$$

where SVI is the sludge volume index (mL/g).

3. Results and Discussion

3.1. Sludge Volume Index (SVI)

The observed TSS concentrations and SV_{30} values for all the sampling dates as well as the corresponding computed SVI are summarized in Table 2.

Table 2. *SV_{30}, TSS and SVI in the Anaerobic Pond (A.P) and Primary Facultative (P.F) Pond.*

Sampling	SV_{30} (ml/L)		TSS (mg/L)		SVI (mL/g)	
Date	A.P	P.F	A.P	P.F	A.P	P.F
1-Jul	120	50	1271	585	94.4	82.1
10-Jul	45	170	1053	496	42.7	342.7
20-Jul	200	150	998	416	200.4	360.6
30-Jul	150	90	1331	1225	112.8	65.3
10-Aug	70	45	600	202	116.7	225
20-Aug	220	120	6500	2806	33.8	21.4
30-Aug	265	200	5610	2520	47.2	79.4
10-Sep	180	140	2130	1245	84.5	112.4
20-Sep	140	90	1875	1164	74.7	77.3
30-Sep	120	100	1690	887	71.1	112.7

According to Table 2, relatively higher TSS concentration values were observed in the anaerobic pond serving as the primary sedimentation tank compared to the primary facultative pond. This was attributed to the low HRT (1 day) characterizing the anaerobic pond compared to the relatively higher HRT in the primary facultative pond (5 days). The significant TSS increase in August from 600 to 6500 mg/L and 202 to 2806mg/L was attributed to significant resuspension of solids in the anaerobic ponds [21]. Death of microorganisms, fragmentation and formation of chemical precipitates were responsible for the production and increase in TSS [21, 22, 23].

Whereas SVI above 150 mL/g characterizes a bulking sludge, that ranging from 40 to 120 mL/g represents good settling sludge [24]. On the other hand, a sludge characterized by quick settling (SVI below 70 mL/g) was responsible for effluents with high turbidity levels. A different study demonstrated high organic compounds removal under low SVI conditions [25]. Based on this study, SVI values summarized in Table 2 revealed good sludge settling behavior for all the sampling dates in September 2022. However, on 20^{TH} July the highest SVI values were recorded in all the ponds (Table 2). Similarly, high SVI values of 342.7 and 225 were recorded on 10^{TH} July and 10^{TH} August respectively. The high values were attributed to bulking sludge within the ponds due to denitrification [24, 26]. Based on a previous study, the sludge mass made buoyant by the nitrogen gas produced in the process caused the sludge to rise [27].

3.2. Sludge Blanket Height (SBH) Against Time in Anaerobic and Primary Facultative Ponds

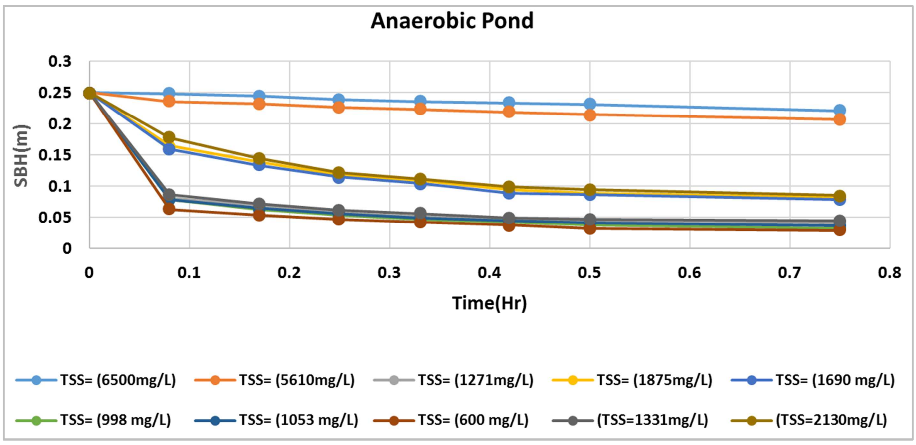

Figure 3. *Graph of Sludge Blanket Height against time for different sludge concentrations in the Anaerobic Pond.*

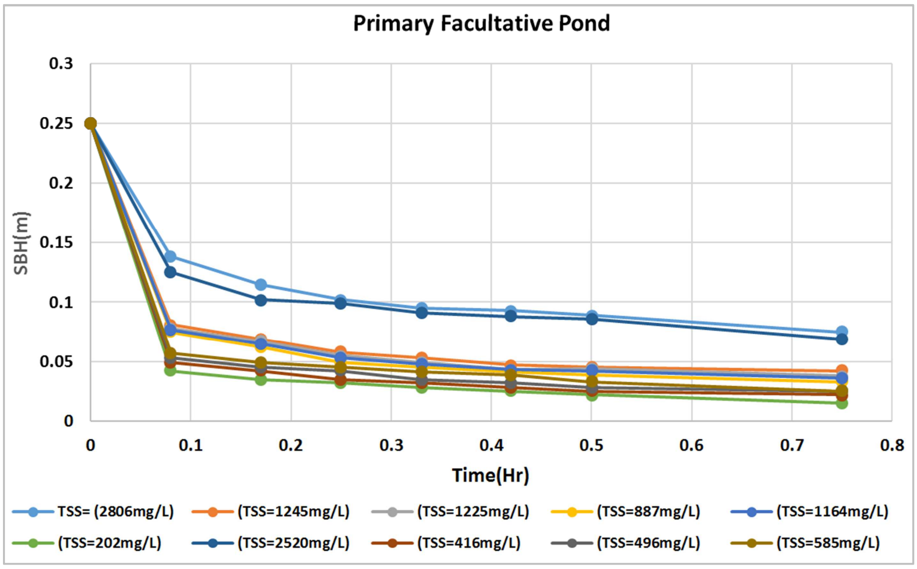

Figure 4. *Graph of Sludge Blanket Height against time for different sludge concentrations in the Primary Facultative Pond.*

3.3. Settling Velocity Against Solids Concentrations in Anaerobic and Facultative Ponds

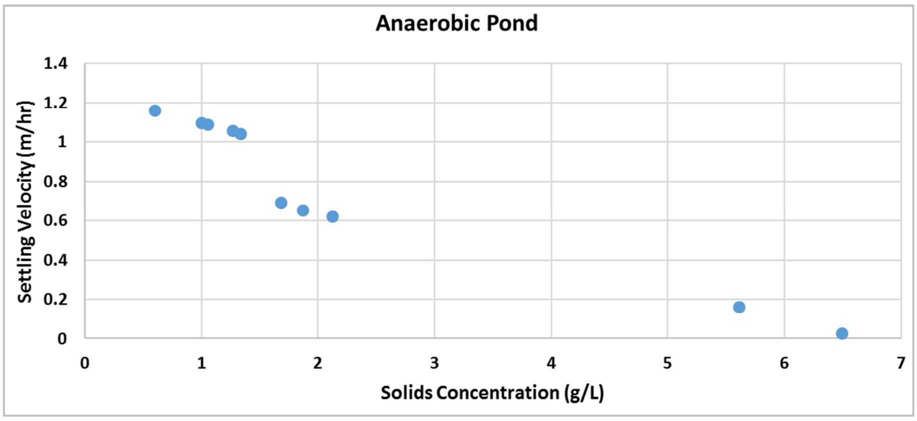

Figure 5. *Graph of Hindered Settling velocities under varying solids concentration in the Anaerobic Pond.*

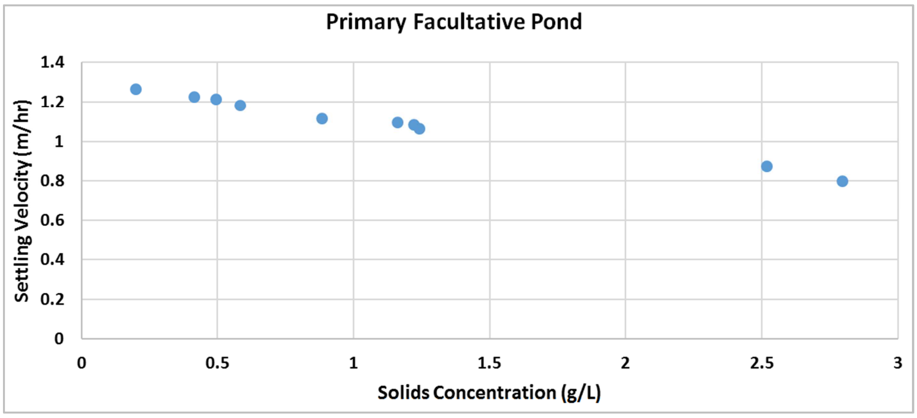

Figure 6. *Graph of Hindered Settling velocities under varying solids concentration in the Primary Facultative Pond.*

Based on the results summarized in Figures 5 and 6, least settling velocities of 0.03 m/hr and 0.794 m/hr were observed in the anaerobic and primary facultative pond respectively under TSS concentrations of 6.5 g/L and 2.8 g/L. The corresponding highest settling velocities of 1.16 m h^{-1} and 1.22 m h^{-1} were recorded for TSS concentrations of 0.6 g/L and 0.416 g/L. The anaerobic pond acted as the primary settling tank (PST) where flocculent settling occurred. On the other hand, the primary facultative pond served as the secondary settling tank (SST). Although settling occurred in both ponds, the characteristics of the particles were different. It was observed that as a result of the various particle sizes, stokes velocities of large particles are higher than for small ones. This produced collisions inducing flocculation which, in turn, yielded larger flocs, and thus particles settled faster in the primary facultative pond compared to anaerobic ponds [9]. In addition, an increase of sludge concentration was responsible for decreased sedimentation velocity due to the high quantity of floes that hindered settling [28, 29]. In a previous study, distinguishing the compression point for sludge was a challenge in cases where the sludge concentrations exceeded 4 g/L. Increase of sludge quantity per volume unit resulted in decreased sedimentation velocity triggered by the mutual impediment of settling floes through the "hindrance effect" [26].

Hindered settling has been found to occur typically between sludge concentrations of 1 g/L and 6 g/L. However, the limits are dependent on the flocculation state of the sludge [30]. Discrete particle settling, flocculent particle settling, hindered settling and compression settling represent the four types of settling behavior observed in primary and secondary settling tanks. The settling regimes are dependent on the concentration and properties of solid particles. [31]. Although it became increasingly challenging to keep track of the solid-liquid interface at low initial concentrations as the sludge entered the discrete settling regime, high concentrations were responsible for sludge compression [17].

3.4. Estimated Parameters of the Settling Function

Whereas the estimated model parameters in both anaerobic and primary facultative ponds are summarized in Table 3, Figures 5 and 6 illustrates and compares the settling velocities as obtained from the experimental data and the fitted Vesilind model.

Table 3. *Optimal estimated model parameters.*

Parameter	Anaerobic Pond		Primary Facultative Pond	
	Initial Value	Optimal Value	Initial Value	Optimal Value
V_{max} (m/hr)	2.67	3.42	2.2	1.78
n (L/g)	0.49	0.47	0.54	0.51

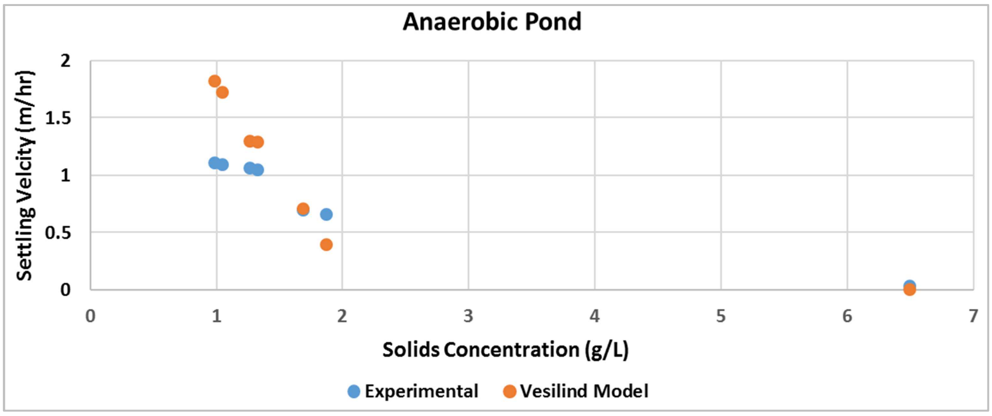

Figure 7. *Settling velocity as a function of the solids concentration in the Anaerobic Pond.*

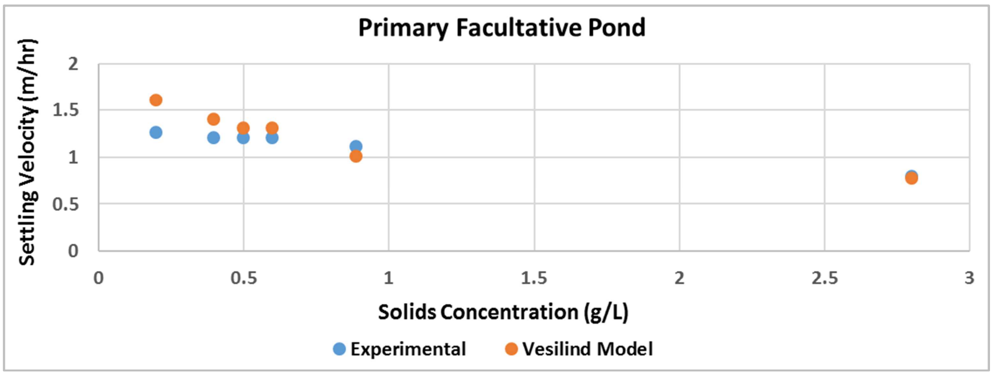

Figure 8. *Settling velocity as a function of the solids concentration in the Primary Facultative Pond.*

Figures 7 and 8 show that the settling parameters that were empirically calculated were able to accurately describe the measured data. In other studies however, the accurate description of the measured data has not been achieved since similar SVI but varying sludge properties may cause different settling behavior [17]. Moreover, when using the empirical relations, the estimation of two parameters based on only one data point is done. Considering that the study was conducted during the dry weather flow regime, the obtained model parameters may be used to characterize the sedimentation behavior for dry weather flow regimes.

4. Conclusion

The 3-month experimental and modelling studies on the sludge settling behavior in the anaerobic and primary facultative ponds of the Kibendera WSP were conducted between July and September 2022. Although poor settling behavior (SVI>150 mL/g) was observed on 10^{TH} July, 20^{TH} July and 20^{TH} August indicating bulking of sludge due to presence of filamentous bacteria, good settling characteristics were recorded during the other sampling dates implying that TSS removal from the ponds during the dry weather flow regime was satisfactory. Highest settling velocities of 1.16 m/h and 1.22 m/h were recorded in the anaerobic and primary facultative ponds respectively for TSS concentrations of 0.6 g/L and 0.416 g/L. Based on the results obtained from the study, increase of sludge concentration hence the high quantity of floes hindered and decreased the sedimentation velocity. Optimal maximum velocity (V_{max}) values of 3.42 m/hr and 1.78 m/hr were observed in the anaerobic and primary facultative ponds respectively. The corresponding optimal model parameters (n) of 0.47 L/g and 0.51 L/g were able to describe the measured data accurately. In addition, they can be used to predict the sludge settling behavior in the anaerobic and primary facultative ponds of the Kibendera WSP. Evaluating the sedimentation process was important in quantifying the sludge settling behavior as well as fitting the Vesilind Model for the ponds. Considering the velocity variations in the ponds, optimization of the sedimentation process may be enhanced by investigating the effect of particle diameter and overflow rate on the sludge settling velocities.

References

[1] Bundi, L. K., & Njeru, C. W. (2018). Use of vegetative wastewater treatment systems for counties' effluent management in Kenya. Rwanda Journal of Engineering, Science, Technology and Environment, 1 (1).

[2] Sewe, H. A. (2013). *A study on the Efficiency of Dandora Domestic and Industrial Wastewater Treatment Plant in Nairobi* (Doctoral dissertation).

[3] Musungu, P. C., Lalah, J. O., Jondiko, I. O., & Ongeri, D. M. (2014). The impact of nitrogenous and phosphorous nutrients from selected point sources in Kisumu City on River Kisat and Nyalenda Wigwa Stream before their discharge into Winam Gulf, Lake Victoria. Environmental earth sciences, 71 (12), 5121-5127.

[4] Muriuki, C., Kairigo, P., Home, P., Ngumba, E., Raude, J., Gachanja, A., & Tuhkanen, T. (2020). Mass loading, distribution, and removal of antibiotics and antiretroviral drugs in selected wastewater treatment plants in Kenya. Science of the Total Environment, 743, 140655.

[5] Mburu, N., Tebitendwa, S. M., Van Bruggen, J. J., Rousseau, D. P., & Lens, P. N. (2013). Performance comparison and economics analysis of waste stabilization ponds and horizontal subsurface flow constructed wetlands treating domestic wastewater: A case study of the Juja sewage treatment works. Journal of environmental management, 128, 220-225.

[6] Kirumba, G. C, Thumbi, G. M, Mwangi, J. M, Mbugua, J. M (2022). Evaluation of Sewage Treatment Efficiency of the Kibendera Waste Stabilization Ponds in Ruiru, Kenya. *Journal of International Academic Research for Multidisciplinary*, 10 (8). https://www.jiarm.com/Oct2022.html

[7] Becker F. A., Hedges, P. D. & Smission R. P. M. (1996). The distributions of chemical constituents within the sewage settling velocity grading curve. Water Sci. Technol., 33, 143-146.

[8] Toprak, H. (1994). Empirical modelling of sedimentation which occurs in anaerobic waste stabilization ponds using a lab-scale semi-continuous reactor. *Environmental technology*, *15* (2), 125-134.

[9] Effebi, K. R., Keffala, C. & Vasel, J. L. (2011). Suspended solids settling and half removal time in stabilization ponds (Tunisia). Revue des sciences de l'eau / Journal of Water Science, 24 (1), 53–61. https://doi.org/10.7202/045827ar

[10] Minnie, J., Gaszynski, C., Basitere, M., & Ikumi, D. (2022). Modelling Filamentous Bacteria in Activated Sludge Systems and the Advancements of Secondary Settling Tank Models: A Review. *Biochemical Engineering Journal*, 108598.

[11] Ekama, G. A., Barnard, J. L., Gunthert, F. W., Krebs, P., McCorquodale, J. A., Parker, D. S., (1997). Secondary Settling Tanks: Theory, Modelling, Design and Operation. International Association on Water Quality.

[12] Eslami, H., Ehrampoush, M. H., Ghaneian, M. T., Mokhtari, M., & Ebrahimi, A. (2017). Effect of Organic Loading Rates on biodegradation of linear alkyl benzene sulfonate, oil and grease in greywater by Integrated Fixed-film Activated Sludge (IFAS). *Journal of environmental management*, *193*, 312-317.

[13] Sah, L., Rousseau, D. P., & Hooijmans, C. M. (2012). Numerical modelling of waste stabilization ponds: where do we stand? *Water, Air, & Soil Pollution*, *223* (6), 3155-3171.

[14] Ramin, E., Wágner, D. S., Yde, L., Binning, P. J., Rasmussen, M. R., Mikkelsen, P. S., & Plósz, B. G. (2014). A new settling velocity model to describe secondary sedimentation. *Water Research*, *66*, 447-458.

[15] American Public Health Association (APHA) (2005), American Water Works Association (AWWA) & Water Environment Federation (WEF): Standard Methods for the Examination of Water and Wastewater, 21st Edition.

[16] Vanderhasselt, A., & Vanrolleghem, P. A. (2000). Estimation of sludge sedimentation parameters from single batch settling curves. *Water Research*, *34* (2), 395-406.

[17] Torfs, E., Nopens, I., Winkler, M., Vanrolleghem, P., Balemans, S., Smets, I. (2016). Experimental Methods In Wastewater Treatment. IWA Publishing, London, UK.

[18] Cacossa, K. F., & Vaccari, D. A. (1994). Calibration of a compressive gravity thickening model from a single batch settling curve. *Water Science and Technology*, *30* (8), 107.

[19] Vanrolleghem, P. A., Jeppsson, U., Carstensen, J., Carlssont, B., & Olsson, G. (1996). Integration of wastewater treatment plant design and operation—a systematic approach using cost functions. *Water Science and Technology*, *34* (3-4), 159-171.

[20] Härtel, L., Pöpel, H. J., (1992). A dynamic secondary clarifier model including processes of sludge thickening. Water Sci. Technol. 25: 267-284.

[21] Rajbhandari, B. K., & Annachhatre, A. P. (2004). Anaerobic ponds treatment of starch wastewater: case study in Thailand. *Bioresource technology*, *95* (2), 135-143.

[22] Tiehm, A., Herwig, V., & Neis, U. (1999). Particle size analysis for improved sedimentation and filtration in waste water treatment. *Water science and technology*, *39* (8), 99-106.

[23] Shukla, R., Gupta, D., Singh, G., & Mishra, V. K. (2021). Performance of horizontal flow constructed wetland for secondary treatment of domestic wastewater in a remote tribal area of Central India. *Sustainable Environment Research*, *31* (1), 1-10.

[24] Jenkins, D., Palm, J. C., Strom, P. F., Koopman, B. L., Lau, A. O., Lee, S. E., & Hao, O. (1980). Bulking, Deflocculation and Pinpoint Floc. *Journal (Water Pollution Control Federation)*, 622-624.

[25] Rensink, J. H., & Donker, H. J. G. W. (1991). The effect of contact tank operation on bulking sludge and biosorption processes. *Water Science and Technology*, *23* (4-6), 857-866.

[26] Janczukowicz, W., Szewczyk, M., Krzemieniewski, M., & Pesta, J. (2001). Settling properties of activated sludge from a sequencing batch reactor (SBR). *Polish Journal of Environmental Studies*, *10* (1), 15-20.

[27] Louzeiro, N. R., Mavinic, D. S., Oldham, W. K., Meisen, A., & Gardner, I. S. (2003). Process control and design considerations for methanol-induced denitrification in a sequencing batch reactor. *Environmental technology*, *24* (2), 161-169.

[28] Daigger E., Ropere. J R. (1985). The Relationship between SVI and Activated Sludge Settling Characteristics. Journal WPCF, 8, 859.

[29] Daigger G. T. (1995) Development of Refined Clarifier Operating Diagrams Using an Updated Settling Characteristics Database. Wat. Environ. Res., 67, 95.

[30] Balbierz, P., & Rucka, K. (2017). Sludge settling characterization for the mathematical modelling of sidestream treatment processes. In *E3S Web of Conferences* (Vol. 17, p. 00003). EDP Sciences.

[31] Metcalf & Eddy, Wastewater Engineering: Treatment and Resource Recovery (G. Tchobanoglous, F. L. Burton, H. D. Stensel, ed.), McGraw-Hill Education (2014).