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Impact of Baffle Walls on Area and Hydraulic Detention Time Needed for Wastewater Stabilization Ponds at Different Pollutant Loads

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Abstract: This paper mainly presents the in-depth analysis performed to explore the effect of baffle walls (BWs) on the requirement of the area and hydraulic detention time (D_T) for wastewater stabilization ponds (WSPs). In addition, the influence of various concentrations of fecal coliforms and BOD_5 is also presented. The meteorological parameters used to perform the analysis represent Ayvadere, a neighborhood in Arakli city of the Trabzon Province, Turkey. There were 12 different combinations of fecal coliforms and BOD_5 influent loads. The analysis also included 3 different configurations of ponds, 6 various numbers, and 5 different lengths of the BWs, with which 720 analyses were performed. Configuration 1 gave minimum area and D_T by meeting all the WSPs design and irrigation class-B effluent standards. There were 2 BWs with a length of 50 % of the design length of facultative ponds. Moreover, fecal coliforms and BOD_5 were 10^6 (MPN/100 ml) and 300 (mg/l) simultaneously. According to the findings of the study, increasing the number and length of BWs reduces the area and D_T required for WSPs. Furthermore, the results also show that the need for both things increased by increasing the pollution load. The cost of BWs is an essential factor compared to the decrease in area. So, an optimization study is recommended using various methods available in the literature. Besides, an examination must be conducted experimentally to compare the results of the analysis performed in this research.

Keywords: Baffle walls, Biochemical Oxygen Demand, Fecal Coliforms, Mathematical Analysis, Wastewater Stabilization Ponds

INTRODUCTION

Various wastewater treatment systems employed in Turkey differ based on factors: climatic conditions, topography, wastewater characteristics, population, and cost of land (Maryam and Büyükgüngör, 2019). Wastewater stabilization ponds (WSPs) are cheaper than all other methods, considering both construction and maintenance (Mahapatra et al. 2022). Maintenance of WSPs is easy, and the treatment process needs minimum electrical energy in the presence of solar energy (Garrido et al. 2018). Wastewater treatment through WSPs is ideal for developing countries. Besides, they are equally important and employed in developed countries, with more than 50 % of the wastewater treatment systems based on or including WSPs in Brazil, China, Switzerland, Denmark, etc. (Majumder et al. 2021).

The provision of WSPs helps to remove three major contaminants: organic matter, pathogenic microbes, and nutrients (Merchán-Sanmartín et al. 2021). The main hurdle in their implementation is the highest area requirement compared to other available treatment methods (Mahapatra et al. 2022). Due to the stated reason, they are most appropriate for small communities with enough terrain away from a residential area. WSPs have primarily three types, i.e., anaerobic, facultative, and aerobic maturation ponds, typically provided in series for effective treatment; however, they can also be provided separately and parallel to each other (Liu et al. 2020).

There are two primary types of flows in wastewater treatment reactors such as continuous and discontinuous (Mathur and Singh, 2022). The discontinuous flow is used in laboratory studies (Garcia-Rodriguez et al. 2022). In contrast, the continuous flow is further subdivided into dispersed, mixed, and plug flow (Liotta et al. 2014). In plug flow, there is no horizontal mixing, but in the perpendicular direction. Also, the dispersion number is small. This type of flow is possible with a higher length-to-width ratio. The plug flow is provided to minimize the short circuits in the ponds. Contrarily, mixed

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flow occurs when there is a complete uniform flow throughout the pond, and the dispersion is greater. Likewise, the length-to-width ratio is smaller compared to the plug flow. Lastly, the dispersed flow lies between these two limits: plug and mixed flow. In this flow condition, the length-to-width ratio mostly varies from 1 to 3, and the dispersion number from 0.2 to 1 (Sperling, 2007).

As mentioned earlier, the main hurdle in the provision of WSPs is the highest requirement of the area as compared to all other available wastewater treatment systems. Therefore, it highlights the necessity of detailed analysis, considering various alternatives available in the literature. This research focuses on the inclusion of baffle walls (BWs) and different configurations of WSPs to reduce the requirement of area for the project implementation. Several researchers have evaluated the treatment performance of WSPs. They concluded that the addition of BWs in WSPs can improve hydraulic and treatment efficiency (Goodarzi et al. 2022; Li et al. 2018). In addition, it raises construction costs and stagnation points as a result of a decrease in the flow velocity, which eventually leads to low efficiency. These researchers have also concluded that the 70 % length of the BWs is optimal. On the other hand, (Li et al. 2018; Olukkanni and Ducoste, 2011) contradicted the statement; therefore, it is vital to perform a detailed analysis that includes various configurations and arrangements. Furthermore, none of the authors discussed the impact of variant pollution load. This study, in addition to the effect of BWs on the area and hydraulic detention time (D_T), also addresses the effect of various concentrations of the pollution parameters under consideration.

The aim of this research was to do the analysis of WSPs for their feasibility at various loads of input parameters. The goals of this research were: 1). To select the best configuration and arrangements of WSPs that meet the Turkish design standards of WSPs and class-B effluent standards for irrigation, with the minimum possible area and D_T. 2). To suggest the maximum allowed concentrations of both fecal coliform and BOD_5. 3). To suggest various alternatives if standards do not meet, for the implementation of WSPs in the study area.

MATERIALS AND METHODS

Acronyms and Abbreviations

MPN, Most probable number; **LPCD**, Liter per capita per day; $\mathbf{N_{BW}}$, Number of BWs; L_{BW}, Length of BWs; **BWs**, Baffle walls; **WSPs**, Wastewater Stabilization Ponds; **APs**, Anaerobic Ponds; **FP**, Facultative Pond; **MP**, Maturation Pond; $\mathbf{D_T}$, Detention time; $\mathbf{O_L}$, Organic load; $\mathbf{Q_i}$, Inflow of the wastewater stabilization ponds (m^3/d); $\mathbf{Q_e}$, Outflow from the wastewater stabilization ponds (m^3/d); $\mathbf{(BOD_5)_i}$, Concentration of 5 days influent biochemical oxygen demand (mg/l); $\mathbf{(BOD_5)_e}$, Concentration of 5 days effluent biochemical oxygen demand (mg/l); $\mathbf{T_{avg}}$, Region's coldest average monthly air temperature (°C); $\mathbf{V_p}$, Pond volume (m^3); $\mathbf{d_p}$, Pond depth (m); $\mathbf{A_P}$, Area of the pond (m^2); **Kt**, Overall decay constant (d^{-1}); $\mathbf{K_b}$, Bacterial decay constant (d^{-1}); $\mathbf{K_f}$, BOD_5 decay constant at the average temperature of the coldest month in the region (d^{-1}); **N**, Population (Number of persons); $\mathbf{N_i}$, Influent concentration (MPN/100 mL) of fecal coliforms; $\mathbf{N_f/N_o}$, Effluent concentration (MPN/100 mL) of fecal coliforms; $\mathbf{N_e}$ (MPN/100 mL), Effluent fecal coliforms; **X**, Ratio between length and width; $\mathbf{W_{avg}}$, Pond's average width (m); $\mathbf{L_{avg}}$, Pond's average length (m); $\mathbf{L_{top}}$, Length from top of the pond (m); $\mathbf{W_{top}}$, Width from top of the pond (m); $\mathbf{A_{top}}$, Area from top of the pond (m^2); $\mathbf{A_f}$, Area of the facultative pond (m^2); $\mathbf{d_f}$, Dispersion factor; **a**, Dimensionless constant; $\boldsymbol{\lambda_v}$, Volumetric load (g/m^3/d); $\boldsymbol{\lambda_s}$, Surface loading (kg/ha.d).

Methodology

The Marais approach was considered to design the anaerobic ponds. The remaining two ponds were designed following the Yanez approach and reflecting the dispersed flow conditions. (Martinez et al. 2012), have discussed in detail the design process of these ponds following the above-mentioned approaches. To design WSPs for the study area under consideration in this research, the same steps were followed. Three configurations were involved in the analyses, to select the best possible that gave minimum area and D_T. (a). Configuration 1: All three ponds were in series; anaerobic is at the start, facultative at the middle, and maturation ponds at the end were considered. (b). Configuration 2: Two ponds were in series; at start facultative followed by maturation ponds were considered. (c). Only facultative pond. Listed below are the modifications made to the design calculations depending on the weather conditions of the research area.

Anaerobic Ponds (APs)

In the design of the anaerobic pond, first the equations for the volumetric load (see equation 1) and percentage BOD_5 removal (see equation 2) were decided based on the average temperature of the coldest month in the study area. Then, based on these and other influent parameters, the dimensions of the pond were calculated.

i. Volumetric load $\left(\frac{g.\ BOD_5}{m^3.d}\right) = \lambda_v = 100$ (Equation 1)

ii. BOD_5 removal (%) = 40 (Equation 2)

Facultative Ponds (FPs)

The changes made to the design of FPs are mentioned below. First, the maximum surface loading rate of biochemical oxygen demand (BOD_5) was calculated using the equation 3 given below.

iii. $\lambda s \left(\frac{kg}{ha.d}\right) = 350 \text{ x } \left(1.107 - 0.002 \text{ x } T_{avg}\right)^{T_{avg} - 25}$ (Equation 3)

The equation incorporates safety factors to give a design equation for FPs that can be used globally (Mara, 2013). The coefficient of bacterial reduction was also different. First, $(K_b)_{20}$ was calculated based on the depth of FPs and MPs. Then $(K_b)_{T_{avg}}$ was calculated using equation 4, based on the last ten years' average temperature during the coldest month of the study area.

iv. $(k_b)_{T_{avg}} = (k_b)_{20} \times \theta^{T_{avg} - 25}$ (Equation 4)

Where: $(k_b)_{20} = 0.542 \text{ x } H^{-1.259}$, and the value of θ was taken constant; Marais 1974 used 1.19. However, Yanez 1993 mentioned the value is overestimated and must be taken as 1.07 (Sperling, 2007).

Maturation Ponds (MPs)

The only change that was made to the design of MPs is the calculation of the bacterial reduction coefficient. Which was calculated using the process explained for equation 4 given above in the design of FPs.

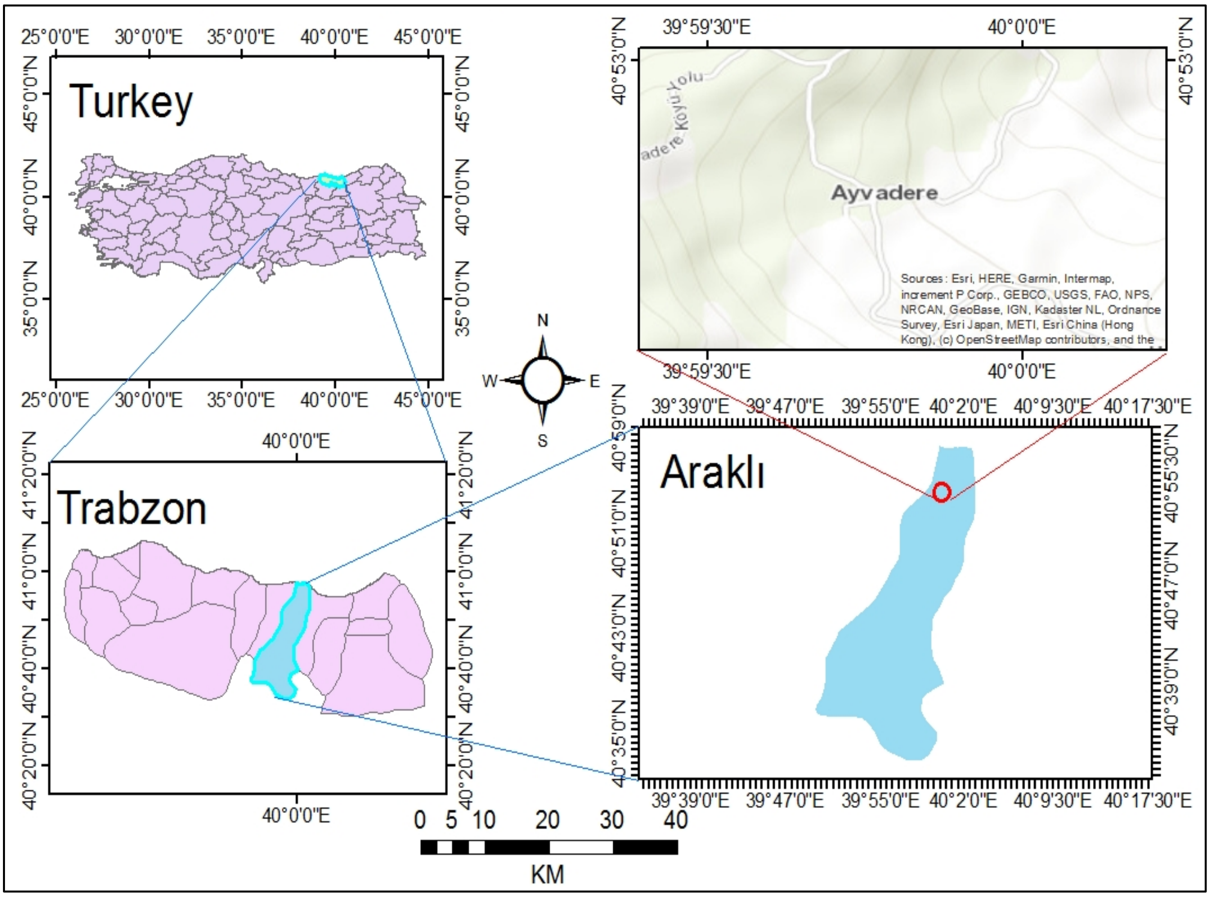

Figure 1. Study Area Map of Ayvadere, Arakli, Trabzon, Turkey.

Application of the Method

Ayvadere is in the city of Arakli, Trabzon, Turkey (Figure. 1). WSPs were designed for this neighborhood considering three different configurations, as mentioned above. The number of residents in the study area was calculated by considering 20 years design period = 950; water supply rate (LPCD) = 179, wastewater generation rate was considered 80 % of the water supply; design flow in m^3/day (Q_i) = 214.8 (Tuik, 2022). The average temperature of the study area's coldest month calculated from the last ten years' meteorological data is 8.9 °C. The evaporation rate was also calculated from the last ten years' metrological data, which is 5.8 mm/day. The influent BOD_5 concentrations were (200, 250, 300 and 350 mg/L). This is the typical range from lowest to average for the wastewater generated from a domestic source. The concentrations of fecal coliforms were (10^6, 10^7, and 10^8 MPN/100mL). This is the typical range of values for wastewater generated from a domestic source (George et al. 2002).

The class-B Irrigation Standards of Turkey were considered to check the effluent's quality. According to the standards, effluent BOD_5 must be less than 30 mg/L, whereas fecal coliforms concentration must be less than 200 MPN/100 mL. As mentioned above, the BWs increased in even number and analyzed up to 10. Their length varied between 50 to 90 percent of the total calculated length. The range for D_T in the Turkish design standards for a facultative pond is 30-50 days, but for a maturation pond, it is 18-20 days (Resmî Gazete, 27676).

RESULTS AND DISCUSSIONS

Generally, it was observed that with an addition in the number and increase in the length of the BWs, the requirement of area and detention time decreased, but this rate was significant up to 4 BWs in every block of the change in their length (e.g., 50% to 60 %). In general, the maximum reduction in detention time and area was 22 ± 4 % in configurations 1 and 2 (see Appendix A). However, in configuration 3, this reduction was 45 ± 5 % in detention time and 50 ± 5 % in the area (see Appendix A). Besides, it is important here to keep in mind that configurations 2 and 3 with 0 BWs in facultative ponds also satisfied the D_T criteria in some concentrations of the contaminants, but they are not recommended due to the non-compliance with this study's primary goal. The above-mentioned percentages were calculated between the area and D_T of configuration 2 with no BWs and other configurations with or without adding BWs. As mentioned in the introduction, the major disadvantage of WSPs is the required area. The percentage reduction, mentioned above, is essential regarding land acquisition and infrastructure development.

Table 1 below presents the sample design calculations for configuration 1. As mentioned earlier in the introduction part of this paper, it is comprised of a three-pond series. The series starts with an anaerobic pond, facultative in the center and maturation at the end. Similarly, Table 2 and Table 3 represent the sample design calculations for configurations 2 and 3 simultaneously. Configuration 2 includes two ponds in series as in configuration 1 but without having the anaerobic pond at the start. Configuration 3 consists of only a facultative pond. For the purpose of this research, the variation of the length and number of BWs was only done in FPs to check their effect on the overall area and D_T needed for WSPs in the study area. Besides this, in MPs, there was the effect of variation in the length of BWs but not in their number as it was kept constant at 4 BWs. This applies to both configurations that include MPs for the analysis in the present research. Overall, configuration 3 gave a minimum area for all concentrations of pollutants. However, it is not advised to provide it in the study area due to the non-compliance with BOD_5 effluent requirements or criteria for both effluents.

Area and D_T were maximum in configuration 2 at all pollutant loads compared to other configurations. So, it does not satisfy the basic requirement of this research i.e. the selection of minimum possible area. Still, it can be recommended because it meets all of the Turkish design standards for WSPs and class-B effluents standards for irrigation (Resmî Gazete, 27676). The criteria were met at 4 BWs with their 50% length of the total calculated length of FPs (Table 4). Unpredictably, MPs had less D_T in configuration 2 than 1, in all combinations of fecal coliforms and BOD_5 loads (see Appendix A). In configuration 3, there was no change in the design area and D_T; only fecal coliforms were reduced within the same combination of influent fecal coliforms and BOD_5. The reduction in the fecal coliforms and BOD_5 was not meeting the class-B effluent standards for irrigation in Turkey, in most of the pollutants under consideration. In some cases, the BOD_5 standard was not met, which shows the need for maturation ponds. The results are in line with the author's comment that only facultative ponds cannot be provided where effluents are used for unrestricted irrigation (Abagale and Richard, 2021).

Table 1. Sample Design Calculation for Configuration 1

Type of pond	N	LPCD	T_{avg} °C	$(BOD_5)_i$	N_i	d_p	Q_i
Anaerobic	950	179	8.9	200	1000000	4	170.05
Facultative	-	-	8.9	120	571119	1.5	169.74
Maturation	-	-	8.9	32	31214	1	160.85
Continue table							
O_L	% Removal of BOD_5	λv	λs	V_p (m^3)	A_p (m^2)	D_T	$(BOD_5)_e$
34.01	40	100	-	340.10	85	2.00	120
20.37	74.39	-	88	3454.87	2303	20.35	31
-	74.53	-	-	3543	3543	22.03	8
						44.38	-
Continue table							
$(BOD_5)_e$ corrected by evaporation	Q_e	BW Length (% × L)	X	d	a	K_t (d^{-1})	K_f
120	169.74	-	-	-	-	0.3771	
32	160.85	0.7	53	0.0187	1.11	0.1534	0.14271
9	148.09	0.7	81	0.0122	1.13	0.2558	0.14271

Continue table							
N_e	N_e corrected by evaporation	BWs	L-W ratio	Slope	W_{avg}	L_{avg}	W_{int}
570091	571119	-	2	0	6.52	13.04	6.52
29577	31214	4	3	2	27.71	83.12	26.21
156	170	4	-	2	27.71	127.88	26.71
Continue table							
L_{int}	W_{top}	L_{top}	A_{top}				
13.04	6.52	13.04	85				
81.62	29.21	84.62	2472				
126.88	28.71	128.88	3700				
			6257				

While selecting retention time for maturation ponds by hit and trial method, it was kept in mind to achieve minimum possible volume and ultimately the surface area of WSPs because the depth was constant. Detection time factors include dissolved oxygen, pH, solar radiation, physical configuration, and BOD_5 loads. Table 4 shows that relatively higher BOD_5 loads decrease the detention time for the same amount of fecal coliform but for the increased load the requirement of both area and D_T increases (see Appendix A too for the same results). Some of the solutions for higher removal efficiency and lower detention time are discussed below. To obtain higher removal efficiency and lower detention time in WSPs, the dispersion number must be achieved in the range of 0.1 to 0.3, which is possible with a length-width ratio greater than 5; in the analysis performed, it was 3. Another possible solution to achieve higher removal efficiency is to reduce the depth of the pond, which will increase the surface area for the same inflow volume. Moreover, BWs in FPs are parallel to the length of the ponds. For higher removal efficiency, BWs must be provided perpendicular to the length, as mentioned by (Olukkanni and Ducoste, 2011).

Table 2. Sample Design Calculation for Configuration 2

Type of pond	N	LPCD	T_{avg} °C	$(BOD_5)_i$	N_i	d_p	Q_i
Facultative	950	179	8.9	200	1000000	1.5	170.05
Maturation	-	-	8.9	37	14878	1	155.42
Continue table							
O_L	% Removal of BOD_5	λv	λs	V_p (m^3)	A_p (m^2)	D_T	$(BOD_5)_e$
34.01	82.88	-	88	5768	3846	33.92	34
-	71.22	-	-	3051	3051	19.63	10
						53.55	
Continue table							
$(BOD_5)_e$ corrected by evaporation	Q_e	BW Length (% × L)	X	d	a	K_t (d^{-1})	K_f
37	155	0.7	19	0.0516	1.44	0.1534	0.14271
11	144	0.7	42	0.0235	1.21	0.2558	0.14271
Continue table							
N_e	N_e corrected by evaporation	BWs	L-W ratio	Slope	W_{avg}	L_{avg}	W_{int}
13598.3022	14878	2	3	2	35.80	107.41	34.30

158	170	4	-	2	35.80	85.21	34.80
Continue table							
L_{int}	W_{top}	L_{top}	A_{top}				
105.91	37.30	108.91	4062.7				
84.21	36.80	86.21	3173.0				
			7236				

The maximum allowed D_T for configurations 1 and 2 were 120 and 70 days respectively. The design D_T for APs observed between 2-4 for various concentrations of pollutant load considered in this study. As there were no BWs in the anaerobic pond, so, there was nothing to alter in it. It is here important to note that there are no clear instructions regarding D_T for distinct types (plug, dispersed and mixed flow) of flow conditions in the Turkish standards for WSPs. Table 4 shows that based on the analysis, the maximum allowed BOD_5, and fecal coliforms concentrations are 300 mg/l and 10^6 MPN/100 ml, respectively. At these concentrations, all of the Turkish design standards for WSPs and class-B effluent standards were satisfied without any alterations in the detention time. In some combinations, D_T was below the allowed limit given in Turkish standards for WSPs (Resmî Gazete, 27676), at concentrations lower than those mentioned above. It was also observed that the design and effluent standards could be met by manually adjusting the D_T of FPs. The same adjustment was possible in configurations 1 and 2, up to 350 mg/l and 10^7 MPN/100 ml, the concentrations of BOD_5 and fecal coliforms, respectively. Beyond this limit, alteration in D_T was only possible in configuration 1. In the other two configurations, either the class-B effluents standards of irrigation were not met, or D_T was higher than the allowed limit (Resmî Gazete, 27676). Following are some other observations of this study: 1. Achieving desired effluent result of fecal coliforms was also possible with the increased load of BOD_5, but this causes increased requirement of the area and D_T. 2. Although, there were some conditions when D_T in maturation ponds was within limits, but it went beyond the allowed limits for FPs. 3. Facultative ponds (Configuration 3) achieved fecal coliform removal in some cases but could not meet BOD_5 requirements in them.

Table 3. Sample Design Calculation for Configuration 3

Type of pond	N	LPCD	T_{avg} °C	$(BOD_5)_i$	N_i	d_p	Q_i
Facultative	950	179	8.9	200	1000000	1.5	170.05
Continue table							
O_L	% Removal of BOD_5	λs	V_p (m^3)	A_p (m^2)	D_T	$(BOD_5)_e$	Q_e
34.01	82.88	88.44	5768.50	3845.67	33.92	34.24	155.42
Continue table							
$(BOD_5)_e$ corrected by evaporation	BW Length (% × L)	X	d	a	K_t (d^{-1})	K_f	BWs
37.46	0.7	52.5	0.019	1.284	0.256	0.143	4
Continue table							
N_e	N_e corrected by evaporation	L-W ratio	Slope	W_{avg}	L_{avg}	W_{int}	L_{int}
494.34	540.86	3	2	35.80	107.41	34.30	105.91
Continue table							
W_{top}	L_{top}	A_{top}					
37.30	108.91	4062.74					

Table 4. Summary of Various Configurations and Arrangements at Various Influent Pollution Load

Configuration	**Baffle Wall Length**														
	0.5	**0.6**	**0.7**	**0.8**	**0.9**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**
	Fecal coliforms 10^6					Fecal coliforms 10^7					Fecal coliforms 10^8				
	BOD_5 200 mg/l														
1	PA (6)					PA (10)					PA (10)				
2	SAH	SM (4)				PA (8)					DTHAL			PA (8)	
3	BSNM					BSNM					BSNM				
	BOD_5 250 mg/l														
1	DTLAL					PA (10)					PA (10)				
2	PA (6)	PA (8)				PA (8)					DTHAL				
3	BSM					BSNM					BSNM				
	BOD_5 300 mg/l														
1	SM (2)	DTLAL				PA (10)					PA (10)				
2	PA (8)					PA (8)					DTHAL				
3	BSM					BSM					BSNM				
	BOD_5 350 mg/l														
1	PA (6)	PA (4)		PA (2)		PA (10)					PA (10)				
2	PA (8)					PA (8)					DTHAL				
3	BSM					BSM					BSM				

SM (BWs): Standards met (at a number of BWs) without alterations. **PA (BWs)**: Possible with an alteration (at a number of BWs). **BSNM:** Both standards were not met. **BSM:** BOD_5 standard was not met. **DTLAL:** Detention time is lower than the allowed limit. **DTHAL:** Detention time is Higher than the allowed limit.

The BOD_5 removal efficiency was above 95 % in configurations 1 and 2; however, in the case of configuration 3, it was around 80 %. The removal efficiency was similar to what (Araújo and Lima, 2019) achieved in their research. They achieved 70-90 % removal of the organic matter in primary facultative ponds. In the case of fecal coliform removal, the trend was the same, i.e., more reduction was observed in the first two configurations and less in the third configuration with a % removal of more than 99 %.

It is based on the discussion of the results and considering local factors such as temperature, light intensity, evaporation, precipitation, wind, etc. The suggested configuration is the one with the 3 ponds in series with 10^6 (MPN/100 ml) and 300 mg/l influent concentrations of fecal coliform and BOD_5 respectively. Moreover, it is to be noted that there were 2 BWs with their 50 % length when the standards were met. Beyond, the influent concentrations mentioned above, the application of WSPs was only with alterations in the D_T of FPs.

CONCLUSIONS AND RECOMMENDATIONS

This investigation will help the on-field engineers to variate the D_T of the ponds based on pollution load. The requirements of area and detention time of WSPs depend on the quality of effluent; the higher the quality needed, the higher the need for both. The recommendations based on this research for future works are: 1. As the variation in the number of BWs was done in even numbers, it is suggested that further research be conducted using BWs in odd numbers to get more concise results. Moreover, the variation of baffle wall length considered in this research is 0.1. It is suggested to perform the analysis with a 0.05 variation in length for more concise results. 2. A study can be conducted to know the effect of various pollution loads on dispersion factor. 3. A study can be conducted on a real-time existing treatment plant to compare the results achieved in this study and then scaled true. 4. Last but not least, a design optimization study must be done to minimize the volume of concrete and/or soil work needed to construct WSPs in the study area.

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Author Contributions

Hafiz Qasim Ali: Conceptualization, Data curation, Methodology, Formal analysis and interpretation, Writing original draft, Writing-review & editing.

Osman Üçüncü: Data curation, Supervision, Study design, Validation, Visualization, Writing-review & editing.

Conflict of Interest

The authors of this research declare no conflict of interest.

Appendix A (Supplementary Data)

Tables of basic design calculations and a summary of the results are available from the corresponding author upon reasonable request.

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