Design and Performance Evaluation of a Wastewater Treatment Unit

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Abstract

The design and performance evaluation of a model domestic wastewater treatment unit was carried out. The treatment unit was a Waste Stabilization Pond (WSP) comprised of one facultative pond, three maturation ponds, and a contact filtration unit, all in series. The effluent of the WSP, after filtration through clay media, had the BOD reduced to 15.4mg/l, from 356mg/L indicating a 95.67% removal level. A Faecal Coliform (FC) count of the influent sample gave $1 \times 10^8$ FC/100ml., whereas the effluent gave 9 FC/100ml, which was 99.99% FC removal. It was concluded that the effluent from the WSP is therefore suitable for discharge to the environment. It also met the requirement of 25mg/L BOD standard of Federal Environmental Protection Agency (FEPA). A rice husk filter media was found to be non-promising earlier in the removal process. The treatment system can be recommended to private/public estates in order to have a more environmentally friendly discharge of domestic wastewater.

Keywords: Biochemical Oxygen Demand, Waste Stabilization Pond, Faecal Coliform, Effluent. Clay media.

Introduction

As urban and industrial development increases, the quantity of waste generated also increases. These wastes pose a serious threat to public health when they are not readily disposed off. When these wastes are removed by water carriage system, they are termed wastewater. Wastewater is the used water or liquid waste of a community, which includes human and household waste together with street washings. Industrial waste and such ground and storm water may be mixed with it. The use of domestic wastewater for irrigation is advantageous for many reasons including water conservation, ease of disposal, nutrient utilization, and avoidance of surface water pollution. Nevertheless, it must be borne in mind that although the soil is an excellent adsorbent for most soluble pollutants, domestic wastewater must be treated before it can be used for crop irrigation to prevent the risk to both public and the environment.

This study aimed at designing and constructing a model waste stabilization pond and final contact filtration unit, for the treatment of influent domestic wastewater for environmentally friendlier discharge.

Overview of Waste Stabilization Ponds

The most appropriate wastewater treatment that could be applied before effluent discharge to a watercourse would be that which produced as effluent meeting the recommended microbiological and chemical quality guidelines both at low cost and with minimal operational and maintenance requirements (Arar 1988). Adopting as low a level of treatment as possible is especially desirable in developing countries, not only from the point of view of cost but also in acknowledgement of the difficulty of operating complex systems reliably. In many locations it would be better to design the reuse system to accept a low-grade of effluent rather than to rely on advanced treatment, which continuously meets a stringent quality standard. Waste stabilization
ponds (WSP) are now regarded as the method of first choice for treatment of wastewater in many parts of the world. In Europe, for example, WSP are very widely used for small rural communities (up to populations of about 2000, but large systems exist in Mediterranean France, and also in Spain and Portugal) (Bucksteeg 1987). However, in warmer climates (the Middle East, Africa, Asia and Latin America) ponds are commonly used for large populations (up to 1 million). In developing countries like Nigeria, and especially in the tropical and equatorial regions, wastewater treatment by WSP’s has been considered an ideal way of using natural processes to improve wastewater effluents. In natural treatment systems such as WSP, the pathogens are progressively removed along the pond series with the highest removal efficiency taking place in the maturation ponds (Mara et al. 1998).

Methodology

Experimental

The processes involved included the design and construction of a Waste Stabilization Pond, which is the cheapest and most efficient method used in the treatment of domestic wastewater in hot climates where sufficient land is available and where the temperature is most favorable for their operation.

Experimental Site

The study area was around Minna Niger state, Nigeria. It is located approximately 4°-14’ latitude and 3°-15’ longitude. The temperature averages around 32°C during the irrigation period. Rainfall start in April and Ends in October. The heat from the sun is pretty intense all year round but more during the dry season

Design Parameters

The most important parameter for facultative pond and maturation pond design are:

Temperature: The usual design temperature is the mean air temperature in the coldest month or period of irrigation. From data collected from the meteorological center in Minna Airport, the average coldest temperature was found to be 28.3°C.

Wastewater Flow Rate: A suitable flow design value is 80% of the in-house water consumption. This is dependent on population, per capital consumption. The population of the community used for the design was 1680 people.

From a questionnaire administered to the inhabitants, their daily water requirements were found to be 130L/day. Thus, the total quantity of water used by the community;

\[ Q_p = \text{population} \times \text{per capita used} \]
\[ = 1680 \times 130 \text{L/day} = 152,800 \text{litres/day} \]
\[ = 152.88 \text{m}^3/\text{day}. \]

Since 80% of the water consumed is given as the wastewater flow, therefore, \( Q, \) which is the daily wastewater flow = 122.30m³/day

Biochemical Oxygen Demand (BOD)

This is the amount of dissolved oxygen used by bacteria for the chemical oxidation of organic matter after a 5-day incubation period at 20°C. The BOD of the influent wastewater samples was determined by the BOD Track equipment at the Water Monitoring Control Laboratory of Federal Ministry of Water Resources located in Minna. The procedures used are as stated in Hach 2000 BOD Track manual.

Microbial Analysis of Wastewater

This analysis was done at the Microbiology Laboratory of Federal University of Technology Minna. The following tests were conducted.

Presumptive Test: This is the preliminary test of water sample. It gives an idea of water sample condition.

Confirmatory Test: This is the analysis to confirm the result obtained from preliminary
test. It involves the use of solid medium so as to know the colonial morphology of the microorganism isolated

**Completed Test:** This is the final analysis of sample. It involves grains morphology that explains the evolutionary trend of microorganism in a given sample. It is followed by series of biochemical test so as to know the name of microbial isolates and their pathogenicity; that is, disease-causing or not.

**Design of Facultative Pond**

The equation below can be used in determining the area of the facultative pond from (Mara 1998)

\[
A = \frac{Q}{DK_2} \left[ \frac{L_x}{L_x - 1} - \frac{L_y}{L_y - 1} \right] = \frac{Q}{DK_2} \left( \frac{L_x - L_y}{L_y} \right) \quad \ldots \quad 1
\]

The rate constant varies with temperature because it is temperature sensitive. This is described by Arrhenius equation of the form,

\[
K_T = K_{20} \theta^{T - 20} \quad \ldots \quad 2
\]

\[K_T\text{ and } K_{20} = \text{value of } K \text{ for } T = 20^\circ\text{C and } T = 20^\circ\text{C}\]

\[\theta = \text{Arrhenius constant which is usually between 1.01 and 1.09 for wastewater treatment process. But for waste stabilization ponds, } \theta \text{ is between 1.05 and 1.09.}\]

Using (Mara 1998) \(K_1\) for raw wastewater is 0.3d\(^{-1}\) and the value should be in the range 50 – 70 mg/L for pond depth of 1-1.5m.

Thus, \(K_1(T) = 0.3 (1.05)^{T-20} \quad \ldots \quad 3\)

Substituting equation 3 into 2

\[A = \frac{Q(L_y - 60)}{18D(1.05)^{T-20}} \quad \ldots \quad 4\]

\[A = \text{Area of the pond} \]
\[Q = \text{volumetric flow rate} = \text{Daily flow of wastewater which was determined as 122.30m}^3/\text{day} \]
\[D = \text{Depth of the pond which is 1.5m} \]
\[T = \text{Average temperature of the coldest month} \]
\[L_y = \text{BOD of the influent} \]
\[L_x = \text{BOD of the effluent} \]

\[\text{Area} = \frac{122.3 \times (356 - 60)}{18 \times 1.5 (1.05)^{28.3-20}} = 894.29m^2\]

**Detention time**

\[t = 10.96\text{days, } t \text{ was assumed to be } 11 \text{ days}\]

The length and breath ratio of a facultative pond is usually 3:1

Area of the pond=\(3x^2 = 894.29, x^2 = 894.29/3 =298.10m^2, x = (298.1m^2)^{1/2} =17.3m\)

Therefore, \(3x = 3x 17.3 = 51.9m\)

The dimensions of the ponds are therefore as follows,

Length = 51.9m, Breath = 17.3m, Depth = 1.5m

**Design of Maturation Pond**

**Design Consideration:**

1. The minimum acceptable value of \(t_m\) is 3days, below which the danger of hydraulic short-circuiting becomes too great. \(t_m = \text{detention time in maturation pond}.\)
2. The value for \(t_m\) should not be higher than that of \(t_f.\) \(t_f = \text{detention time in facultative pond}\)
3. The surface BOD loading on the first maturation pond does not exceed the surface BOD loading on the facultative pond.

**Bacterial Reduction:** The reduction of faecal bacteria in a pond whether anaerobic, facultative or maturation has been found first order kinetics, which is given by

\[N_e = \frac{N_i}{1 + K_b t_f} \quad \ldots \quad 4\]

\[N_e = \text{number of faecal coliform /100ml of effluent} \]
\[N_i = \text{number of faecal coliform/100ml of influent} \]
\[K_b = \text{first order rate constant for FC removal, d}^{-1}\]

For a system of facultative pond and \(n\) number of maturation ponds, equation 19 becomes

\[N_e = \frac{N_i}{(1 + K_b t_f) \left(1 + K_b t_m \right)} \quad \ldots \quad 4\]

Where,
\[t_f = \text{detention time in facultative pond} \]
\[t_m = \text{detention time in maturation pond} \]
\[n = \text{number of maturation pond} \]
\[N_i = 1 \times 10^8 \text{ FC/100ml, this is higher than average value normally found in practice} \]
\[t_f = 11\text{days} \]
From the design consideration, $t_f > t_m$, and $t_m \geq 3$ days. Thus, we assume, $t_m = 4$ days. Assume $n = 2$

$$K_b = 2.6 \times (1.19)^{T-20} = 2.6(1.19)^{28.3-20} = 11.02d^{-1}$$

$$N_e = \frac{1.0 \times 10^8}{[1 + (11.02 \times 11)][1 + (11.02 \times 4)]^{1/2}}$$

$$= \frac{1.0 \times 10^8}{(122.22)(2032.21)}$$

$$N_e = 402.61 \; FC \; / \; 100 \; ml$$

The value of $N_e$, signifies that the 2 maturations and 1 facultative pond will treat the domestic wastewater, and the effluent cannot be safely discharge into the environment.

Assuming $n = 3$

$$N_e = \frac{1.0 \times 10^8}{(122.22)(45.08)}$$

$$= 8.93 \; FC \; / \; 100 \; ml$$

The value of $N_e$ signifies effluent standard that is less than 100 FC/100 ml. Thus, 3 maturation ponds are satisfactory for the treatment of the community wastewater along with one facultative pond.

\[ 3 \times 35m = 105m = \text{Length} \]
\[ 3 \times 12m = 36m = \text{Breath} \]
\[ 3 \times 1.2m = 3.6m = \text{Depth} \]

**Modeling of Facultative and Maturation Ponds**

The daily flows of wastewater in the model were computed, using dimensional analysis, Froude number method.

By equating Froude numbers $Fr$:

$Fr_m = Fr_p$

Where, subscript $m$ and $p$ are models and prototype respectively,

$$Fr = \frac{V}{\sqrt{Lg}}$$

Where; $V$ = flow velocity, $L = \text{length}$ and $g = \text{acceleration due to gravity}$

Thus:

$$\left( \frac{V}{\sqrt{Lg}} \right)_m = \left( \frac{V}{\sqrt{Lg}} \right)_p$$

Since $g$ is a constant, then;

$$V_m = V_p \sqrt{Lg} \frac{L_m}{L_p}$$

Flow rate may be determined by introducing the area ratio,

$$A_m \times L_m = A_p \times L_p$$

(By dimensional analysis)

$$\frac{A_m}{A_p} = \left( \frac{L_m}{L_p} \right)^2 = \left( \frac{L_m}{L_p} \right)^2 = \left( \frac{1}{14} \right)^2$$

$$\frac{Q_m}{Q_p} = \frac{A_mV_m}{A_pV_p} = \frac{L_m^2}{L_p^2} \times \frac{L_m}{L_p}$$

Where $Q_m$ and $Q_p$ are the daily wastewater flow in the model and prototype respectively

$$Q_m = Q_p \left( \frac{L_m}{L_p} \right)^{1/2}$$

The model dimensions and flow rates were obtained for both the facultative and the maturation Ponds using the above equations and the results are tabulated in table1. The model ponds were then constructed and a performance evaluation conducted.

**Filter Media**

The filter media used is expanded clay. It was molded in a circular shape with an effective diameter of 10 to 15mm. The filter bed thickness is 1-1.5m.

**Filter Bottom**

Support of filtering materials and Provision of outlet and even extraction of filtered (effluents) were considered in the design.
Results and Discussion

The results of the biochemical oxygen demand (BOD) of the various samples after each stage of the treatment are represented below. Table 3 shows the result of the BOD analysis and it gives the BOD of the influent sample to be 356 mg/L which is higher than FEPA standard for effluent discharge of 25 mg/L. After the first stage of treatment, which is the facultative pond, the BOD reduced to 195 mg/L. The facultative pond was able to remove 45.2% of the BOD. The second stage of treatment which comprises three maturation ponds in series reduced the BOD to 32 mg/L. After filtration through the clay media the BOD was reduced to 15.4 mg/L. This is the final BOD of the treated wastewater which is less than the FEPA standard for irrigation water quality of ≤ 25 mg/L. The total percentage removal of BOD of the treatment process was 95.67%. From table 3, it can be seen that the calculated BOD from each stage of the treatment was less than the observed BOD. This is because the Ponds are assumed to be completely mixed reactors, that is, oxygen is constantly supplied to the pond at any point. But this is usually not the case with the waste stabilization pond that receives oxygen from the air that blows at the surface (Mara et al., 1998).

The result of the presumptive test, which is a preliminary test of the wastewater sample, gives an idea of the wastewater sample condition. It gave the most probable number of microorganism in 100ml of the sample to be 1,100. The result of the confirmatory test is the analysis to confirm the result obtained from preliminary test. The result showed that the Erosin methylene blue Algae, and the McConkey Algae were too numerous to be described. The completed test, which was the final analysis of the wastewater sample, involved the grain’s morphology that explains the evolutionary trend of microorganism in a given sample. The microbial analysis of the influent wastewater shows that coliforms were too numerous to count and the density of the colonies was too heavy to be counted. Completed test showed that the following microorganisms where isolated in the sample: E. Coli, Salmonella spp., Staphlococcus spp., Streptococcus spp., Khebsella spp., Pseudomonas aeroginosa, Bacillus spp.,

Conclusion

The result of the microbial analysis of the influent wastewater showed that the microorganism in the influent wastewater will be harmful to the downstream community if it is discharged without any treatment. The BOD result of the influent wastewater was 356 mg/L; which exceeded the FEPA standard of 25 mg/L for discharge to the environment. This necessitated the design and construction of a treatment system that is cheap and efficient—i.e., the waste stabilization pond (WSP). The result from the treatment process reduced the BOD to 15.4 mg/L and a significant reduction of the microorganism such as the faecal coliform. The effluent from the treatment process could be discharged to the downstream area without damaging the environment.

References

Arar A. 1988. Background to Treatment and Use of Sewage Effluent. Butterworths, Sevenoaks, Kent, UK.
Bucksteeg, K. 1987. German experiences with sewage treatment ponds. Water Science and Technology
Table 1. Prototypes and model dimensions and flow

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prototype facultative pond</th>
<th>Model pond</th>
<th>Prototype maturation pond</th>
<th>Model pond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area (m²)</td>
<td>894.29</td>
<td>0.805</td>
<td>407.67</td>
<td>0.985</td>
</tr>
<tr>
<td>Discharge (m³/s)</td>
<td>1.42x10⁻³</td>
<td>1.9x10⁻⁶</td>
<td>1.42x10⁻³</td>
<td>1.9x10⁻⁶</td>
</tr>
<tr>
<td>Detention time (days)</td>
<td>11</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Length (m)</td>
<td>51.9</td>
<td>1.5</td>
<td>35</td>
<td>1.2</td>
</tr>
<tr>
<td>Breath (m)</td>
<td>17.3</td>
<td>0.7</td>
<td>12</td>
<td>0.78</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>1.5</td>
<td>0.7</td>
<td>1.2</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 2. Result of BOD analysis

<table>
<thead>
<tr>
<th>Sample</th>
<th>Observed BOD (mg/L)</th>
<th>Calculated BOD (mg/L)</th>
<th>Observed percentage removal (%)</th>
<th>Calculated percentage removal (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent wastewater</td>
<td>356</td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Facultative pond effluent</td>
<td>195</td>
<td>137</td>
<td>45.2</td>
<td>61.5</td>
</tr>
<tr>
<td>Maturation pond effluent</td>
<td>32</td>
<td>18.3</td>
<td>83.6</td>
<td>90.6</td>
</tr>
<tr>
<td>Final filtration effluent</td>
<td>15.4</td>
<td></td>
<td>95.67</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig. 1. The designed waste stabilization pond in series with the contact filtration unit.