DESIGN OF FACULTATIVE PONDS FOR BOD_5 REMOVAL

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ABSTRACT

This paper discusses the removal of BOD_5 in facultative ponds under tropical conditions. Data was collected from pilot and field ponds at the University of Dar es Salaam and was compared to other ponds in Dar es Salaam. Results showed deviations of performance, in some cases, from assumptions made during design. Recommendations were made to improve the design procedure for ponds operating in Dar es Salaam, Tanzania.

INTRODUCTION

The construction of municipal waste stabilization ponds in Tanzania began 1960's as an attempt to reduce pollution. Waste stabilization ponds were considered relatively inexpensive and technically feasible. Their operation is not only simple and manageable with low skilled personnel, but they are relatively not sensitive to either hydraulic or organic shock loads (Mayo, 1989; Mayo and Gondwe, 1989). Nine ponds were built in Dar es Salaam and several others in six municipals and towns. Some industries, such as the large pulp and paper mill at Mufindi constructed aerated lagoons and maturation ponds, while Moshi municipal installed trickling filters in 1966. Unfortunately, due to lack of foreign currency for purchase of spare parts from abroad, the trickling filter system at Moshi municipal faced endless operational problems after operating for about 10 years.

By 1983, most of the pond systems in major towns were also filled with sludge because they were never emptied since their construction. The rehabilitation of these ponds began in mid-1980's. Following this exercise, the performance of some of these ponds was evaluated. The removal kinetics of coliforms in these ponds are detailed elsewhere

(Mayo, 1989; Mayo, 1992; Mayo, 1995a). Results of BOD_5 removal suggest that equations used during the design may be partly blamed for the unsatisfactory performance of the ponds, because designers did not take into account the local environmental conditions (Mogensen and Lundall, 1991). Gloyna (1971) and Marais and Shaw (1961) design criteria are among the equations widely adopted for design of waste stabilization ponds in Tanzania (Mogensen and Lundall, 1991; Njau, 1994). These design criteria are unsuitable for Lugalo ponds in Dar es Salaam (Mogensen and Lundall, 1991). The objectives of this work were to determine the efficiency of organic material removal and to propose design equations that may be used for design of waste stabilization ponds in Tanzania. Pilot ponds controlled at pre-determined hydraulic retention times and pond depths were constructed and operated at the University of Dar es Salaam in 1987/88. Pilot ponds were operated in three parallel sets, each with two ponds of equal surface area, pond depth, and hydraulic retention time. The only difference between the first set and second set was the pond depth meant to investigate the effect of pond depth, and that between the second set and third set was the hydraulic retention time for the investigation of the effect of hydraulic retention time. Data was also collected from University of Dar es Salaam field-scale ponds in 1989 and 1991. Comparison was made with data collected from Lugalo ponds (Humphrey, 1988).

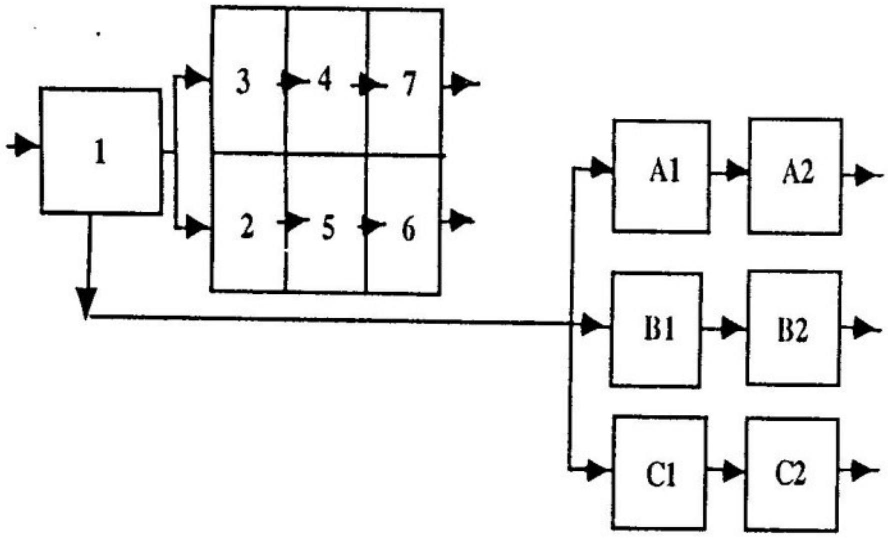
METHODOLOGY

Site description

The University of Dar es Salaam pond system is among nine pond systems constructed in Dar es Salaam where mean monthly temperature varies from 23°C to 28°C. Waste stabilization ponds at the University of Dar es Salaam were designed to serve about 5000 people. They consist of a primary pond and two series each of one facultative pond and two maturation ponds (Fig. 1a). All the ponds were lined with concrete slabs to prevent seepage and damage to the slopes against erosion. The University of Dar es Salaam ponds receive sewage from student and staff houses and cafeterias, but small proportion of wastewater is also received from the laboratories, workshops and a health center. The physical characteristics and hydraulic retention times for each unit are presented in

Table 1. The wastewater flows into the system by gravity. The University of Dar es Salaam field-scale ponds were designed for BOD_5 removal according to the first-order, complete mix approach.

Lugalo ponds consist of two 1.3 m deep facultative ponds in parallel, each of 10.1 d hydraulic retention time. Facultative ponds discharge their effluents into two maturation ponds in series, each 1.0 m deep. The hydraulic retention time in each maturation pond is 4.1 days.



(a) Field ponds (b) Pilot ponds

Fig. 1: Schematic diagram of pond systems at the University of Dar es Salaam.

The pilot ponds were constructed near the existing field-scale waste stabilization ponds at the University of Dar es Salaam. They consisted of six trapezoidal shaped cells, with physical characteristics shown in Table 1. These ponds (Fig. 1b), four of which were 1.0 m deep and two 1.5 m deep, have a surface area of 10.2 m^2 each. All cells were lined with 55 mm. cement sand slabs. The slabs were plastered and fine cement finish applied to reduce possibility of water leakage. Cells in series were interconnected by submerged 75 mm diameter plastic pipes. Wastewater to each set was added daily by a constant flow siphons from the primary field-scale pond. The influent flow rate was measured by a graduated cylinder and a stopwatch. The duration of influent application into each

Table 1. Physical characteristics and wastewater flows

Pond	A1,A2	B1,B2	C1,C2	1	2,3,4,5	6
Basin Volume (m^3)	6.74	4.48	4.48	6990	3070	1800
Mid pond surface area (m^2)	4	4	4	4065	2100	1425
Water depth (m)	1.5	1.0	1.0	1.82	1.51	1.22
Retention time (d)	11.2	11.2	5.6	8.3	7.3	4.3

series of ponds was calculated from the known pond volume, flow rate and the desired hydraulic retention time. All ponds were first inoculated with algae from maturation ponds. Sewage application was continued for about 40 days before sampling commenced.

Sample collection and examination

All samples were collected between 9.00 and 10.00 a.m. and were analyzed in accordance with Standard methods (1985). No effort was made to take composite samples because of labour constraints. Parameters analyzed were pH, dissolved oxygen, filtered and non-filtered five-day 20°C biochemical oxygen demand (BOD_5), and water temperature. Diurnal fluctuations of dissolved oxygen (DO), temperature and pH were monitored at the inlets and outlets. Dissolved oxygen was measured by a DO meter (Delta scientific, model 1010) and pH was measured by a pH meter (Hanna instruments, model HI 8424).

RESULTS AND DISCUSSION

Organic matter removal efficiency

Fig. 2 shows the BOD_5 removals in the University of Dar es Salaam pilot and field-scale ponds. In pilot scale ponds, BOD_5 removal efficiencies were 71.8%, 68.0% and 59.3% in series A, B and C, respectively. About 53% to 63% of organic matter was removed in the first cells. The University of Dar es Salaam field-scale ponds removed 88.5% of organic matter after 27.2 days of retention, about 48% of which was removed in the primary pond. In Lugalo ponds, Humphreys (1988) reported BOD_5 removal of 72.4% of which 67.9% was removed in the primary ponds. For the same organic loading rate, the mean BOD_5 removal efficiency was slightly better in deep ponds (series A) than in shallow ponds (series B). However, the difference was insignificant at 95% confidence interval. Moreover, observation in field scale ponds did not show the dependency of removal rate constant on the pond depth.

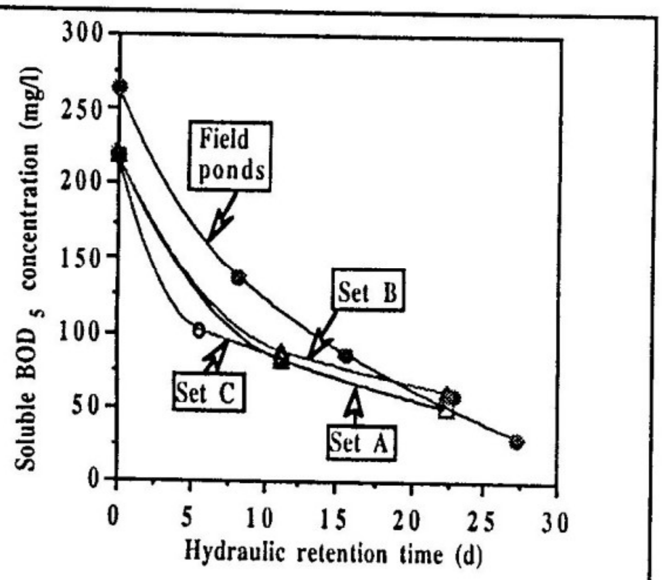


Fig. 2: Influence of hydraulic retention time on BOD removal.

Permissible organic loading rates

Permissible organic loading rate (λ) equations of facultative ponds found in literature are temperature-dependent. These permissible values vary from 305 to 700 kg/ha/d for the same design temperature of 26°C (Table 2), the minimum mean monthly water temperature in Dar es Salaam. This wide range of permissible organic loading rate suggests that in the absence of local data, these equations should be cautiously used. For instance, the University of Dar es Salaam primary pond was loaded at 542 kg BOD_5 /ha/d (range 455 to 579 kg/ha/d), but algae failed to grow. Dissolved oxygen at the pond water surface was consistently below 0.6 mg/l, indicating that primary pond was operating near complete anaerobic conditions. This pond became anaerobic although the loading rate was 25% less than the permissible organic loading rate of 700 kg/ha/d suggested by McGarry and Pescod (1970).

Table 2. Permissible organic loading rate, λ (kg BOD_5 /ha/d) for facultative ponds in literature

Equation	Source	λ for 26°C
$\lambda = 60.3(1.099)_T$	McGarry and Pescod (1970)	700
$\lambda=20T-120$	Mαρα (1974)	400
$\lambda=20T-60$	Arthur(1983)	460
$\lambda=350(1.107-0.002T)^{T-25}$ Valid for T>10°C	Mara(1987)	370
$\lambda=100$ for T<10°C $\lambda=10T$ for 10<T<20°C $\lambda=50(1.072)^T$ for T>20°C	Mara & Pesarson (1987). Based on WHO/EURO meeting recommendations and assumption that degradation doubles with every 10°C rise in temperature	305

Fig. 3 shows the influence of BOD_5 loading rate on the reaction rate. Each data point is an average of 8 samples taken from the same pond. As it can be seen from Fig. 3, that the maximum permissible loading rate is about 450 kg BOD_5/ha/d. This permissible loading rate is close to those proposed by Arthur (1983) and Mara (1974). To allow for a safety factor, the permissible loading rate proposed by Mara (1974) is recommended for design of ponds in Dar es Salaam.

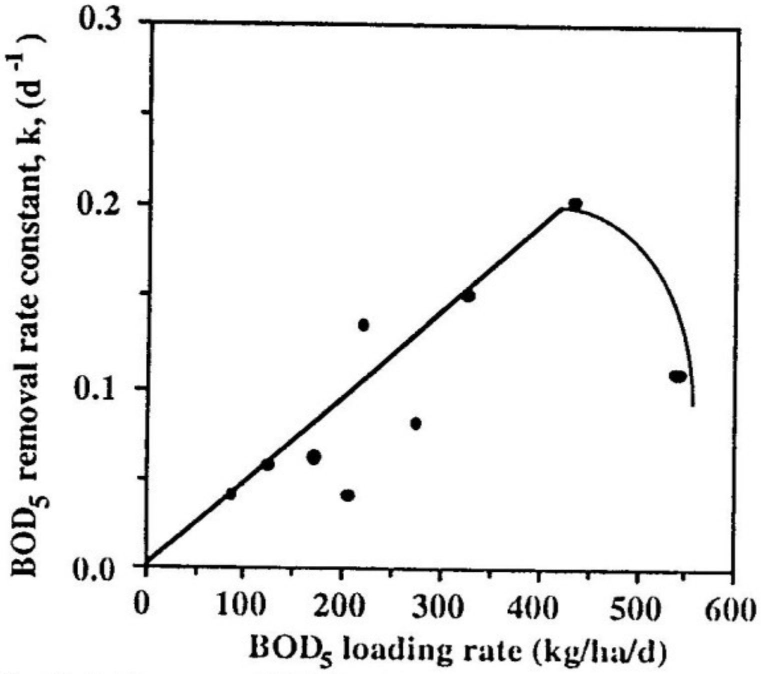


Fig. 3: Influence of BOD_5 loading rate on the reaction rate.

First order reaction rate constant

Marais and Shaw (1961) determined the first order BOD_5 removal rate constant, k, according to Equation (1).

$$k = \frac{1}{2}\left[\frac{L_i}{L_e} - 1\right] \quad (1)$$

where L_e is the effluent five-day biochemical oxygen demand, BOD_5 (mg/l), L_i is the influent five-day biochemical oxygen demand, BOD_5 (mg/l), and t is mean hydraulic retention time (d).

The degradation rate constant, k, in pilot and field-scale ponds ranged from 0.134 to 0.286 d^{-1}. The removal rate constant, k, can be estimated from Arrhenius expression [Eq. (2)]. Because of a limited temperature range at which the ponds in Dar es Salaam operate (26 to 32 °C), θ and k_{20} could not be evaluated. Mara (1974) proposed θ and k_{20} of 1.05 and 0.3 d^{-1}, respectively. Assuming these constants are valid for ponds in Tanzania, then the predicted k is 0.4 d^{-1} for the minimum mean monthly temperature, T, of 26°C in Dar es Salaam. This value was not observed in any pond.

$$k=k_{20}\theta^{(T-20)} \qquad (2)$$

If θ is assumed to be 1.05, then the observed k_{20} varies from 0.100~0.198 d^{-1}. This range is lower than 0.3 to 0.54 d^{-1} (Marais, 1970; Mara, 1974; Thirumurthi, 1979), but compares well with 0.103 to 0.234 d^{-1} (Ellis and Rodrigues, 1993; Siddiqi and Handa, 1971; Gomes de Sousa, 1987). It is considered reasonable to assume a θ value close to 1.00, since θ is known to vary between 1.00 and 1.02 for temperatures between 25 and 37°C (Novak, 1974; Varma and Nepal, 1972).

Influent BOD_5 concentration for design of ponds

Most of the pond systems were designed with an assumption that the influent BOD_5 concentration is 400 mg/l. Arthur (1983) also recommended a BOD_5 concentration of 350 mg/l for ponds in developing countries. These assumptions are far from reality because the observed influent BOD_5 concentration in four pond systems in Tanzania was between 80 and 280 mg/l (Mayo, 1988; Mayo, 1992; Masanja, 1991; Mogensen and Lundall, 1991; Ramadhan, 1992; Humphreys, 1988). The typical influent BOD_5 concentration is between 150 and 220 mg/l.

Model for design of ponds

The hypotheses behind the design procedures for facultative ponds may be divided into three principles: rational models based on first-order kinetics, semi-empirical models based on simplified theoretical concepts, and empirical models mostly based on areal loading rate. The model derived by Marais and Shaw (1961) has been widely applied in Tanzania for designing facultative ponds. In developing the model they assumed that BOD_5 removal follows first-order kinetics and ponds are completely mixed. In contrast to assumptions made by Marais and Shaw (1961), Thirumurthi (1969) proposed a dispersed flow model for prediction of BOD_5 removal rates in facultative ponds. In the absence of dispersion data, he suggested that removal of BOD_5 should be approximated by a plug flow model [Eq. (3)].

$$L_t = L_i e^{-kt} \tag{3}$$

where L_i is the initial (influent) BOD_5 concentration (mg/l), and L_t is the BOD_5 concentration (mg/l) at hydraulic retention time, t.

The experimental data from pilot and field ponds were used to test if the first-order kinetics hold. Only data collected from the University of Dar es Salaam field ponds followed first-order reaction (Fig. 4). A model described by Eq. (4) was satisfactorily followed by experimental data from pilot ponds at the University of Dar es Salaam ($R^2 = 0.979$) and Lugalo ponds ($R^2 = 0.995$).

$$-\frac{dL}{dt} = \frac{kL}{1+t} \tag{4}$$

Eq. (5) is obtained by integrating Eq. (4).

$$L_t = L_i(1+t)^{-k} \tag{5}$$

The degradation rate constants for pilot ponds at the University of Dar es Salaam and Lugalo ponds were 0.42 and 0.46 d^{-1}, respectively (Fig. 5). It is interesting to note that pilot and field ponds at the University of Dar es Salaam followed different kinetic models although they received wastewater of the same nature. It is possible that degradation kinetics are influenced by hydraulics of the pond system. Unlike pilot and Lugalo

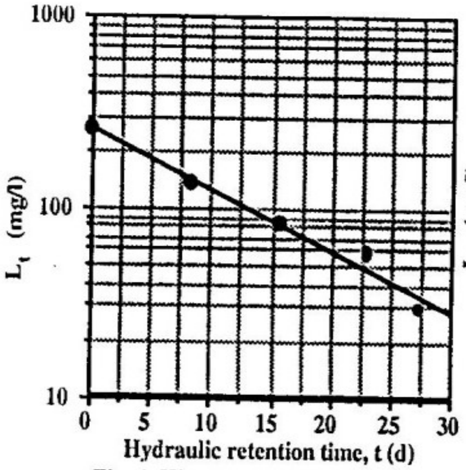


Fig. 4: Kinetic model for field ponds at the University of Dar es Salaam.

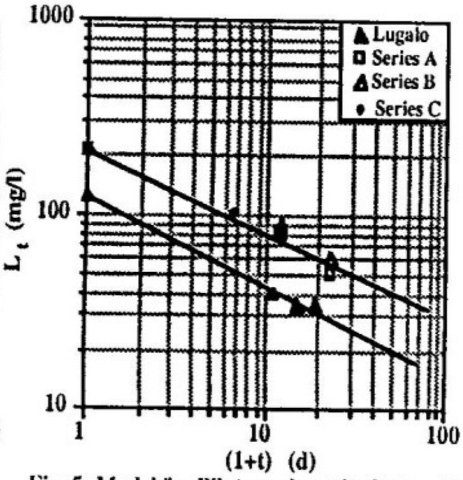


Fig. 5: Model for Pilot ponds at the University of Dar es Salaam and Lugalo pond.

ponds, the University of Dar es Salaam has more ponds in series, which increases the possibility of approaching a plug flow model. These models differ with the assumption made during the design.

Effect of BOD_5 loading rate on removal rate

Figure 6 shows that organic removal rate does not only depend on loading rate, but also on hydraulic retention time. This is contrary to McGarry and Pescod (1970) who concluded that hydraulic retention time have little influence on areal BOD_5 removal. The low removal rates in ponds with hydraulic retention times of 7.3 to 8.3 d is probably because these ponds were operating below optimum conditions, thus prematurely flushing out microorganisms responsible for degradation of organic matter. At 35°C, an optimum hydraulic retention time of 7.0 to 7.5 d was reported (Marais, 1966; Huang and Gloyna, 1968). Since the pond temperature was 28°C, the optimum hydraulic retention time for ponds in Dar es Salaam was estimated from Eq. (6) (Hermann and Gloyna, 1958) to be 12.4 to 13.3 d.

$$t_1 = t_o \, \theta^{(To-T)} \qquad (6)$$

where θ = 1.085 (Marais, 1966; Gloyna, 1971); t_o is the original time for reaction at an original temperature, T_o, and t_1 is the reaction time required at any temperature, T_1. From this analysis it seems that ponds with hydraulic retention times of 7.3 to 8.3 d were operating below the optimum hydraulic retention time and may therefore be expected to produce lower BOD_5 removal rates.

The performance of waste stabilization ponds was evaluated using empirical model proposed by McGarry and Pescod (1970), who reported a linear relationship between areal organic loading rate, L_o, and areal organic removal rate, L_r [Eq. (7)].

$$L_r = 10.37 + 0.725 L_o \qquad (7)$$

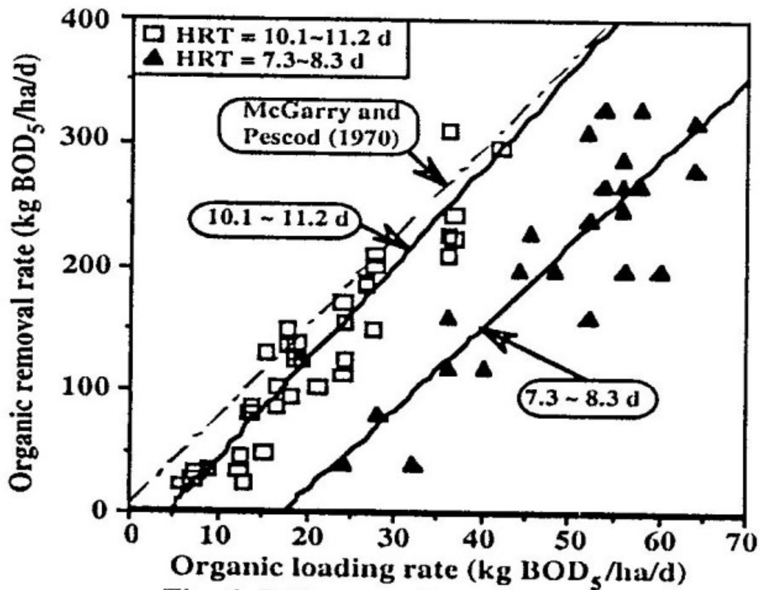


Fig. 6: Influence of hydraulic retention time on BOD_5 removal efficiency.

This equation was reported to be valid for any loading between 34 and 560 kg BOD_5 /ha/d, which was comparable to loading rates for ponds in Dar es Salaam (55 to 640 kg BOD_5 /ha/d). Eq. (7) was tested using data from pilot and field-scale ponds (Fig. 6). Most of the data deviated from a model proposed by McGarry and Pescod (1970), but deviation was more pronounced with decreasing hydraulic retention time. The best line of fit for two sets of hydraulic retention time is given by Eq. (8a) and (8b).

For HRT = 10.1 to 11.2 d $L_r = 0.788\ L_o - 33.12$ (R = 0.94) (8a)

For HRT = 7.3 to 8.3 d $L_r = 0.672\ L_o - 115.53$ (R = 0.88) (8b)

To improve the model for prediction of the removal of organic material, it was necessary to incorporate the effect of hydraulic retention time in the model. This was done by averaging the removal rate by hydraulic retention time. A good fit was obtained (R = 0.925) from the plot of BOD_5 loading rate on retention time averaged BOD_5 removal rate (Fig. 7). Eq. (9) shows the model that can be used to predict BOD_5 removal rate.

$$\frac{L_r}{t} = 0.062 L_o - 1.6 \tag{9}$$

Eq. (9) suggests that removal of organic material stops when organic loading rate falls below 25.8 kg BOD_5/ha/d. The residue BOD_5 is probably due to regeneration of soluble material from dead microorganisms. Using the surface area, wastewater flow rate and hydraulic retention time of the University of Dar es Salaam ponds, the residue BOD_5 concentration in the final effluent of 38 mg/l was predicted. This concentration agrees well with the observed mean effluent quality of 30 mg/l (range 20 ~ 40 mg/l). The effluent quality of 28 mg/l (range 15 ~ 42 mg/l) for Lugalo ponds (Mogensen and Lundall; 1991) also agrees well with the predicted residue BOD_5 concentration of 18 mg/l for these ponds. This means prolonged incubation in Lugalo and University of Dar es Salaam ponds may not improve the quality of the final effluent.

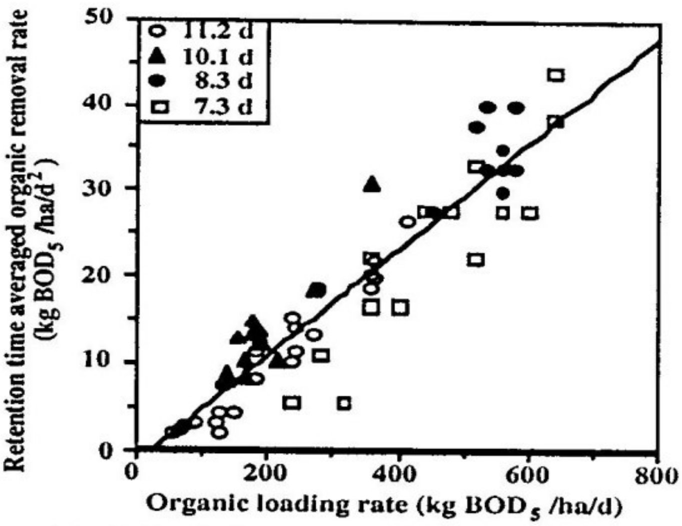


Fig. 7: Prediction of BOD_5 removal rate from the organic loading rate and hydraulic retention time.

Suspended solids in effluent

Although waste stabilization ponds provide an effective and economical method of wastewater treatment, the effluents contain high concentration of algae, which cause eutrophication problems in receiving waters. As previously mentioned, the effluent mean soluble BOD_5 concentration in Lugalo and the University of Dar es Salaam ponds was 28 and 30 mg/l, respectively. These concentrations meet the temporary Tanzanian standards for effluents discharged to receiving waters. Unfortunately, algae in effluents increase the total BOD_5 concentration considerably. Data from pilot ponds indicate that suspended solids increase BOD_5 concentration by 160 to 240% (Table 3), and the suspended solid concentration is expected to increase as incubation time is prolonged (Mayo and Noike, 1993; Mayo, 1995b). Comparison of data from series B (1.0 m depth) and series A (1.5 m depth) suggest that pond depth did not have influence on the particulate BOD_5 concentration (Table 3).

Since the outlet design consist of open channels, they enhance algal washout because algae grows in the top 30 cm of the wastewater body. Nevertheless, removal of suspended solids by sand and/or rock filters is considered necessary for improvement of the final effluent quality. At the moment, algae separation from the effluents is not done in any pond system in Tanzania.

Table 3. Proportion of soluble and particulate matter in the final effluent of pilot ponds.

Pond	Total BOD_5 in the effluent (mg/l)	Soluble BOD_5 in the effluent (mg/l)	%	Particulate BOD_5 in the effluent (mg/l)	%
Series A	152	63	41.7	88	58.3
Series B	160	70	43.7	90	56.3
Series C	148	93	62.8	55	37.2

CONCLUSIONS

From the findings of this work, the following conclusions are made:

(i) The permissible organic loading rate was 450 kg BOD_5/ha/d. To allow for a safety factor, a loading rate of 400 kg BOD_5/ha/d was recommended for design of facultative ponds in Tanzania.

(ii) BOD_5 removal rate was not only dependent on the BOD_5 loading rate, but also on hydraulic retention time. The following equation was recommended for prediction of BOD_5 removal rate:

$$\frac{L_r}{t} = 0.062L_o - 1.6$$

(iii) Improvement of outlet structures is recommended. It is also recommended to remove algae from the final effluent to prevent receiving waters from pollution.

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