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Biochemical oxygen demand (BOD) rate constant for the microbial rock plant filter (MRPF) located at Benton, Louisiana was evaluated based on field data. Longitudinal dispersion was estimated at this full-scale treatment system by conducting a tracer test using lithium chloride (LiCl2). The observed reactor behavior agreed with the classical first-order dispersed plug-flow model, thus showing that longitudinal dispersion cannot be neglected as is normally done in designing MRPFs.
Key words: subsurface flow (SF) constructed wetlands, microbial rock plant filters (MRPFs), BOD reaction kinetics, dispersed plug fort

INTRODUCTION

Microbial Rock Plant Filters (MRPFs) consist of filter media, vegetation, and microorganisms, with each entity performing a set of functions in the treatment of wastewater. The nutrient supply to the emergent vegetation is from the wastewater flowing through the filter media. Physical, chemical and biological removal mechanisms are believed to be responsible for the treatment of the wastewater (TVA, 1991; U.S. EPA, 1988; 1993'; Kura, 1994).

Wastewater treatment using MRPFs has been considered by some to be an application of hydroponics which is defined as the growing of plants in a nutrient solution without soil, also termed "soilless agriculture" (Jones and Wolverton, 1990). However, from a practical standpoint, MRPFs are indistinguishable from subsurface flow constructed wetlands of the "rock-reed-filter" type (U.S. EPA, 1988, 1993'). A schematic of the MRPF at Benton is shown in Figure 1.

MRPFs arc very attractive for small to medium size communities. They can reduce 5-day biochemical oxygen demand (BODS) from septic tank and oxidation lagoon effluents from 50-110 mg/1 to 210 mg/l in 24 to 48 hours (Jones and Wolverton, 1990). Some of the advantages of the MRPF over conventional systems cited in the literature are: reduced capital, operation and maintenance costs; less sophisticated to operate; natural disinfection; and high BOD5 and total suspended solids (TSS) reduction. However, a major problem observed at existing facilities built in the United States is a lack of consistency in effluent quality. In most cases this can be attributed to improper hydraulic design and incorrect geometry rather than to the process itself (U.S. EPA, 1993").

One of the disadvantages of this treatment process appears to be a lack of consensus regarding design, construction, and operation methodology (Reed and Brown, 1992). A first-order plug-flow model for BOD removal, described in Equation 1 (U.S. EPA, 1993'), has been used by a number of engineers for the design of these systems in the United States, Europe, and Australia (U.S. EPA, 1993').

$$C_e / C_0 = e^{-K_1 \bar{t}} \qquad (1)$$

where
C_e = Effluent BOD_5 concentration, mg/l
C_0 = Influent BOD_5 concentration, mg/l
K_1 = First-order BOD_5 decay constant, d^{-1}
$\bar{t}$ = Mean hydraulic retention time (HRT), d.

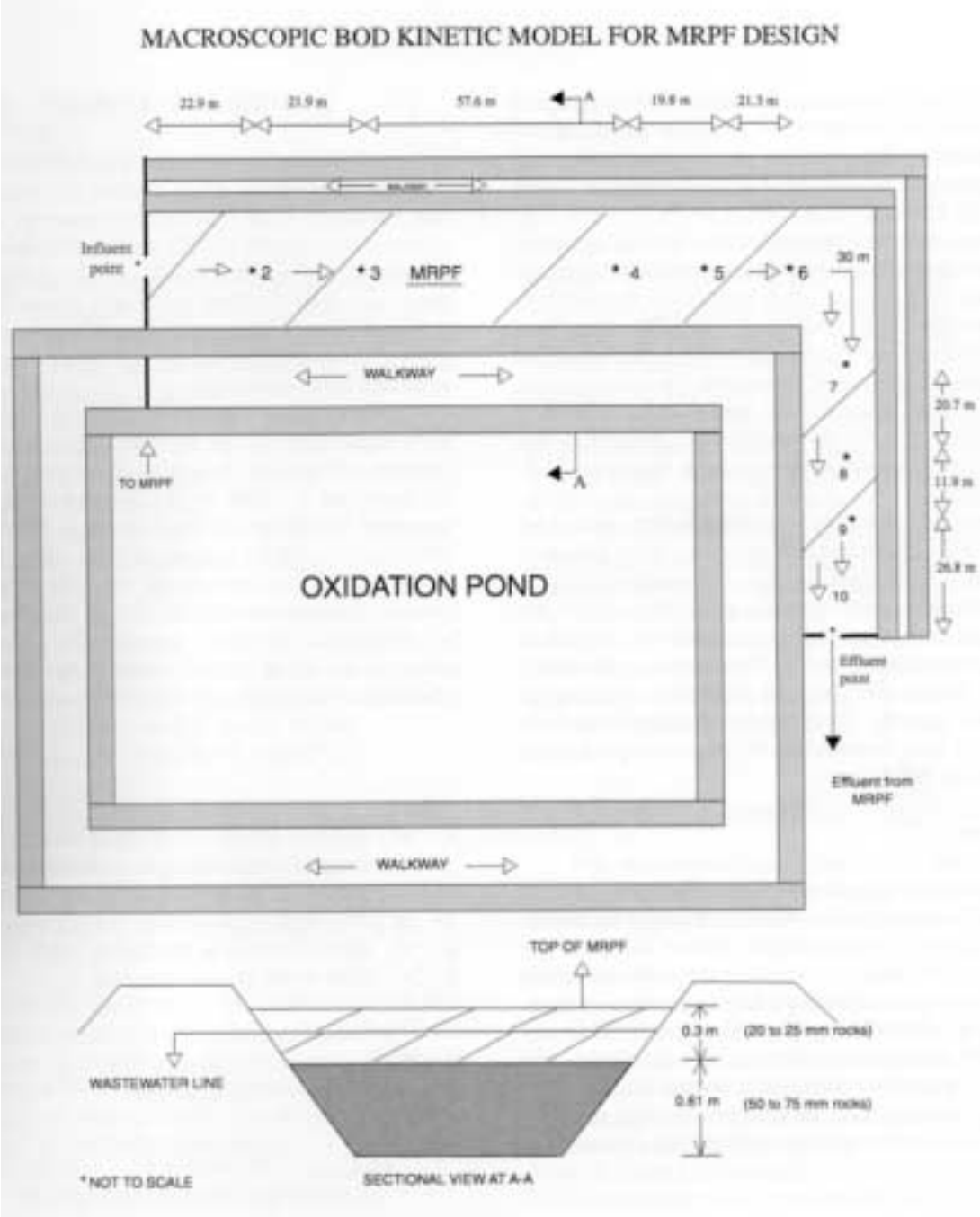

Figure I . MRPF at Benton, Louisiana

The plug-flow assumption is usually based on the fact that MRPFs are relatively long structures, with approximate length-to-width ratios ranging from 4:1 and 17:1. Wastewater is applied at the influent end and flows by gravity along the reactor length. The plug-flow reactor behavior has not been demonstrated by tracer tests and the first-order kinetic model has not been validated by longitudinal BOD5 concentration profiles measured along the reactor length. Most of the available information on the performance of existing **MRPF units** corresponds to input and output BOD5 data from a limited number of systems.

In MRPFs the wastewater is applied only at one end: therefore, the organic loading, in terms of kg BOD5/m2.d, is higher for the initial sections of the filter. Due to the porous nature of this reactor, most of the solids and settleable BOD are removed in the initial few meters of the filter length. Concurrently, additional BOD is being produced from decomposing

plant detritus. Consequently, the combined removal of settleable and dissolved BOD and its simultaneous generation by the growing plants complicates the development of an accurate and precise design model for BOD5 removal (U.S. EPA, 1993`).

It has been well recognized by several agencies that more research is needed to understand the kinetic behavior of these systems before an appropriate design model can be developed. The EPA's document titled "Subsurface Flow Constructed Wetlands for Wastewater Treatment" states that the development of the ultimate design model must Nvait for collection of a sufficient body of reliable data describing the internal performance within these systems (U.S. EPA, 1993').

The environmental conditions for microbial activity in MRPF treatment systems are not the same along the filter length. A few examples of variable environmental conditions along the filter length are density of semi-aquatic plants, density of subsurface root system growth, nutrient concentration, dissolved oxygen, and surface area of plant root systems for microbial growth. The research described herein is a first step in understanding the macroscopic kinetic behavior of MRPFs.

Objective

The overall objective of this study was to develop an understanding of the MRPF system performance and to study its macroscopic kinetic behavior by collecting field data in an existing full-scale treatment unit. One way of adjusting a kinetic model to a plugtlow type reactor is by observing the BOD decay along the reactor length, and by identifying the possible deviations from ideal reactor behavior by means of a tracer test. To achieve this objective, the project methodology was planned as described below:

- Perform a tracer test to determine if the plug-assumption normally made in MRPF design can be verified.
- Measure the wastewater total BOD5 along the length of the MRPF at Benton, LA, through field sampling and laboratory analysis.
- Fit a macroscopic kinetic model to the observed total BOD5 data to determine the rate constant.

The results discussed in later sections show that a first-order dispersed plug flow model is more appropriate than the classical ideal first-order plug flow reactor (PFR) model to design these MRPF systems.

BOD REMOVAL MODEL

As indicated before, the physical removal of BOD is believed to occur rapidly through settling and entrapment of particulate matter in the void spaces in the gravel or rock media. Soluble BOD is removed by microbes on the media surfaces and those attached to plant roots and rhizomes penetrating the bed. Plant roots provide aerobic micro sites but the remainder of the filter bed can be expected to be anaerobic.

Most of these systems in the U.S. and Europe have been designed as attached growth biological reactors using a first-order plug flow model as given by Equation 1. This model appears to be widely accepted for design of these systems (EPA, 1988, 19933; TVA, 1991; Cooper, 1990). However, no longitudinal concentration profiles have been presented to support the validity of this model.

The basic continuity equation for a first-order reaction occurring in a dispersed plug-flow reactor under steady-state conditions is (Levenspiel, 1972):

$$U(dC/dx) - D\,(d^2C/dx^2) + k_1 C = 0 \qquad (2)$$

where

U = average longitudinal liquid velocity, m/s
x = longitudinal distance measured from the reactor inlet, m
D = longitudinal dispersion coefficient, m^2/s
C = concentration in the liquid, mg/l
k_1 = first-order kinetic constant, d^{-1}.

The boundary conditions applicable to the MRPF are those corresponding to a closed-closed reactor (Wen and Fan, 1975), which are:

$$UC\big|_{x\to 0^+} - UC_i = D\left.\frac{dC}{dx}\right|_{x\to 0^+} \quad \text{at } x = 0 \qquad (3)$$

$$dC/dx = 0 \text{ at } x = L \qquad (4)$$

where L = distance at which C = 0.

Equation 4 reflects the fact that in the MRPF at Benton, LA, the BOD removal reaction was complete at a distance L from the origin. Thus, no further BOD removal was observed beyond the distance L.

The solution of Equation 2 subject to the boundary conditions indicated by Equations 3 and 4 was originally presented by Wehner and Wilhelm in 1956, and is given below:

$$\frac{C}{C_i} = \frac{2\left[\exp\left(\frac{Pe}{2}\right)z\right]\left\{(1+a)\exp\left[\left(\frac{Pe}{2}\right)a(1-z)\right]-(1-a)\exp\left[\left(\frac{Pe}{2}\right)a(z-1)\right]\right\}}{(1+a)^2\exp\left(\frac{Pe}{2}a\right)-(1-a)^2\exp\left(-\frac{Pe}{2}a\right)} \quad (5)$$

In the above equation, C, is the concentration of the reactor feed stream, z is the dimensionless abscissa, x/L, L is the reactor length, Pe is the Peclet number given by the ratio UL/D, and the dimensionless number `a' is given by:

$$a = \sqrt{1+\frac{4k_1\bar{t}}{Pe}}$$

where t is the mean hydraulic retention time.

The value of the BOD concentration at x = 0 (C(,) inside the reactor, under the influence of dispersion, will be lower than the BOD concentration in the influent stream (C,). Its value is given by Equation 7 (Wehner and Wilhelm, 1956):

$$C_0 = \frac{2C_i}{(1+a)\exp\left(\frac{Pe}{2}a\right)-(1-a)\exp\left(-\frac{Pe}{2}a\right)}{(1+a)^2\exp\left(\frac{Pe}{2}a\right)-(1-a)^2\exp\left(-\frac{Pe}{2}a\right)} \quad (7)$$

To test the applicability of Equation 5, it is first necessary to measure the single parameter of the model, i.e., the Peclet number, by means of a tracer test. Next, a BOD longitudinal concentration profile is needed to determine if it matches the profile predicted by the dispersion model.

MATERIALS AND METHODS

The research program included the field monitoring work at the MRPF located in Benton, LA. At this MRPR wastewater is first treated in an oxidation pond and then passed through the MRPF for polishing prior to final disposal.

Site Description

The town of Benton, Louisiana is located in Bossier Parish on the east bank of the Red River, twelve miles north of Bossier City, Louisiana. The estimated design average dry weather wastewater flow is approximately 284 m;/d, generated by 2030 people. The MRPF unit was built in 1955, and has been operated continuously during this period. However, as demonstrated by the tracer test, the operator sends just a fraction of the entire flow rate generated by the 2030 people through the MRPF

As shown in Figure 1, the plan layout of this unit is L-shaped, 233.4 m long, 16.7 m wide, and 0.91 m deep. Although a hydraulic retention time of 24 hours was given by the Benton treatment plant staff, the EPA 1993 Guidance for Design and Construction of a Subsurface Flow Constructed Wetland shows a design holding time of 2.1 days. The types of plants used for the Benton filter are bulrush, soft rush, canna lilly, and arrowhead. The filter media consists of limestone, granite or concrete aggregate. The media size ranges from 50 to 75 mm for the bottom rocks, to 20 to 25 mm for the top media.

Field Monitoring Program

For wastewater characterization, three sets of data were generated to characterize the wastewater at ten sampling locations as described in Table 1.

Tracer Study

As indicated above, to test if the plug-flow assumption can be justified in designing MRPFs, a pulse-input tracer study was conducted using a lithium chloride solution as a tracer. An automatic continuous sampler was used to collect the samples every 2 hours for a period of 2.5 days. The duration of the sampling period was estimated based on the theoretical detention time. The sampler was capable of collecting 30 sequential, discrete samples and was programmable for delaying the collection of the first sample. The continuous sampler was set up at the

m'd I

I -point of the filter. The samples were acidified on the site with nitric acid to lower the pH to a value below 2 to keep lithium in dissolved form. Samples were collected over a three day period and the lithium analysis was conducted on the fourth day. The analysis was performed to measure lithium concentration using an Atomic Absorption Spectrophotometer using the technique described in SW846, Method 7430(6), of Standard Methods. The

Table 1. Sampling Points at MPPF, Benton

Sampling points	Distance from the inlet, m
Point 1 (Influent)	0
Point 2	22.9
Point 3	44.8
Point 4	102.4
Point 5	122.2
Point 6	143.5
Point 7	174.0
Point 8	194.7
Point 9	206.6
Point 10 (Effluent)	233.4

* The sampling points were located along the reactor center line

Total BOD5

To collect wastewater samples at each sampling point, cast iron pipes with pointed ends at the bottom were driven into the filter bed. Openings of 38 x 6 mm were made on the bottom length of the pipe at a suitable height to allow wastewater to flow into the pipe from the total depth of wastewater in the filter. A manual suction pump was used to collect the wastewater samples. At each location, samples were collected for total BOD5 analysis. The analytical procedure described in Method 5210 of Standard Methods for the Examination of Water and Wastewater was used.

RESULTS AND DISCUSSION

The hydraulic retention time was calculated based on the lithium concentration profile obtained in the samples collected at the filter mid-point at various time intervals after the application of lithium chloride at the influent point of the MRPF. A background concentration of 13.18 mg/1 of Li was detected; therefore, this figure was subtracted from all the tracer readings. A plot of the net lithium concentration as a function of time is presented in Figure 2. Unfortunately, due to difficulties experienced with the automatic sampler, it was not possible to continue the sampling for a time sufficiently long to define the tail of the tracer curve, and sampling was terminated after 55 hours. To prevent a distortion of the dispersion coefficient that would result by cutting off the tracer curve at 55 hours, the authors decided to extrapolate the tail of the curve using a semi-log plot as shown in Figure 2 by the dotted line;

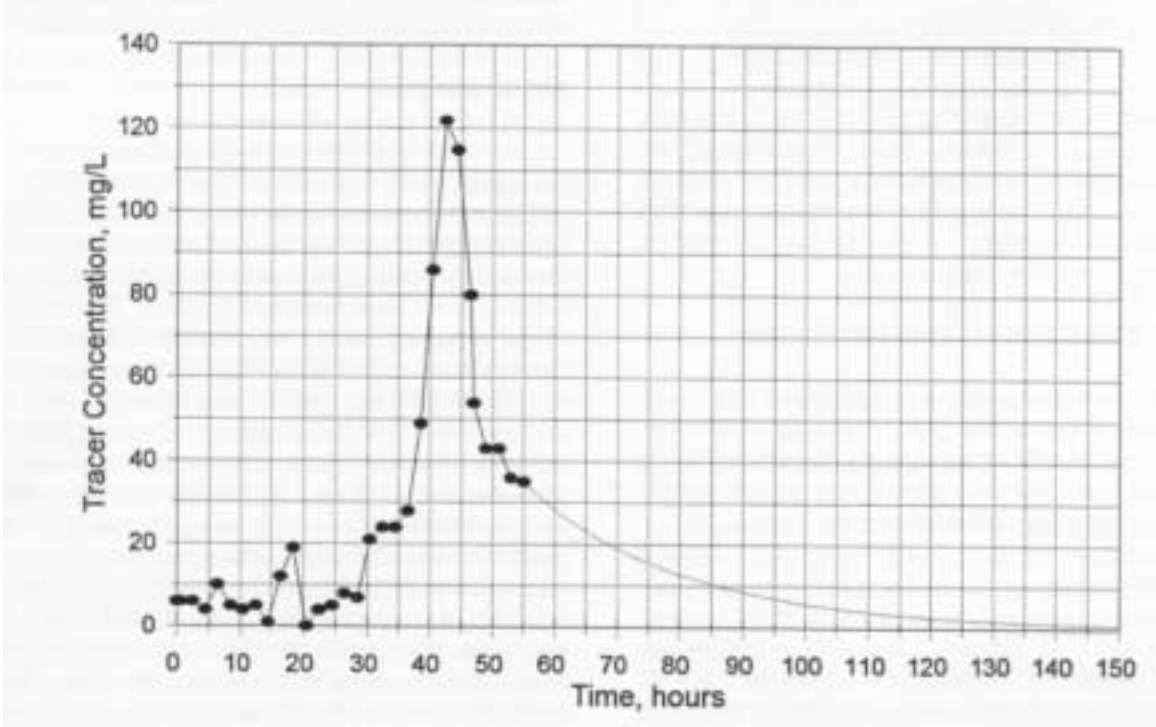

Figure 2. Tracer Curve

this extrapolation would provide a better approximation to the real value of dispersion in the reactor.

Calculations of the mean hydraulic retention time (t) and the variance (6 `) based on the data presented in Figure 2, which correspond to one-half of the reactor, give values of t = 53.69 hours and $c7_2$ = 589.51 h-. Since there was no visual difference between the first and the second halves of the reactor, it was assumed the filter packing is the same throughout its length; therefore, the total HRT in the system, at the time the tracer test was performed, would be 107.38 hours (4.47 days). Based on the total mass of the tracer used (3175.2 g), the liquid flow rate is 0.362 Us, much lower than the average design flow, and the longitudinal velocity is 2.17 m/h. Based on the wine tracer data, the useful volume was calculated to be 70 m`, which is a fraction of the total MRPF volume (2960 m'). Obviously, at the time of the experiment, the flow rate through the unit was much smaller, at least ten times smaller, than the one generated by 2030 people. The rest of it was being held at the stabilization pond.

Using the variance matching procedure described by Levenspiel (1972), the Peclet number. Pe, was found to be 8.65. According to the same author, since Pe < 100, the case being analyzed would correspond to a plug-flow reactor with a large degree of dispersion.

Therefore, it can be stated that during the time of the experiments the MRPF at Benton, LA, was performing far from an ideal PFR, with a dispersion coefficient of 29.35 m` /h. Under the hypothesis that the dispersion coefficient in **MRPFs** would depend on factors such as bed porosity, particle shape, depth of flow, geometric characteristics of the unit and others, it is unlikely that this coefficient would remain constant if the flow rate through the unit were increased to the total value being generated by 2030 people (3.3 L/s). This hypothesis, however, would have to be tested by performing tracer experiments on several existing MRPFs; these additional tests would allow development of predictive correlations for the dispersion coefficient that could later be used for design applications.

As an alternative to the dispersion model presented herein the tanks-in-series model, described by Levenspiel (1972), could also be used. This method uses the variance matching procedure to determine the number of identical completely mixed tanks in series that would reproduce the tracer curve observed in actual experiments. Both the dispersed plug-flow model and the tanks-in-series model are equivalent. In fact, Bailey and Ollis show that if the Pectlet number is greater than 4, the key parameters of the two models are related by the following relationship:

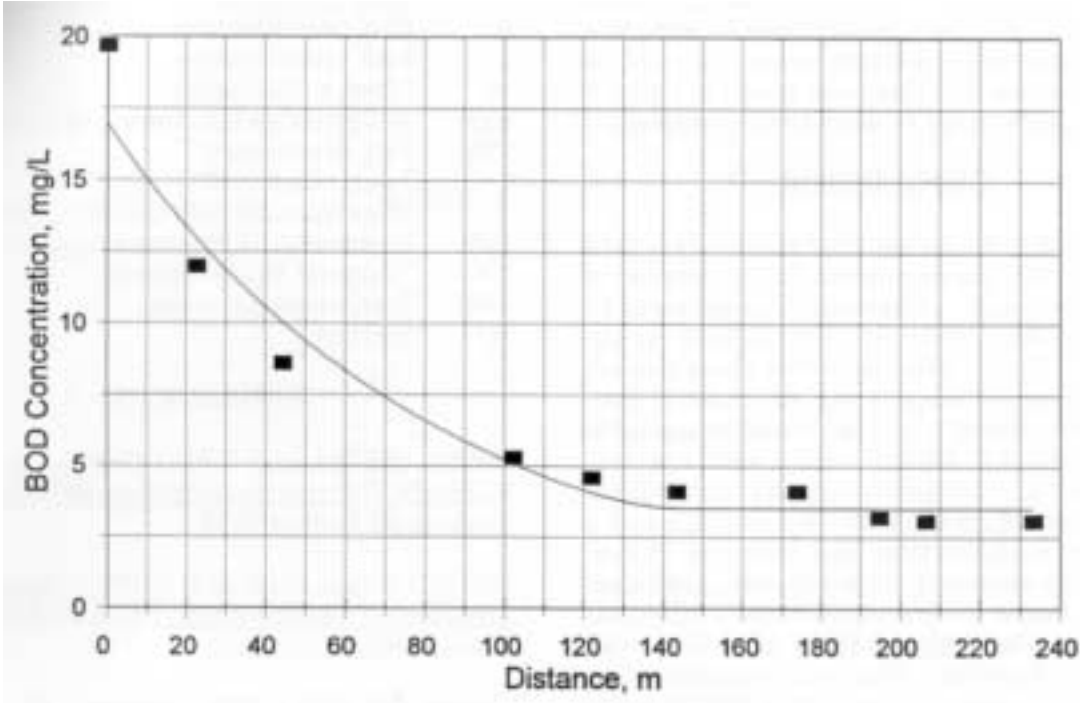

Figure 3. Dispersion Model. D = 29.35 m^2/h, k = 0.0298 h^{-1}

$$\frac{1}{N} = \frac{2}{Pe}\left(1 - \frac{1}{Pe}\right) \quad (8)$$

where N is the number of identical tanks in series.

Using Equation 8, the number of identical completely mixed tanks connected in series that could be used to model the observed behavior of the Benton, LA MRPF at the time of the tracer test is 9.78, i.e., approximately 10 tanks.

Macroscopic Reaction Rate Constant

Based on the assumption that the MRPF being analyzed can reasonably be represented by a dispersed plug-flow reactor, the following procedure was used to determine the first-order kinetic constant, k,. First, a simple inspection of the data shown in Figure 3 shows that no significant change in the total 130D remaining could be observed after the sixth sampling point, located 143.5 m from the reactor origin. Therefore, the value of L in Equation 5 is 143.5. According to this equation the reaction ends at this abscissa and the BOD concentration is constant beyond this point. Using this value as a fixed point and a dispersion coefficient of 29.35 m2 h, computed from the tracer test, a value of k, = (_1.0298 h-' provides the best fit of the model to the experimental data points. Figure 3 shows that, as predicted by Equation 7, the concentration of BOD at x = 0 inside the reactor is lower than the respective concentration in the influent stream. It must be emphasized that each data point shown in Figure 3 represents the average of three different readings.

CONCLUSIONS

Because of the multitude of reactions involved in MRPFs that are responsible for the removal of BOD from sewage, a macroscopic model based on the performance observed in the field is recommended. The longitudinal BOD concentration profiles measured suggest that the classical firstorder BOD removal model can indeed be applied to the Benton, LA MRPF, with a rate constant k,=0.0298 h'. However, contrary to the usual assumption of ideal PFRs, this unit showed a significant deviation from ideal behavior. In fact, based on the magnitude of the dispersion coefficient found by means of the tracer test (29.35 M2 /h), this system can be categorized as plug flow with significant dispersion. Whether this conclusion can be made applicable to other existing MRPFs has to be demonstrated by performing the respective tracer tests. If axial dispersion were found to be a general characteristic of MRPFs, a model would have to be developed to predict the dispersion coefficient as a function of design parameters such as particle size, porosity, particle shape, depth of flow, geometric characteristics and other factors to take dispersion into consideration while designing these units. Otherwise, the reactor volume computed based on the ideal plug-flow assumption would be smaller than the one actually needed, and the reactor performance would be below the design expectations.

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NOMENCLATURE

BOD	Biochemical oxygen demand
BOD_5	5-Day Biochemical oxygen demand
C_e	Effluent BOD_5
C_o	Influent BOD_5
d	Day, unit of time
mg	milligram, unit of mass
MRPF	Microbial Rock Plant Filter
h	Hour, unit of time
HRT	Hydraulic retention time
K_t	Temperature dependent first-order BOD removal reaction rate constant, d^{-1}
k_1	First-order kinetic constant, d^{-1}
l	Liter, unit of volume
m	Meter, unit of length
mg/l	Milligrams per liter, measure of concentration
PFR	Plug flow reactor
t	Temperature in °C
$\bar{t}$	Mean hydraulic retention time (HRT)
EPA	Environmental Protection Agency
TVA	Tennessee Valley Authority
TSS	Total suspended solids
σ^2	Variance

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