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AMMONIA AND BOD REMOVAL MODEL FOR A CONSTRUCTED WATER HYACINTH TREATMENT SYSTEM

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ABSTRACT

A pilot scale water hyacinth treatment system was constructed near a small Alabama town to investigate the feasibility of using this type of process as a low cost, easily implementable alternative for upgrading small community wastewater treatment systems in southern states. Design equations have been developed based on a series of multiple regression analyses using experimental data obtained from harvested and non-harvested treatment trains. The best predictive equations for effluent five-day biochemical oxygen demand concentration and effluent ammonia-nitrogen concentration were developed based on wastewater characteristics and operational parameters. These parameters include influent and effluent five-day biochemical oxygen demand concentration, influent and effluent ammonia-nitrogen concentration, hydraulic loading rate, organic loading rate, ammonia loading rate, pH, average water temperature and plant growth rate.

INTRODUCTION

The water hyacinth treatment system and other aquatic treatment systems have been used successfully for levels of treatment ranging from primary to advanced secondary treatment. Although such systems have been in use for more than 20 years, there has been a reluctance to forego conventional treatment and adopt aquatic treatment

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systems. Reasons for this reluctance include the availability of low-cost energy, a lack of aquatic system technology, and little operating experience. In recent years, however, increased energy costs have forced communities to reconsider the use of aquatic treatment systems as low-costs treatment alternatives. While several species of plants have been found to be useful in this regard, water hyacinths, *Eichhornia crassipes*, appear to offer the most promise in areas where the climate is mild enough for them to flourish most of the year. Aquatic treatment systems employing water hyacinths have the potential for dramatically lower capital, operation, and maintenance costs, compared to the more conventional approaches to wastewater treatment.

One purpose of this research was to develop design criteria for constructed aquatic treatment systems that use water hyacinths. A series of multiple-regression equations were developed based on previously reported experimental results [1] to predict the performance of the treatment systems in removing five-day biochemical oxygen demand (BOD_5) and ammonia-nitrogen (NH_4+-N). These design/operation equations was evaluated by comparing the predicted performance to experimental results of other research involving similar types of treatment systems.

Design Parameters for Aquatic Treatment Systems

Parameters used in designing water hyacinth treatment systems include hydraulic residence time (HRT), hydraulic loading rate (HLR), hydraulic application rate (HAR), organic loading rate (OLR), total nitrogen loading rate (NLR), ammonia-nitrogen loading rate (ALR), and water column depth. The HRT, typically expressed in days, is a commonly used design parameter. Ideally, systems are most often considered to be either plug flow or completely mixed. However, accurate determination of the HRT in water hyacinth systems is difficult due to the complex flow patterns and the volume displacement by the plants. Additionally, systems that have similar theoretical HRT's, may significantly differ hydraulically due to geometric design variations. Systems which consist of long, narrow rectangular channels may approach an actual-to-theoretical HRT ratio of 0.75. Circular or freeform ponds and other systems adapted to water hyacinth treatment may have actual-to-theoretical ratios as low as 0.5 or possibly less [2].

The hydraulic loading rate (HLR) is the volume of water applied per day divided by the surface area. Common units of expression are m^3/m^2/day, m^3/ha/day and gal/ha/day. This parameter is equivalent to the surface overflow rate and stems from its use in land application systems [3].

The HAR is the volumetric flowrate of water divided by the cross-sectional area of the channel. It is therefore an indication of the average flow-through velocity in the system. This design parameter has not been widely used, but it may be a more appropriate indicator of system performance than the other design parameters [2, 3].

Organic loading rates (OLR) are estimated by considering the rate of organic substrate applied per unit surface area of the treatment system. Common units of expression are kg/ha/day or lb/ac/day. This rate typically depends on a balance between the applied biodegradable carbon and the available oxygen. Many times the OLR is dependent on the effective distribution of the wastewater to the system. A wide range of OLR has been reported from systems receiving secondary effluent. Odor problems may develop if some critical OLR is exceeded [2, 3].

The nitrogen loading rate (NLR) is determined by considering the rate of the mass of nitrogen applied per unit surface area. The NLR depends on the concentration of nitrogen in the wastewater as well as the flowrate to the system. One design criterion that has been used is to match the NLR with the plant uptake rate. In this case the system design is based on the harvesting rate and the optimum plant density to maximize the plant uptake rate.

Other design considerations which have been explored in recent years are nitrification and denitrification rates. In this case some differences must be associated with the nitrogen loading rate. When considering plant uptake the NLR includes the various ionic forms of nitrogen. However, system conditions which favor nitrification may not favor denitrification, and the grouping together of the various forms of nitrogen may not be an accurate loading rate indicator [3-5]. In such cases the ALR may be a more accurate indicator.

The influence of system geometry on flow characteristics can not be neglected. The design length-to-width ratios, baffling and other channel obstructions or devices can influence flow characteristics. Another factor is the effect of the depth of the water column on the total suspended solids, biochemical oxygen demand, and total nitrogen removal efficiencies. Associated with this design parameter are the water hyacinth root zone characteristics and the rate of the detrital layer accumulation and decomposition. Research has indicated that longer roots develop with lower nutrient concentrations [6]. This may be an important design consideration depending on the quality of wastewater which the system receives. The ranges for selected design criteria presented in Table 1 are based on the performance of existing systems across the United States treating secondary effluents.

DESCRIPTION OF EXPERIMENT

A wastewater treatment plant which employs the activated sludge process followed by two 1.2 hectare polishing ponds in series to treat a flow of approximately 3785 m^3/d was selected for this study. More than 80 percent of the incoming wastewater is generated by a local poultry processing plant. The organic strength of the raw wastewater is quite high and, as a result, the treatment provided has often been inadequate; the discharge permit frequently has been violated.

Phase I Research

The initial pilot scale water hyacinth treatment system (WHTS) consisted of four growth channels for continuous-flow analysis and four growth basins for

Table 1. Ranges of Selected Design Criteria for Employing Water Hyacinth Systems to Upgrade Wastewater Treatment Plant Effluents

Parameter	Range	Units
HRT	1–15	days
HLR	47–4700	m^3/ha/d
OLR	< 50.4	kg/ha/d
ALR	5.6 – 22.4	kg/ha/d
Optimum plant density (wet wt.)	4.9 – 24.4	kg/m^2
Depth	0.23 – 1.2	m
Length-to-width	1:1 – 15:1	—

Note: The data from this table were compiled from the following systems [1, 2, 3, 7-12]: Hercules, CA (full scale); Roseville, CA (pilot scale); Coral Springs, FL (full scale); Gainesville, FL (full scale); Lake Buena Vista, FL (full scale); Lakeland, FL (full scale); Melbourne, FL (full scale); Orlando, FL (pilot scale); Orlando, FL (full scale); Lucedale, MS (full scale); NSTL, MS (full scale); Orange Grove, MS (full scale); Alamo, TX (full scale); Austin, TX (pilot scale); Austin, TX (full scale); College Station, TX (full scale); Hornsby Bend, TX (full scale); Rio Hondo, TX (full scale); San Benito, TX (full scale); San Juan, TX (full scale); Abbeville, AL (full scale); Enterprise, AL (#1) (full scale); Enterprise, AL (#2) (full scale; Millsy, AL (full scale); New Brocton, AL (full scale); Davis, CA (pilot scale).

batch studies. The four growth channels, constructed of marine plywood 2 cm thick, were 9.75 m long, 2.43 m wide, and 0.61 m deep. The channels were constructed above ground on a gradient so that each could be connected to provide treatment in a series configuration. Each channel was doubly lined with 6 mil polyethylene plastic. A constant head was provided by placing a tank at the top of a ten-foot tower. Secondary effluent from a clarifier was pumped to the constant head tank. The channels were gravity-fed through a 3.8-cm feed line and a 3.8-cm PVC header pipe suspended approximately 10 cm above the channel water surface at the influent end. Because of operation and maintenance problems, the system was initially configured as three channels in series and placed into operation by August 1986. This configuration, used until April 1987, is represented in Figure 1. A more detailed discussion of the operation and maintenance problems encountered can be found in [1].

Phase I covers data collected from September 28, 1986 to April 15, 1987. A single flowrate of 6.5 m^3/d which represents an individual channel HLR of 2712

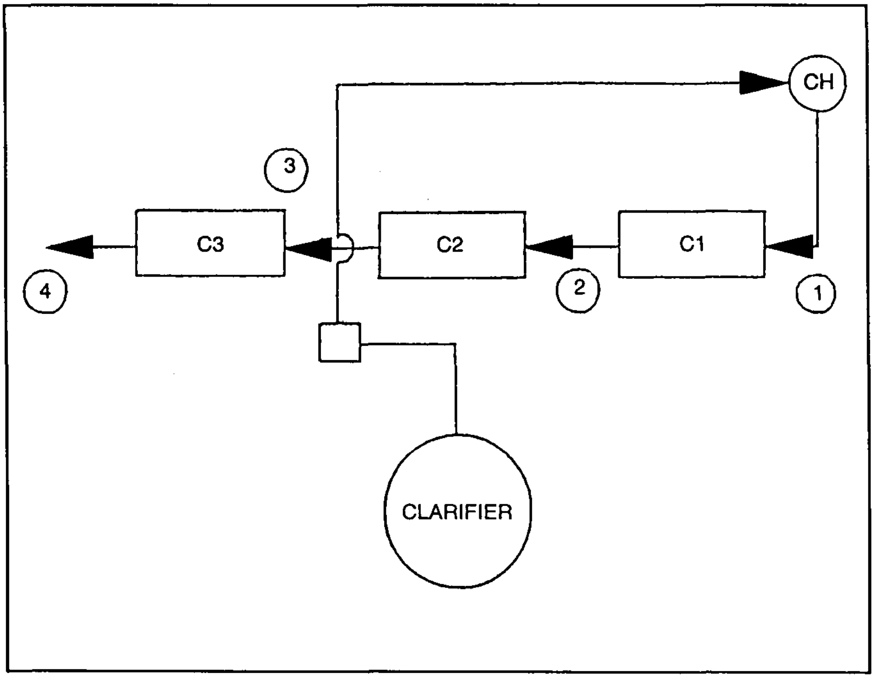

Figure 1. Phase I system configuration and sampling point locations.

m^3/ha/day was employed. Samples were collected at the influent and effluent ends of each channel three times per week. On each sampling day three grab samples were taken and composited into 1-L nalgene bottles and refrigerated on site until they could be transported to the environmental laboratory. The samples were typically analyzed for total BOD_5, total suspended solids (TSS), NH_4^+-N, total Kjeldahl nitrogen (TKN), nitrate-nitrogen (NO_3^--N), nitrite-nitrogen (NO_2^--N), and total phosphorus (TP). All analyses were made according to procedures outlined in the seventeenth edition of *Standard Methods for the Examination of Water and Wastewater*. The monthly values reported for the various parameters during this phase are averages of twelve sampling events. Water temperature and dissolved oxygen (DO) measurements were made with a DO/temperature probe. Plant densities were measured by collecting plants from 0.28 m^2 plots at several locations along the length of channel. The plants were drained for fifteen minutes, placed in baskets and weighed with a Homs Model 20 fish scale.

Air and water temperature highs and lows, rainfall amounts, and rates of evaporation and evapotranspiration were recorded. The evaporation/ evapotranspiration rates were investigated in the four small growth basins each 0.37 m^2 ×

0.6 m deep. These batch basins were constructed from 2 cm marine plywood and doubly lined with 6 mil polyethylene plastic. A removable standpipe allowed a maximum water depth of approximately 0.5 m (the same depth as in the continuous-flow system) while also providing drainage for basin cleaning. Three basins were stocked with plants and the fourth remained uncovered and plant-free. Precipitation and weekly changes in the water depth were monitored for the four basins. A comparison could be made of the evaporation rate in Basin 4 with the average evapotranspiration rate in the other three basins.

Phase II Research

In this phase the system was reconfigured as two water hyacinth treatment units. A schematic of the overall treatment system is presented in Figure 2. The first treatment unit consisted of channels one and two (C1 and C2) connected in series and continually harvested. The second treatment unit consisted of channels three and four (C3 and C4) connected in series but not harvested. The influent was pumped from the polishing pond due to operational problems at the wastewater treatment plant (WWTP) which resulted in excessively high BOD_5 and solids loading to the WHTSs. In order to simulate a secondary effluent of fair quality (similar to Phase I), the pond water was diluted with tap water to give more realistic concentration levels of total BOD_5, TSS and NH_4^+-N. Prior to dilution, total BOD_5 concentrations were as high as 80 mg/L, Tss as high as 100 mg/L and NH_4^+-N as high as 30 mg/L. A sampling scheme similar to that used in Phase I was employed in this phase. Four flowrates were investigated: 3 m^3/d, 6.4 m^3/d, 10 m^3/d and 15 m^3/d (770 gpd, 1710 gpd, 2650 gpd, and 3970 gpd). The values for the various water quality parameters recorded in Tables 2 and 3 represent the average of ten to fifteen sampling events.

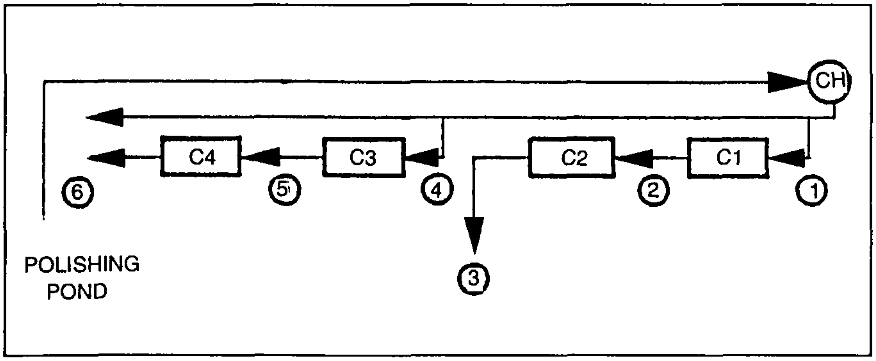

Figure 2. Phase II system configuration and sampling point locations.

RESULTS AND DEVELOPMENT OF MODELS

Experimental data were analyzed for two different operational phases. Data representing Phase I were obtained from the system configuration presented in Figure 1 during the time period from October 1986 to April 1987. During this period the system was operated at a single channel HLR of 2720 m^3/ha/day (or 907 m^3/ha/day for the entire system). No harvesting was performed.

The data representing Phase II were obtained from the system configuration presented in Figure 2 during the time period from June 1987 to September 1987. Four HLRs were investigated during this time period ranging from 1222 m^3/ha/day (per channel) to 6345 m^3/ha/day (per channel). During this phase, experimental data were collected from both harvested and nonharvested systems.

A summary of average influent and effluent characteristics as well as average operating parameters during Phase I and Phase II is presented in Tables 2 and 3, respectively. More detailed results are presented in [1].

The performance of the WHTS was most reliable from May to December. In the central and northern regions of Alabama treatments outside this window show

Table 2. Design and Operating Parameters during Phase I (Monitoring Period 1)

Configuration	Three (3) Channels in Series
Flowrate (m^3d)	6.5
HLR (m^3/ha/d)	2712 (each channel)
Theoretical HRT (d)	3 (entire system)
Water depth (m)	0.5
HAR (m^3/m^2/d)	5.1

Influent Wastewater Characteristics

Parameter	Influent Mean	Effluent Mean
BOD_5 (mg/L)	33.7	5.0
TSS (mg/L)	47.3	4.0
NH_4^+-N (mg/L)	9.3	4.5
Alkalinity (mg/L as $CaCO_3$)	60.8	17.0
pH	7.1	5.9
TP (mg/L)	4.7	1.4
TN (mg/L)	13.8	10.2

Table 3. Average Influent: Effluent Concentrations of Selected Constituents and Average System Loading Rates for Operational Parameters during Phase II Experimentation

	Constituent Concentration Ratio, mg/L	
Constituent	Harvested	Nonharvested
TSS	28:6	21:3
Total BOD_5	17:9	22:9
Total COD	57:44	51:33
NH_4^+-N	11:5	11:3
TN	11:6	11:5
TP	4:3	4:3
ALK	110:75	99:70
pH	6.8-7.6 : 6.2-7.0	7.0-7.9 : 6.3-6.9
Parameter	System Loading Rate, kg/ha/d	
OLR	83.0	96.2
ALR	36.0	35.2
TNLR	37.5	38.4
TPLR	11.8	11.3

rapid deterioration of NH_4+-N removal if greenhouse protection is not provided. The BOD_5 removal may continue to be effective until the dead plant material disperses throughout the water column in February or early March. The TSS solids removal will also be effective in a similar time frame as the BOD_5 removal.

Since the purpose of this research was to develop design parameters applicable to systems within the state of Alabama, the data collected from June to December were used. Even though the wastewater treated in Phase I (Monitoring Period 1) and Phase II (Monitoring Period 2) came from different sources, the performance results were similar. Therefore, the data base for the following analyses includes both Phase I and Phase II. Figure 3 presents a simple regression analysis of the effluent total BOD_5 concentrations resulting from different OLRs. These data include all four channels (both the harvested and the nonharvested treatment train). Clearly, a significant amount of data variability is not explained by the regression.

A series of multiple regression analyses were conducted using each treatment train or both treatment trains together as a data base. The possible variables

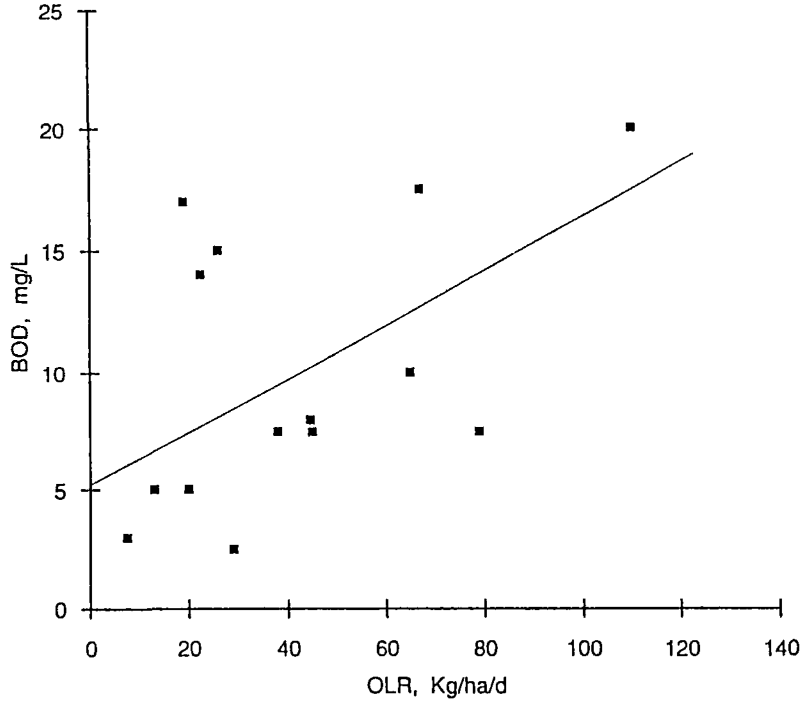

Figure 3. Simple regression of variation of effluent BOD_5 concentration versus OLR utilizing phase II monitoring data.

considered were: HLR, OLR, ALR, influent BOD_5 concentration, effluent BOD_5 concentration, influent NH_4^+-N concentration, influent pH, average water temperature and plant growth rate. The best predictive equation for BOD_5 effluent concentrations was obtained from the data base which included all four channels (harvested and nonharvested). The predictive equation is:

$$BOD_{5\,eff} = -0.87 + 0.40 \times BOD_{5\,in} + 0.00181 \times HLR - 0.31 \times NH_{4\,in} \quad (1)$$

where,

$BOD_{5\,eff}$ = effluent BOD_5, mg/L
$BOD_{5\,in}$ = influent BOD_5, mg/L
HLR = hydraulic loading rate, m^3/ha/d
$NH_{4\,in}$ = influent NH_4^+-N, mg/l

The r^2 coefficient for this equation was 0.72, indicating that the additional parameters help explain the data variability.

The inverse relationship between effluent BOD concentration and ammonia-nitrogen concentration can be explained by the possible anoxic denitrification activity within the channels. Even though aerobic processes are occurring within the water columns, anoxic denitrification probably occurred to varying degrees in the bottom detrital layer of the growth channels. Since denitrification required the presence of a variety of facultative heterotrophic bacteria, the degradation of carbonaceous organics would have also resulted. Figure 4 compares the percent fraction of the total nitrogen removal in each channel of each treatment train due to plant uptake. A significant percentage of nitrogen removal (40-80%) occurred with mechanisms other than plant uptake, such as nitrification/denitrification at hydraulic loading rates of 1222 m^3/ha/d and 2726 m^3/ha/d.

Based on Equation 1, a family of curves (Figure 5) was developed estimating the BOD_5 removal efficiency versus increasing OLR and ALR. The ALR was

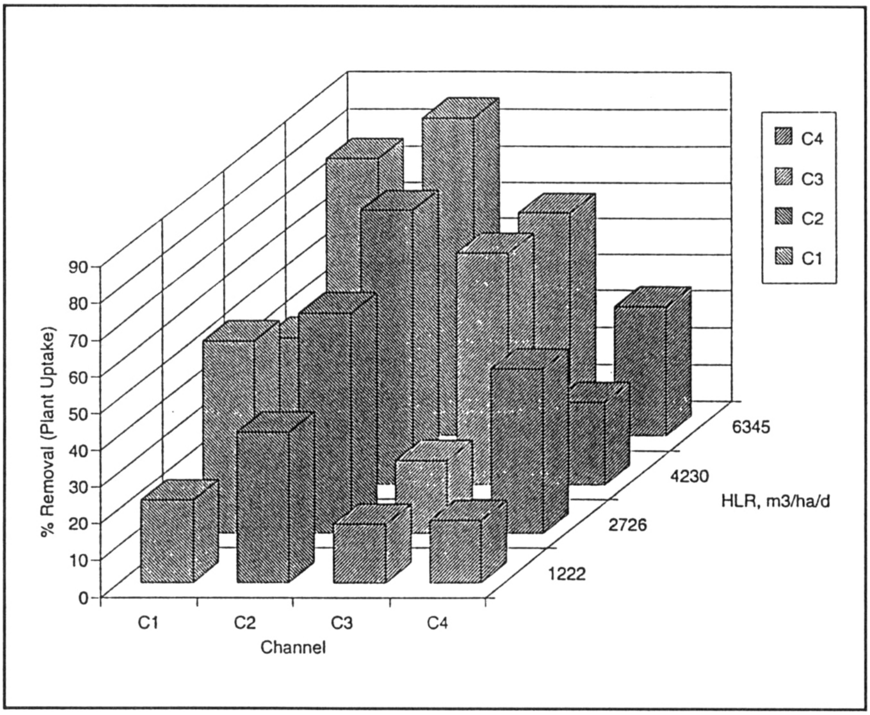

Figure 4. Comparison of average percent total nitrogen removal due to plant uptake in each channel of the harvested and unharvested treatment trains.

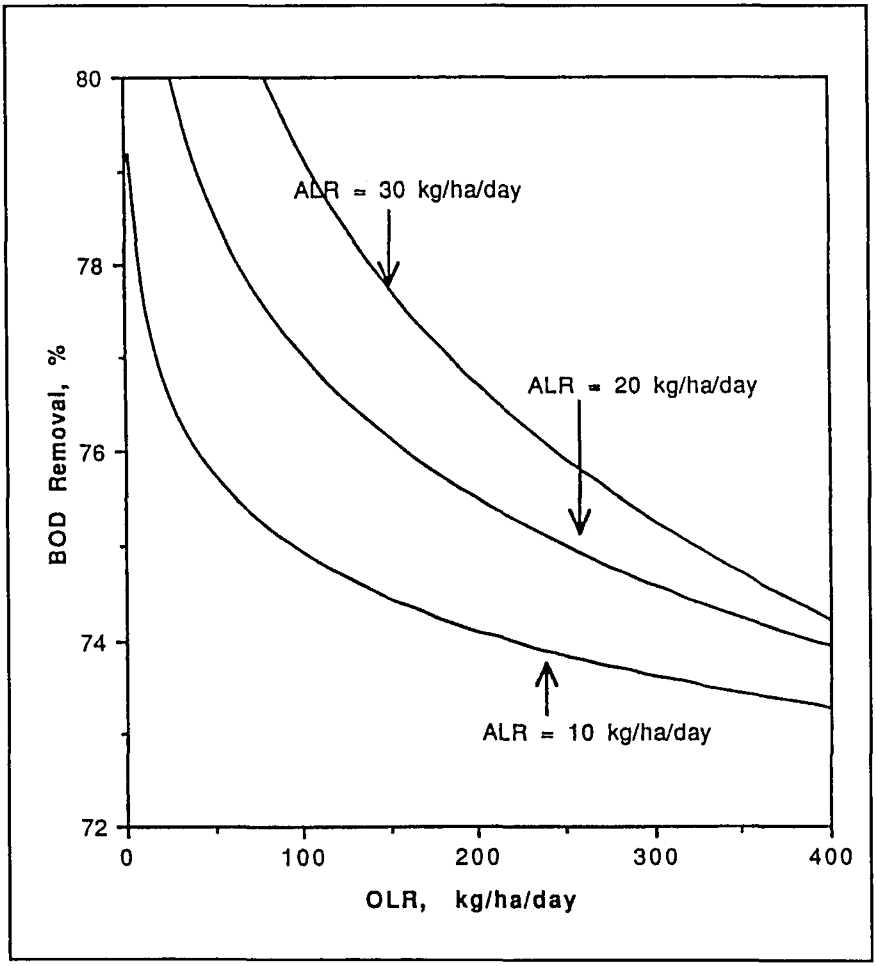

Figure 5. Estimated BOD5 removal efficiency versus varying OLR and ALR using Equation 1.

estimated by multiplying the $(NH_4^+\text{-}N)_{in}$ concentration with the HLR from Equation 1.

The same time period and data base were used to develop an NH_4^+-N treatment performance equation. Figure 6 presents a simple regression analysis of the effluent NH_4^+-N concentrations resulting from varying ammonia-nitrogen loading rates. These data include all four channels (harvested and nonharvested). Although the data variability is much less than for the BOD_5 curve, it is still significant.

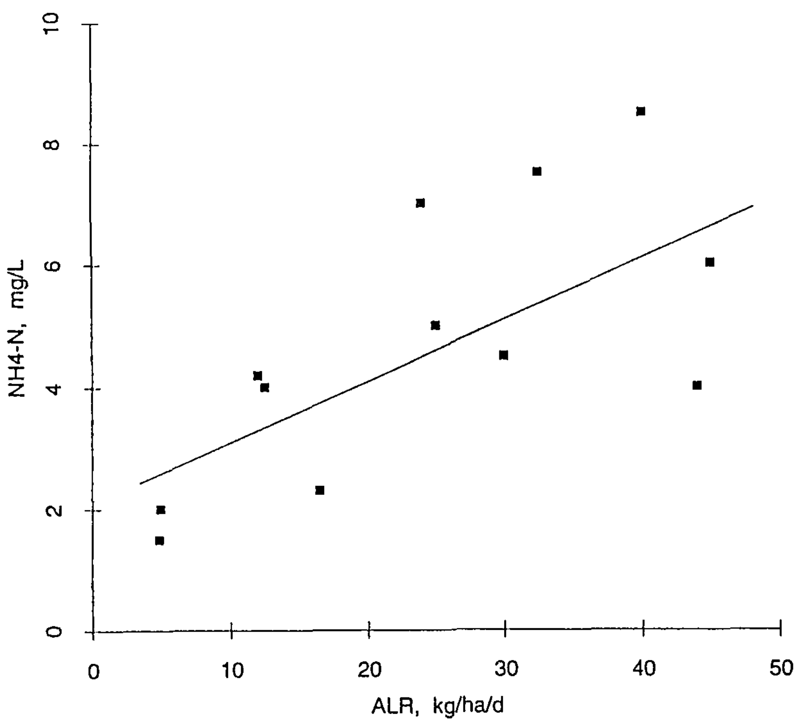

Figure 6. Simple regression of variation NH_4^+-N concentration versus ALR utilizing phase II monitoring data.

A series of multiple regression analyses were conducted using each treatment train separately and both trains together as a data base. The parameters considered were the same as for the BOD_5 performance equation, except for the fact that the $(NH_4^+\text{-}N)_{eff}$ was the dependent variable. The best performance prediction was obtained from using data collected from channels C3 and C4 (harvested treatment train):

$$(NH_4^+)_e = 0.58 - 0.019(OLR) + 0.29(ALR) - 0.12(T) + 6.00(GR) \tag{2}$$

where,

$(NH_4^+)_e$	= effluent NH_4^+-N, mg/L
OLR	= organic loading rate, kg/ha/d
ALR	= ammonia-N loading rate, kg/ha/d
T	= water temperature, C
GR	= plant growth rate, kg/ha/d

The r^2 coefficient was 0.84. The growth rate parameter increased the predictive capability as expected in a continually harvested system. The difficulty with use of this equation is the necessity for the design engineer to supply the growth rate. A simpler equation is recommended:

$$(NH_4^+)_e = -6.41 + 0.011(OLR) + 0.22(ALR) + 1.42(pH)_{in} - 0.14(T) \qquad (3)$$

The parameters are the same as in equation 2 with the replacement of the growth rate with influent pH. The r^2 coefficient for this performance equation is slightly less at 0.80. However, the influent pH is a more convenient parameter estimate than plant growth rate. Figure 7 presents a family of curves generated from Equation 3 estimating the NH_4^+-N removal efficiency versus increasing ALR and OLR.

COMPARISON WITH OTHER STUDIES

The discussion in this section compares experimental results of various research studies to the predicted results for effluent BOD_5 and NH_4+-N concentration using equations 1 and 3, respectively. Research studies involving small and large pilot scale systems to full scale operations have been evaluated based on BOD and NH_4+-N removal. The systems were located in Roseville, California [7], Reedy Creek, Florida [8], The National Space Technology Laboratory, Bay St. Louis, Mississippi [9], Hornsby Bend, Texas [10], San Diego, California [11], and Davis, California [3]. Table 4 presents a summary of the research locations along with some of the key operating parameters.

The study in Roseville, California involved a pilot system receiving secondary treated wastewater from an activated sludge process. Three modes of operation were investigated, a nonharvested (unmanaged channel), an aerated-nonharvested channel, and a harvested channel. Each channel was loaded at a HLR of 1530 m^3/ha/d [7]. The pilot study at Reedy Creek, Florida involved a treatment train of five channels in series receiving secondary treated effluent from an activated sludge process at a HLR ranging from 246 m^3/ha/d to 1970 m^3/ha/d [8]. The system at National Space Technology Lab (Bay St. Louis, Mississippi) involved a facultative pond with a surface area of 2 ha and a depth of 1.22 m covered with water hyacinth [9]. The system at Williamson Creek, Texas involved a stabilization pond converted to a hyacinth basin receiving wastewater pretreated through

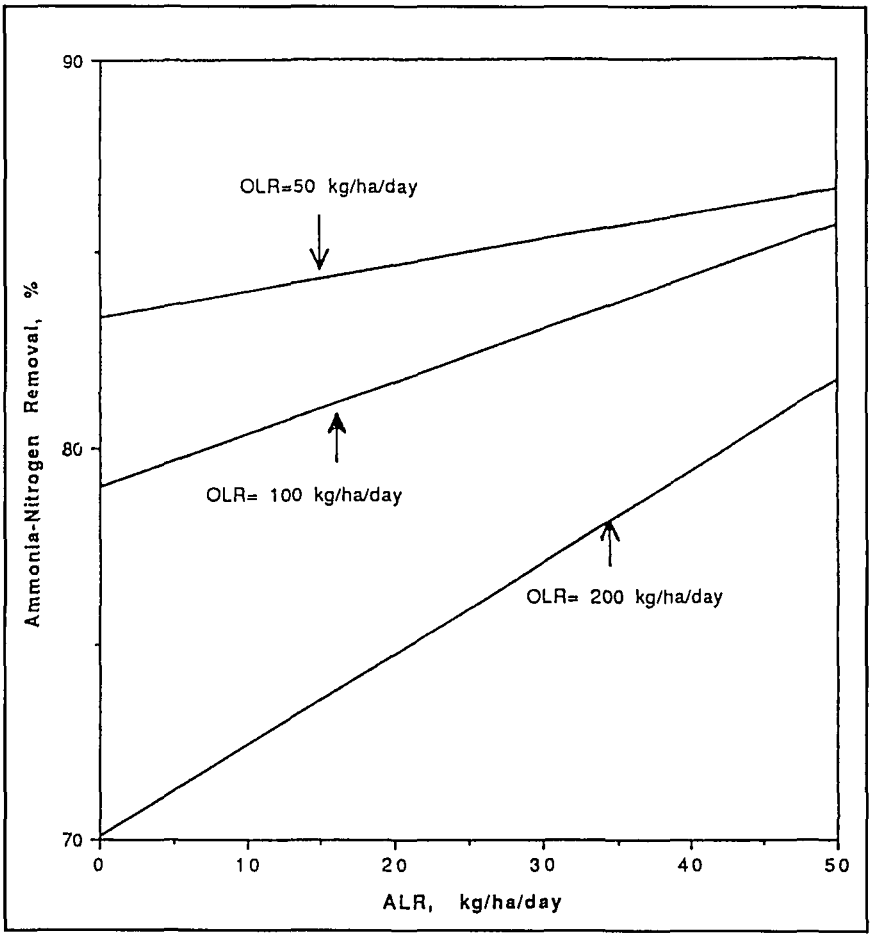

Figure 7. Estimated NH_4^+-N removal efficiency versus varying ALR and OLR using Equation 3.

an aeration basin, clarifier, and two lagoons in series. The basin had a surface area of 12 ha and depth of 0.7 to 1.3 m [10]. The San Diego, California system was a pilot project in which a 0.097 ha water hyacinth channel with supplemental course bubble aeration received primary effluent through a step feed configuration with effluent recycle. The channel was hydraulically loaded at a rate of 1010 m^3/ha/d [11]. The system at Davis, California (UCD) was a plug flow pilot research facility in which channels 9.5 m long by 3.5 m wide (0.0033 ha) received secondary effluent at a hydraulic loading ranging from 240 m^3/ha/d to 1000 m^3/ha/d [3].

Table 4. Comparison of Average Effluent BOD_5 and NH_4^+-N Concentration from Various Research Studies with Predicted Concentrations Using Equations 1 and 3, Respectively

Research Study	HLR m^3/ha/d	BOD_{in} mg/L	NH_4^+-Nin mg/L	Effluent BOD mg/L		Effluent NH_4^+-N mg/L	
				E. V.[a]	P. V.[b]	E.V.[a]	P.V.[c]
San Diego	1010	120	23	9.5	18	—	—
Roseville	1530	11.6	14.1	5, 3.5[d]	2.1	6.1, 9.5[d]	6.6
Reedy Creek	246	208	32	23.5	30.8	—	—
	492	230	32	31.6	35.2	—	—
	984	220	34	33.1	32.6	—	—
	1970	220	30.3	40	34	—	—
NSTL	240	110	12	7	10	—	—
Williamson Creek	109	46	7.7	6	5.9	3.3	2.2
U.C. Davis	480	5.6	23.2	—	—	7.2	7.3
	960	10.2	21.3	—	—	17.7	16.3

[a]Experimental value obtained during respective research study.
[b]Predicted effluent BOD value on Equation 1.
[c]Predicted effluent NH_4^+-N value based on Equation 3.
[d]Nonharvested channel value and harvested channel value, respectively.
[e]National Space Technology Laboratory, Bay St. Louis, Mississippi
Sources: [7-12].

The systems mentioned represent a range of HLRs from 109 m^3/ha/d to 1970 m^3/ha/d. This corresponds to a range of OLRs from 5 kg BOD_5/ha/d to 500 kg BOD_5/ha/d and a range of LARs from 0.9 kg NH_4^+-N/ha/d to 75 kg NH_4^+-N/ha/d. The BOD removal performance predictions represented by Figure 5 and equation 1 were within a 2 percent error for the systems with low organic and ammonia loading and ran to as high as a 50 percent error for the systems such as San Diego, California, where supplemental aeration was utilized. The comparisons are presented in Table 4.

Equation 2 predictions (Figure 7) of NH_4^+-N removal efficiencies were within a 10 percent error for systems operating in the nonharvested mode, and within a 30 percent error for systems operating in the harvested mode. Of the systems studied only three locations provided adequate NH_4^+-N data for evaluation and only one of these systems was tested in the harvested mode. The comparisons are presented in Table 4.

CONCLUSION

The nomographs (Figures 5 and 7) produced from the design equations, based on multiple regression analyses, can be used to predict system performance for BOD_5 and NH_4^+-N removal efficiency. The nomographs were developed from data from a pilot treatment system receiving secondary effluent from an activated sludge plant at hydraulic loading rates ranging from 1222 to 6345 m^3/ha/d. The resulting performance curves were applied to other research studies involving pilot-scale and full-scale treatment systems loaded with primary and secondary treated wastewater. The organic loading rates for these systems ranged from 5 to 500 kg BOD_5/ha/d and ammonia-nitrogen loading rates from 1 to 75 kg H_4^+-N/ha/d. The performance curves were very successful in predicting the system response from these other research studies.

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