AN ABSTRACT OF THE THESIS OF

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ABSTRACT

This study investigated the effect of plant surface area (plant density) on the efficiency of organic carbon removal in a bench-scale constructed wetland.

Constructed wetlands are commonly assumed to be biofilm reactors in which organic carbon removal occurs primarily through sedimentation and aerobic degradation by attached microbial biofilms. In conventional biofilm reactors, aerobic degradation of organic carbon is proportional to the amount of surface area for microbial attachment, provided that sufficient oxygen is available. In contrast, current design equations for constructed wetlands assume that the amount of surface area is not an important parameter.

A bench-scale simulation of a constructed wetland was conducted, using bulrushes planted at varying plant densities in soil with a free water surface depth of about 0.27 m. The carbon source was diluted ENSUR (TM). Total organic carbon (TOC) removal was measured. Concentration of TOC was correlated with biochemical oxygen demand (BOD). Tests were conducted in conditions of light and dark, and under two different carbon loadings. Performance of bulrushes was compared with that of inert acrylic rods.

The rate of carbon removal by mature bulrushes was found to increase with increasing plant density until oxygen

became depleted. Higher densities degraded carbon at rates much faster than those predicted by current design equations. Young bulrushes degraded carbon at faster rates than mature bulrushes. Once oxygen was depleted, rates of degradation were reduced to rates anticipated by current models. When plant density was 15% or greater, oxygen became depleted in less than 6 hours. Removal efficiency was greater at higher loadings (70 mg/l BOD) than at lower loadings (25 mg/l BOD).

Bulrushes performed significantly better than inert rods, sometimes by a full order of magnitude. The microbial community on the bulrushes appeared to be more complex and robust than that on the rods. Also, the presence of light did not significantly increase degradation rates for the bulrushes but was significant for the rods. The microbial community on the rods contained a larger proportion of epiphytic algae. The presence of light did result is greater overall efficiency of removal for both bulrush and rods.

Currently, a major drawback of constructed wetlands in wastewater treatment has been their demand for large areas of land. This study suggests that it would be possible to reduce the land area requirements for constructed wetlands for both carbon removal and nitrification/denitrification provided designs gave more consideration to oxygen supply. Using current designs, a retention time of 4-8 days typically results in 70% BOD removal. This experiment suggests that wetlands with a retention time of about 1 day could provide the same performance if additional oxygen were supplied.

Effect of Plant Surface Area on Organic Carbon Removal in Wetlands

by

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Elaine Jinx Kuehn, Author

DEDICATION

This is dedicated to Barry Gorden, my spouse, and to Laule'a Gorden-Kuehn, my daughter, who gave me cheerful encouragement at every point, even though they had to do without Mom much more than they should have.

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CONTRIBUTION OF AUTHORS

Dr. Marshall J. English was involved in analysis and interpretation of data. Dr. Kenneth J. Williamson assisted in understanding the performance of biofilms, oxygen limitation and interpretation of data.

"...a yellow Ganymeadean slime mould ... had silently flowed under the door of the conapt and was gathering itself into the heap of small globes which comprised its physical being.

'Could I carry a business card,' the slime mould said, 'I would now present it to you.'"

Philip K. Dick
in Clans of the Alphane Moon

when asked if we are living in the age of mammals, replied:

"we are in the age of bacteria, we have always been, and we always will be in the age of bacteria"

Stephen J. Gould
speech in Eugene, OR
November 1993

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CHAPTER 1: INTRODUCTION

1.1. Statement of the Problem

Constructed wetlands (also known as artificial wetlands) have been in use for wastewater treatment for about 20 years. They produce high quality effluent, are relatively inexpensive to construct and maintain, and do not require highly trained staff. Provided that there is a large treatment area and a long detention time, constructed wetlands provide excellent removal of biochemical oxygen demand (BOD) and total suspended solids (TSS) in a variety of climates and using a wide variety of plants (Gearheart 1992, Reddy and DeBusk 1981). The drawbacks of constructed wetlands include the following: 1) a large surface area is required to provide a sufficient safety factor; 2) apparently similar designs vary considerably in performance; 3) oxygen depletion can sometimes lead to anaerobic conditions with slow degradation rates.

How do constructed wetlands work? Most researchers believe that the primary treatment processes are sedimentation and biofilm microbial transformation. But very little work has been done to study methods for optimizing these processes (Reddy and Debusk 1981). Design equations have been based on total volume (Reed et al. 1988) or total area (Hammer and Knight 1992). Biofilm surface area is included in some equations but has been treated as a constant, even though biofilm attachment surface area is known to be approximately proportional to treatment efficiency in conventional biofilm reactors (Meunier and Williamson 1981).

In its 1991 design manual, the United States Environmental Protection Agency (EPA) found that the most commonly used wetland design equation was not sensitive to specific surface (biofilm surface area expressed in square meters/cubic meter of water)(m^2/m^3). However, the EPA considered only specific surface values of 12-16 m^2/m^3. These values correspond to the very narrow range of 3.8% - 5.1% of wetland volume occupied by plants (EPA, 1991). In the literature values of 3-15% of volume occupied by plants have been reported (Watson and Hobson 1989, Kadlec 1990) which would correspond to the much larger range of 3 - 48 m^2/m^3 for specific surface. Both Gearheart (1992) and Lakshman (1993) suggest that higher plant densities are related to improved carbon removal. Neither paper gives details of the densities studied.

Constructed wetlands are of two basic designs: free water surface (FWS) wetlands in which plants are grown in soil with the water level kept several inches above the soil surface; and subsurface flow wetlands (SFS) in which plants are rooted in a gravel bed and the water level is kept below the surface of the gravel.

This study examines the effects of different amounts of biofilm surface area on removal efficiency of organic carbon in a bench scale setting designed to mimic a constructed FWS wetland. When water depth is held constant, plant density is proportional to biofilm surface area. In this study varying plant densities are compared relative to carbon removal rates and efficiency.

1.2. Objectives

The objective of this study is to gain an improved understanding of the effect of the plant surface area (plant density) on the efficiency of organic carbon removal in constructed wetlands.

If it is assumed that constructed wetlands are primarily biofilm reactors, one would expect treatment efficiency for aerobic removal of organic carbon to be proportional to plant surface area and that treatment efficiency would be limited by the availability of oxygen, the electron acceptor. Wetland plants are living rather than inert substrates which support communities including epiphytic algae, and also create detritus and dissolved organic matter. Constructed wetlands systems may supply oxygen or nutrients, or, alternately, may increase oxygen demand so that efficiency of carbon removal is affected. The specific objectives of this research are therefore:

1. To evaluate the effect of biofilm surface area, expressed as plant density, on wetland treatment efficiency.

2. To evaluate whether oxygen becomes a limiting factor.

3. To evaluate whether biofilms on bulrushes perform similarly to biofilms on inert substrate.

The major drawback to the use of constructed wetlands for wastewater treatment has been the need to set aside large areas of land. This is required by the current design equations. If as studies indicate, most of the treatment occurs in the first 20% of the system (Gearheart 1992), then a better understanding of the microbial treatment mechanisms could reduce area requirements and improve constructed wetland efficiencies.

CHAPTER 2: LITERATURE REVIEW

2.1. Performance of Existing Systems

Constructed free water surface (FWS) wetlands exceed the performance of typical lagoons and have been shown to be suitable for advanced treatment, reducing solids below 5 mg/l (Gearheart 1992) and biochemical oxygen demand (BOD) to about 10 mg/l (Knight et al 1993).

Constructed wetlands act as excellent filters for total suspended solids (TSS) (Hosokawa and Furukawa 1992). Gearheart (1992) reports up to 75% removed in one day and 95% after 6 days with effluent concentrations of less than 5 mg/l TSS. A dense group of vegetation near the outflow promotes a final filtration. Constructed wetlands have proven to be excellent denitrifiers (Reed and WPCF, 1990) but have limited capacity to remove ammonia or organic nitrogen, probably as a result of oxygen limitations (Reed 1992, Gearheart 1992, Watson and Danzig 1993).

Constructed wetland reduction of biochemical oxygen demand (BOD) has been quite varied. Gearheart (1992) reports 41-65% removals while others report about 70% removal rates (Knight et al 1993), with lower efficiencies when influent organic loading rates drop below 50 kg/ha/day (Knight et al 1993). With relatively long retention times of about 6-9 days, effluent quality did not drop until organic loading rates exceeded 200 kg/ha/day. Thus, constructed wetlands perform well when shock loaded (Gearheart 1992).

Because BOD treatment has yielded acceptable results from current designs, little work on optimization has been done even though researchers have found most treatment of BOD and nitrogen occurring in the first 11-50% of the systems (Reed 1992, Swindell and Jackson, 1990).

2.2. Current Design Equations and Assumptions

Design equations for constructed wetlands have been based on a plug flow model with first order kinetics for BOD removal (Reed et al. 1988). Long retention times were advocated as early studies seemed to show "the longer the better". Length to width ratios of 10:1 were thought to be best but 4:1 have proven to be adequate and more affordable (Hammer and Knight 1992).

By 1988, Reed et al. (1988) had created a design equation based on hydraulic retention time (HRT) but which included modifying factors for the specific surface and for the porosity (plant density) of the constructed wetland system. Typical values for sewage effluent were developed by estimating plant density, plant surface area and by using rate constants from overland flow systems. To calculate the plant surface area, it was assumed that plants occupied 5% of the volume, and that cattails and bulrush had an average diameter of 1.27 cm (Reed et al. 1988).

The equation for FWS wetlands now recommended by the Water Pollution Control Federation (WPCF) is a variant on the Reed equation. Removal is assumed to be a function of <u>both</u> HRT and of surface area, as it is in biofilm reactor analysis. This demonstrates that a better understanding of surface area should improve design reliability. However, the WPCF equation assumes that the surface area is approximately constant when it is almost certainly highly variable.

The assumption that surface area may be treated as a constant derives from the EPA (1991) analysis showing that the Reed design equation was not very sensitive to biofilm surface area. However, in their analysis, the EPA studied only surface area variability in the range 12-16 m^2/m^3. This narrow range represents only 3.8 - 5.1 % of volume occupied by plants. Detrital surface area was not considered. Researchers have measured 3-15% of volume occupied by plants (Watson and Hobson 1989, Kadlec 1990) and porosity measured by dye studies is typically 0.75 indicating 25% of the volume is either occupied by plants or by dead space in the flow pattern. Fifteen percent of volume occupied by plants corresponds to 48 m^2/m^3 specific surface (for calculations, see Appendix 1). Moreover, it is possible for specific surface to be one order of magnitude larger (Gearheart 1993 lecture). If specific surface is on the order of 3 - 48 m^2/m^3 then this parameter would be much more important in design standards. Nevertheless, the WPCF design manual followed the EPA analysis that specific surface was not a sensitive parameter.

Various other criticisms of the current design model have been made. Kadlec has pointed out that this equation is seriously flawed in assuming plug flow, that the settlable portion may really account for a different flow model and that the specific surface has never been measured (Kadlec 1993). Tchobanoglous (1993) has pointed out that the organic matter in a constructed wetland system is constantly changing so that it is very difficult to predict stoichiometric oxygen demands. Constructed wetlands produce BOD in the form of dissolved organic matter, especially when plants senesce in the fall (Wetzel 1993). The magnitude of this effect varies considerably with changes in plant type, age, density and conditions.

The primary basis for design of existing systems other than the WPCF equation is experience. Gearheart (1992) shows that constructed wetlands can consistently produce effluent below secondary treatment standards and typically at or below 20 mg/l, with loading rates of up to 200 kg/ha/day. This is consistent with the recent database analysis conducted by Knight et al (1993). Their analysis supports a linear relationship between effluent and influent concentration and shows that hydraulic loading rate (HLR) is not significant for BOD removal. This suggests that area is not a primary design parameter for BOD removal.

2.3. Biofilm Reactors

Biofilm reactors are noted for being more resistant to shock loads and less temperature sensitive than suspended growth reactors (Williamson and McCarty Jan 1976, Characklis 1990, Characklis et al 1990). While suspended growth reactors do not work well if the clarifier fails, biofilm reactors are subject to solids accumulation which can result in clogging and sloughing. A constructed wetland eliminates most problems resulting from the accumulation of solids because constructed wetlands act as excellent clarifiers without clogging (over periods of up to 10 years - Gearheart 1992).

While biofilms are complex, modelling of biofilms is now relatively advanced, especially under controlled conditions. The kinetics of biofilms reactors are commonly modelled as plug flow, using a Monod equation and chemostat experiments to develop substrate utilization rate constants (Williamson and McCarty Jan and Feb 1976, Meunier and Williamson 1981, Characklis et al 1990). The number of cells in a biofilm reactor is a function of surface area in proportion to unit volume (specific surface) rather than a function of cell concentration in the water as in a suspended growth reactor. Thus, the change in concentration of a wastewater component is thought to be proportional to the surface area available for microbial attachment.

Biofilm reactors also differ from suspended growth reactors in that the flux rate through the biofilm must be considered. Reactions can be substrate limited (e.g. rate limited) as in suspended growth reactors, but can also be flux limited (e.g. gradient across the biofilm to a given depth). Typically the electron donor molecule (such as glucose) has a slower flux rate than the electron acceptor. Thus, if the electron acceptor is supplied in stoichiometric ratio, then the electron donor will usually be both flux and substrate limiting. However, as the concentration of the electron acceptor is reduced, the reactions can become mixed; that is, flux limited by one species and substrate limited by the other. When mixed systems occur, which is thought to be common with reactors such as trickling filters, it is much more difficult to model behavior (Williamson and McCarty, Jan 1976).

2.4. Plant Biofilm Surface Area

Do live plants act as neutral surface areas? Studies comparing bulrush stems with plastic rods have shown that the live bulrush stems supported a similar but smaller periphyton community than plastic rods, unless the rods were waxed. Some aquatic plants are known to have waxy surfaces and some excrete allelochemicals which discourage bacterial and algal colonization. Senescent bulrush stems behaved much more like plastic rods. While this area is currently under study and results are not always consistent, research suggests that hydrophobic surfaces such as the somewhat waxy surfaces of live emergent macrophytes do not support communities as complete as neutral surface areas (Goldsborough and Hickman 1991).

However, studies in a wetland treating pulp mill effluent show active communities of bacteria (10^4 colonies) and fungi (10^6 colonies) on the stems (Hatano 1992). Hatano also found that the populations of bacteria in an SFS wetland were 2-3 orders of magnitude larger in planted cells than in plain gravel cells, indicating that plants in some way provide oxygen or nutrients conducive to bacterial growth (Hatano 1993). Benham and Mote (1993) report that TOC removal was greater in stock tanks containing bulrush than in tanks containing wooden rods.

In summary, while plant biofilm surface areas are assumed to be the major treatment mechanism for biological transformation in constructed wetlands, their contribution to treatment and their comparability to biofilms on inert substrates are complex and not well understood.

2.5. Oxygen Supply

Plants are thought to provide oxygen to the treatment system. Studies disagree about quantities, but it is established that aquatic plants do pump oxygen to their roots and some leaks out. An oxygen supply to the root zone of 5 g/m^2 has been considered typical (Reddy and Debusk 1987, Rogers et al. 1991). Young macrophyte stems support higher internal oxygen transport pressure than do older stems (Stengel 1993, Brix #41 1993). Gearheart (1993) found that epiphytes also contribute oxygen to the system. In contrast, other researchers indicate that most of the oxygen in the root zone is consumed almost immediately for respiration by the bacteria in the rhizosphere and that little would be available to support additional wastewater degradation (Brix 1993, Wetzel 1993).

The EPA design manual (1991) assumes that oxygen is <u>not</u> limiting in constructed wetlands. The manual notes studies showing oxygen transport rates of 5-45 g O_2/m^2-day through wetland plants to their roots. More recent papers on constructed wetlands increasingly mention oxygen limitation (Cronk and Shirmohammadi 1994, Gearheart 1992, Reed and Brown, 1992, Knight et al 1993, Watson and Danzig 1993). Oxygen limitation has been most often suspected as limiting the nitrification process but as early as 1987, Reddy and Debusk reported that constructed wetlands should be rate limited by both O_2 and NO_3^- as electron acceptors (Reddy and DeBusk 1987). If oxygen is limiting in wetlands one would expect predictable rapid carbon removals until the oxygen is exhausted, followed by somewhat unpredictable behavior after exhaustion.

Researchers now actively propose combining constructed wetlands with other methods such as intermittent loading, sand filters and overland flow that supply more oxygen (Reed and Brown 1992, Brix 1993, Watson and Danzig 1993). However, little specific analysis of the behavior of oxygen in wetlands is available. Gearheart (1992) has shown that in a large wetland for post-secondary treatment, dissolved oxygen levels are at or below 1.1 mg/l when open water constituted 25% of the area, while dissolved oxygen was at 5 mg/l when 75% of the area was open water. Unfortunately duckweed (oxygen consumers), rather than photosynthesizing algae (oxygen producers), tend to take over such open areas further restricting reaeration. Gearheart also found that epiphyton could supply extra oxygen to the systems (Gearheart 1993).

2.6. Oxygen Demand and Other System Components

The components of an FWS constructed wetland are somewhat different from those of a trickling filter or expanded bed reactor. The treatment components include the water column, free and attached photosynthetic organisms, live macrophytic plant stems, live plant root areas that are exposed near the surface, benthic organisms, mucky sediment, and detritus.

The plants, benthic organisms and sediments can all affect the carbon, oxygen and nutrient balances. Overall, wetland ecosystems are thought to act as carbon sinks. While some dissolved organic matter (DOM) is released when plants undergo senescence, at least 50% of the plant matter for most aquatic macrophytes remains in the wetland where it falls to the bottom and is incorporated into the sediments. Decomposition of this material is very slow, carried out in predominantly anaerobic conditions. In some wetlands sediments accumulate rapidly, burying the organic material.

Mass balances for these processes vary widely with geographic area, type of sediments and plants, and are not well quantified (Wetzel 1993, Mitsch 1986). No studies of the rate of carbon uptake for *Scirpus Acutus* were found.

Large and active communities of aquatic organisms, including tubificids, naid worms and many smaller invertebrates thrive in wetland conditions. Phytoplankton and epiphyton may contribute substantial oxygen during daylight hours but aquatic sediment/organism oxygen demand can also be quite high. Unpolluted sediment/organism communities have been measured as having respiration rates of about 30% of the total oxygen demand. Polluted sediments consume even more (Sculthorpe, 1967). Thus, constructed wetland systems may consume additional oxygen beside that used for wastewater treatment.

Finally, synergistic effects may occur in constructed wetlands that result in differing behavior from similarly designed but less complex systems. Formerly, it was assumed that there were few floating algae in wetland systems because the macrophytes shaded the systems. It is now thought that epiphytic algae on macrophytes actively outcompete the phytoplankton for phosphorous.

In wetlands fed sewage, photosynthesis is greater than would be predicted from that of plants alone (Round, 1981). It has also been found that if snails are moderately abundant, they contribute to a healthier community of both epiphytes and macrophytes, probably because they consume aging portions of the biofilm, maintaining its health (Bronmark 1989).

The complexity of wetland systems makes it difficult to assess which oxygen supply and demand mechanisms or which carbon supply mechanism will predominate in a constructed wetland.

CHAPTER 3:

EFFECT OF PLANT SURFACE AREA AND OXYGEN LIMITATION ON TREATMENT EFFICIENCY IN WETLANDS

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American Society of Civil Engineers

3.1. Abstract

This study found that the rate of carbon removal by mature bulrushes increased with increasing plant density until oxygen was depleted. Higher plant densities degraded carbon at rates much faster than those predicted by current design equations. Young bulrushes degraded carbon at higher rates than mature bulrush at the same plant density. After oxygen was depleted, degradation rates were reduced to rates predicted by current models. When plant density was 15% or greater, oxygen was depleted in less than 6 hours. Bulrushes removed carbon more efficiently than the inert rods, and host very different microbial communities.

This study suggests that it would be possible to substantially reduce the land area requirements for constructed wetlands for both carbon removal and nitrification/denitrification if future designs provided more oxygen than current design recommendations.

3.2. Introduction

Constructed wetlands have proven to be reliable and effective for removal of biochemical oxygen demand (BOD) and total suspended solids (TSS) in a variety of climates and using a wide variety of plants (Gearheart 1992, Reddy and DeBusk 1981). Primary treatment processes include sedimentation and biofilm microbial transformation. But very little work has been done to study how these processes can be optimized (Reddy and Debusk 1981). Design equations have been based on total volume (Reed et al. 1988) or total area (Hammer and Knight 1992). Biofilm surface area is included in some equations but has been treated as a constant, even though biofilm attachment surface area is known to be approximately proportional to treatment efficiency in conventional reactors (Meunier and Williamson 1981).

Constructed wetlands are of two basic designs: free water surface (FWS) wetlands in which plants are grown in soil with the water level kept several inches above the soil surface; and subsurface flow wetlands (SFS) in which plants are rooted in a gravel bed and the water level is kept below the surface of the gravel.

This study examines the effects of different amounts of biofilm surface area on removal efficiency of organic carbon in a bench scale setting designed to mimic a constructed FWS wetland. When water depth is held constant, plant density is proportional to biofilm surface area. In this study, varying plant densities are compared for carbon removal efficiency.

3.3. Background

The predominant treatment mechanism for organic carbon removal in constructed wetlands is thought to be the biofilm on the plants and detritus in the system (Reed et al. 1990, Tchobanoglous 1987) rather than microbes in the water column or plant uptake. However, the components of an FWS constructed wetland are somewhat different than those of conventional biofilm reactors. The treatment components include free and attached photosynthetic organisms, live macrophytic plant stems, live plant root areas that are exposed near the surface, mucky sediment, and detritus, rather than simply inert surface area.

Reported removal efficiencies for biochemical oxygen demand (BOD) vary in constructed wetlands. Gearheart (1992) reports 41-65% removal efficiencies while others report about 70% removal efficiencies (Knight et al 1993), with lower efficiencies when organic loading rates drop below 50 kg/ha/day (Knight et al 1993). Typical retention times are

4-10 days (Gearheart 1992). Because BOD treatment has yielded acceptable results (10-20 mg/l effluent) from current designs, little work on optimization has been done even though researchers have found most treatment of BOD and nitrogen occurs in the first 11-50% of the system. (Reed 1992, Swindell and Jackson, 1990).

The equation for FWS wetlands now recommended by the Water Pollution Control Federation (WPCF), is shown in Figure 3.1. The removal rate is assumed to be a function of both HRT and of biofilm surface area, as it is in other biofilm reactors (Williamson and McCarty Jan and Feb 1976, Meunier and Williamson 1981, Characklis et al 1990). This demonstrates that a better understanding of surface area should improve design reliability. However, the WPCF equation assumes that the specific surface (surface area as a ratio to unit volume), Av, is approximately constant when in fact it is highly variable.

The assumption that surface area may be treated as a constant derives from the EPA (1991) analysis showing that the WPCF design equation was not very sensitive to biofilm surface area. However, in their analysis, the EPA studied only surface area variability in the range 12-16 m^2/m^3. This narrow range represents only 3.8 - 5.1 % of volume occupied by plants. Researchers have measured 3-15% of volume occupied by plants (Watson and Hobson 1989, Kadlec 1990). Porosity, as measured by dye studies, is typically 0.75, indicating 25% of the volume is either occupied by plants or by dead space in the flow pattern. Fifteen percent of volume occupied by plants corresponds to 48 m^2/m^3 specific surface. If specific surface is on the order of 3 - 48 m^2/m^3 then the sensitivity of design standards to this parameter would be much higher as illustrated in Figure 3.2.

Live plants in constructed wetlands may perform differently from neutral surface areas in biofilm reactors. Studies comparing bulrush stems with plastic rods have shown

WPCF MANUAL OF PRACTICE DESIGN EQUATION
FREE WATER SURFACE WETLANDS

$$Ce/Co = F * \exp(-0.7 * kt * Av^{1.75} * HRT * n) \quad \text{(Eq. 3.1)}$$

where,
- F = fraction not settled at inlet of wetland
- kt = rate constant for 20 degrees centigrade (days^-1)
- Av = specific surface (m^2/m^3)
- HRT = retention time (days)
- n = porosity (fraction)

Figure 3.1 WPCF Design Equation
(WPCF; and Reed,1990)

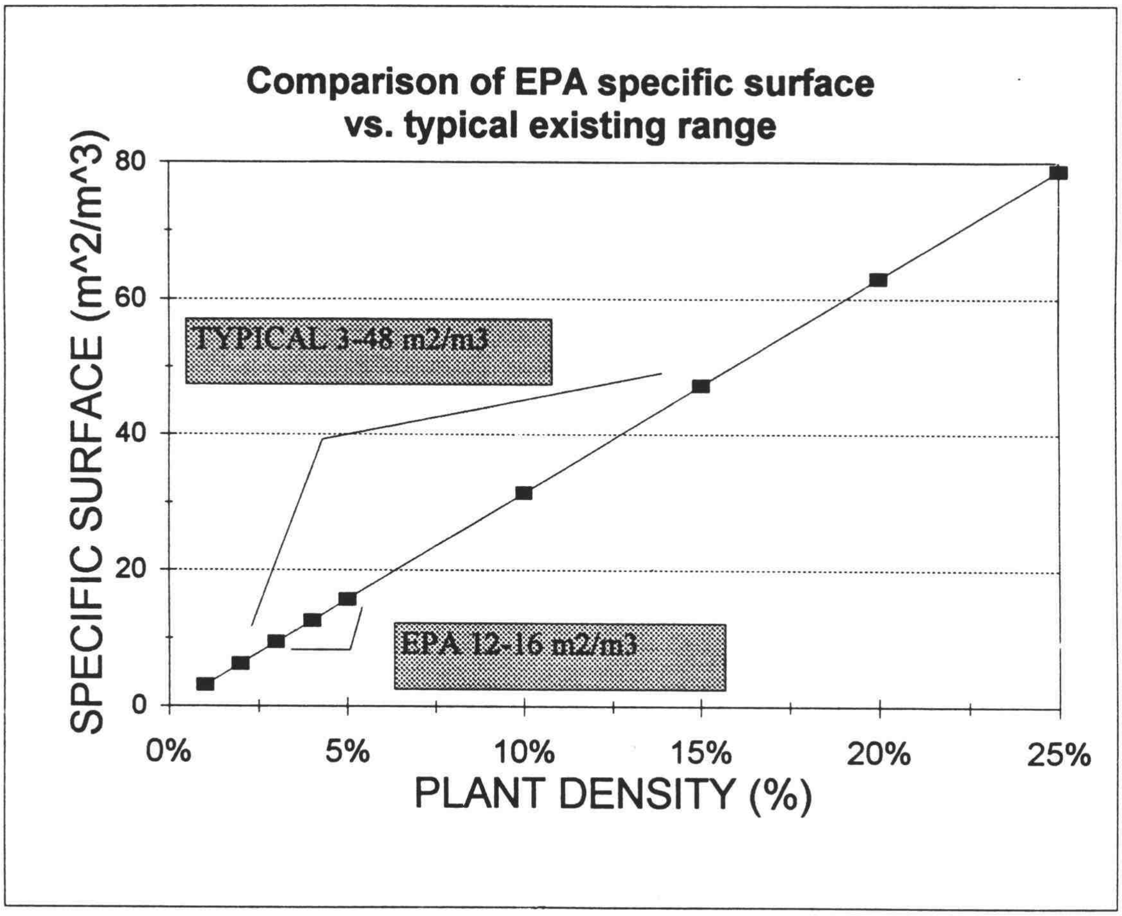


Figure 3.2 Graph of specific surface ranges

that the live bulrush stems supported a similar, but lower density periphyton community than plastic rods (Goldsborough and Hickman 1991). In contrast, Hatano found that the populations of bacteria in an SFS wetland were 2-3 orders of magnitude larger in planted cells than in plain gravel cells, indicating that plants in some way provide oxygen or nutrients conducive to bacterial growth (Hatano 1993). Benham and Mote (1993) report that TOC removal was greater in stock tanks containing bulrush than in tanks containing wooden rods.

Constructed wetlands also differ from conventional reactors in having multiple potential sources of oxygen supply and demand. Plants are thought to provide oxygen to the treatment system by pumping oxygen to their roots. Some research indicates a daily oxygen supply to the root zone of 5 g/m^2 (Reddy and Debusk 1987, Reed et al. 1988, Rogers et al. 1991), while others report very little excess oxygen available (Brix #41 1993, Wetzel 1993). Young macrophyte stems support higher internal oxygen transport pressure than do older stems (Stengel 1993, Brix #41 1993). However, wetland sediments may produce as much as 30% additional oxygen demand (Sculthorpe 1967). Dying stems also release dissolved organic carbon which produces additional oxygen demand. Overall, constructed wetlands still are thought to be rate limited by the availability of electron acceptors (O_2 or NO_3^-) (Reddy and DeBusk 1987).

In a biofilm reactor, if electron acceptors are supplied in stoichiometric balance to electron donors, then treatment performance is proportional to surface area. If oxygen is limiting in wetlands one would expect predictable rapid removals until the oxygen is exhausted, followed by reduced removal rates and somewhat unpredictable behavior after exhaustion (Williamson and McCarty, Jan 1976).

In summary, while biofilm surface areas are assumed to be the major treatment mechanism for biological transformation of organic carbon in constructed wetlands, their contribution to treatment and their relationship to plants, oxygen and detritus are complex and not well understood.

3.4. Objectives

The objectives of this study are as follows:

1. Does biofilm surface area (BSA), expressed as plant density, effect wetland treatment efficiency?

2. Is oxygen limiting in these systems?

3. Do biofilms on bulrush perform similarly to biofilms on inert substrate?

The major drawback to the use of constructed wetlands for wastewater treatment has been the need to set aside large areas of land as required by the current design equations. However, if as studies indicate, most of the treatment occurs in the first 20% of the system (Gearheart 1992), then a better understanding of how the microbial treatment occurs in the system could reduce area requirements and improve constructed wetland efficiencies.

3.5. Methods and Materials

The experiment was designed to compare organic carbon removal by biofilm surface areas under varying conditions of light and organic carbon loading.

3.5.1. EXPERIMENTAL SET-UP

Twenty-four batch experiments measuring the removal of total organic carbon (TOC) in an environment simulating a constructed wetland were carried out between November 1993 and March 1994 in Corvallis, Oregon. Six variations in the amount of biofilm surface area in the test tanks (referred to as % plant density) were each tested under two concentrations of influent carbon (High and Low) and two lighting conditions (Light and Dark). Three ROD HIGH tanks contained acrylic rods, at a starting density of 25% which was decreased over time. Three ROD LOW tanks started at zero density which was increased over time. Four MATURE BULRUSH tanks began with mature bulrush (*Scirpus acutus*) at 15% or 20% density, which was cut back during the experiment to decrease density. Two YOUNG BULRUSH tanks began with newly planted bulrush roots/stems at 7.5% initial density. Finally, three WATER-ONLY tanks held soil and water only. The water-only tanks provided a baseline for the soil and water column contribution to carbon removal. The rods were used because 1) the surface area is more readily measured, 2) they provided some assessment of whether plants act simply as inert supports for microbes, and, 3) the rods provided a control for time effects. The detailed treatment structure is shown in Table 3.1. The shaded portion represents a balanced treatment structure used for part of the statistical analysis.

The batch experiments were conducted in a greenhouse with diurnal ambient temperature ranging from 60°F to 80°F. Fifteen rectangular 18-gallon, Rubbermaid Roughtotes (TM) (35.6 cm W X 50.8 cm L X 40.6 cm D) were used as tanks to create a simulated wetland environment. All tanks were filled to a depth of 10 cm with river loam from the Willamette River from Corvallis Landscape Supply, Corvallis, OR. They were then attached to a through-flow system to allow acclimation of the microbial population and plants to

TABLE 3.1 DETAILED TREATMENT STRUCTURE

LEVEL 1:

HIGH RODS			LOW RODS			MATURE BULRUSH				YOUNG BULRUS		WATER ONLY		
R2	R3	R5	R1	R4	R6	B1	B3	B5	B6	B2	B4	W1	W2	D1
25	25	25	25	25	25									
20	20	20	20	20	20	20	20	20		7.5	7.5			
15	15	15	15	15	15	15	15	15	15	7.5	7.5			
10	10	10	10	10	10	10	10	10	10	7.5	7.5			
5	5	5	5	5	5	5	5	5	5	5	5			
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

[medium shading] Balanced ANOVA for split-split-split plot analysis and analysis of density treated as continuous variable

[dark shading] Unbalanced ANOVA uses balanced treatments plus these

[light shading] Young Bulrushes analyzed separately

Numbers in table represent percentage plant densities

Each density of Level 1, tested in each of four conditions:

LEVEL 2: (Within each bin at each density)

LOW ENSUR		HIGH ENSUR	
LIGHT	DARK	LIGHT	DARK

the influent (Fig 3.3) after being placed on a greenhouse table (1.4 m X 3.7 m) in random order. The water volume with no rods or plants was 50.4 liters. Inflow to each tank was controlled by a clamp for even flow to each tank of about 105 ml/min. This resulted in a theoretical retention time during acclimation of approximately 8 hours.

ENSUR(TM), Vanilla flavor, was used as the carbon source. This is a nutritional liquid intended for use by older individuals needing to increase their calorie intake. The components include (by weight) protein (3.5%), fat (3.5%), carbohydrate (13.6%), trace vitamins and minerals and water. Two concentrations of ENSUR were used, 0.015% and 0.04%. Before testing at a given concentration, steady state was established by running that concentration in the through-flow system for at least three retention periods. Bulrush stems from a constructed wetland pond fed by river water (at Pope and Talbot, Inc. in Halsey, OR) were placed in the influent reservoir as a common source of microbial population.

Calibration tests comparing total organic carbon (TOC) and biochemical oxygen demand (BOD) for various concentrations of ENSUR were run. A consistent ratio of 1.7:1, BOD:TOC was found. For the low load ENSUR (concentration at 0.015%), TOC equaled 17 mg/l, corresponding to BOD of 27 mg/l, typical of influent to a constructed wetland following secondary treatment. For the high load ENSUR (concentrations at 0.04%), TOC equaled 43 mg/l, corresponding to 74 mg/l BOD, typical of influent to a constructed wetland after advanced primary treatment. While the tests were completed as batch tests, these BOD loadings would be similar to a load of 70 kg/ha/day and 194 kg/ha/day, respectively, in a typical wetland system.

Artificial light was provided by two high-pressure sodium vapor lights. Tank position relative to the lights was randomized. During the acclimation period the lights were left on for twelve hours (from 6 am to 6 pm) to

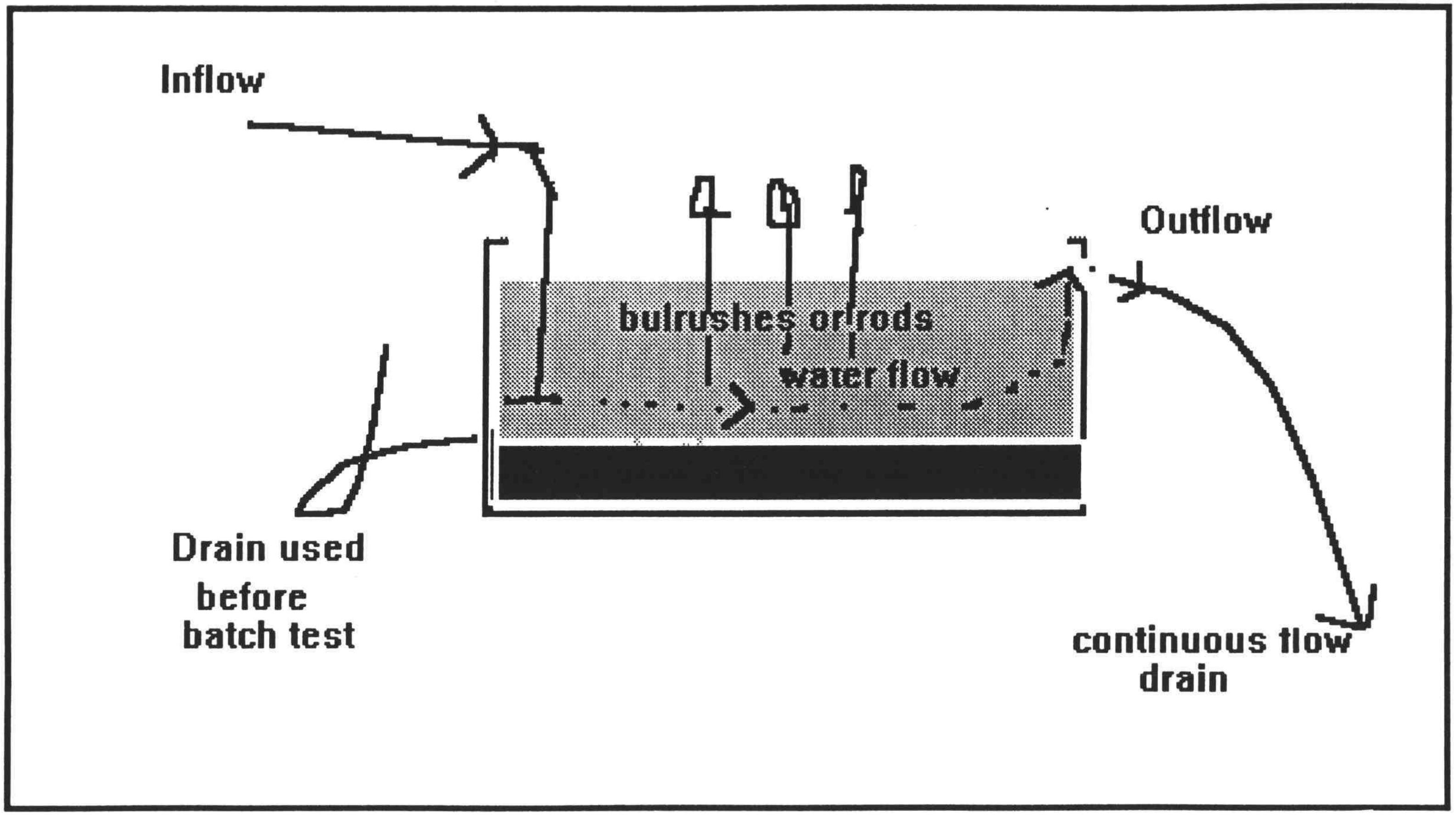


Figure 3.3 Diagram of flow through tanks

supplement the direct sunlight coming to the greenhouse during the main portion of the daylight hours. Tests were run between 4 pm one day and 8 am the next day in winter months. For the LIGHT condition testing artificial lights were left on. For the DARK condition testing, all lights were off.

3.5.2. RODS: ARTIFICIAL BIOFILM SURFACE AREA

The acrylic rods were 1.27 cm in diameter, clear and of a low reactivity. This diameter was chosen to match the assumed size of bulrushes used in specific surface area calculations in the Environmental Protection Agency Manual (EPA, 1991). The rods were cut into 45 cm lengths and suspended from copper rods in groups of fourteen. Each set of fourteen rods was equivalent to 1% plant density. These rods were placed in the tanks in August 1993 and were acclimated with low levels of influent (0.02%) for three months. Visible clear to light green biofilms grew on the rods, with some dark green algae growing near the bottoms.

During the experiments, rod density in the ROD HIGH tanks was reduced by 5% at a time. For each reduction in density, five percent of the rods from a ROD HIGH tank were moved to a ROD LOW tank chosen at random.

3.5.3. BULRUSH (Scirpus acutus): LIVING BIOFILM SURFACE AREA

Bulrush rootstock (*Scirpus Acutus*) for the YOUNG BULRUSH tanks were planted in six tanks with 30 roots per tank. Over three months, these grew to a density of 7.5%. Bulrush for the MATURE BULRUSH tanks were obtained from the same source as the young bulrush roots and from a pilot wetland at Pope and Talbot pulp mill, Halsey OR. The mature bulrush included both live and dead stems and had highly evolved root systems.

All six bulrush tanks were acclimated in the same flow system as the rods from October through December. During this time, many dead stems began to decay and many new stems grew. Before testing, stems were counted and diameters estimated. The surface area was then adjusted in each tank by both cutting stems and by turning over stems so that the surface area in the tanks was 20% for three MATURE BULRUSH tanks, 15% for one mature tank, and 7.5% for the YOUNG BULRUSH tanks. As testing proceeded from high density to low density, quadrants of 9 cm X 10.2 cm were created in each bulrush tank and randomly cut to reduce the density of vegetation and detritus in each tank by 5% at a time. When the bulrush were cut down, the stems and above ground roots were cut off at the soil surface, leaving some roots in the soil. The number of green standing stems as compared with standing dead and detrital stems varied widely. The stems in the young bulrush tanks were almost entirely green while the biomass in the mature bulrush tanks were approximately 1/3 to 1/2 green at any given density.

3.5.4. BATCH TEST PROCEDURE

Batch testing was conducted for a period of approximately 16 hours. TOC and oxygen samples were taken at the approximate geometric center of the tanks. TOC samples were taken immediately after filling and at 5 more times at approximately 1 hour, 3 hours, 5 hours, 7 hours and 16 hours from the start. Dissolved oxygen was measured at the start, after about 6 hours, and at the end. Temperature measurements also varied over the course of the batch tests. The average high temperature was 18.0°C. The average low temperature was 17.2°C.

Samples were preserved by refrigeration at 4°C until testing. No preservative was added. TOC was measured with the Dohrmann DC-190 High-Temperature TOC Analyser (Sunnyvale, CA) by the difference method, total carbon minus inorganic carbon. Dissolved oxygen was measured with a portable YSI 50b dissolved oxygen probe. Note that this is only a measurement of the dissolved ambient oxygen in the tanks. Oxygen concentration at the biofilm surface could differ somewhat, especially in the denser configurations where rods or bulrushes can be touching. However, the dissolved oxygen measured does indicate the general availability of oxygen remaining. Microbial populations were assessed qualitatively twice during the experiment.

3.6. RESULTS

3.6.1. RATE MODEL FOR THE BATCH DATA

Twenty-four batch tests were run, testing TOC removal by six densities of rods and five densities of bulrush under four different conditions:

Ensur Low - Light
Ensur Low - Dark
Ensur High - Light
Ensur High - Dark

The experiment was designed to test 1) whether plant density effected treatment rates, 2) whether oxygen was limiting, and 3) whether bulrush or artificial substrates removed carbon more efficiently. In order to evaluate the batch test results, rate constants, k, were developed for each tank in every batch test. It was expected that the rate constants would follow a first order model, where:

$$\ln (Ce/Co) = (-kt) \qquad \text{(Eq. 3.2)}$$

Ce = concentration at a given time
Co = initial concentration
k = rate constant
t = time

During each batch test, 6 measurements of TOC were taken. The first TOC measured value was used as the Co value. The last TOC measurement was taken at 16.5 hours (on average) later. In addition, oxygen was measured at the start, at T3 (5.5 hours average) and at the end (16.5 hours average). Using the equation above a linear regression was run on the data, with the intercept driven to zero.

When the initial regressions were completed, it was found that more than 70% of the data showed an r^2 value of over 0.7. Two examples of the data from these tanks are illustrated in Figure 3.4. However, the first order model did not fit the other 30% of the data. The data which did not match the first order model was typical of two different types of tanks, showing two different patterns of carbon removal. Mature bulrush tanks in which oxygen was very limited (O_2 < 1 mg/l) at T3 (about 5.5 hours), the time of the third sampling, did not fit the model well. Tank B5, Figure 3.5 is an example of this behavior. This was common in bulrush tanks at higher densities. The other pattern occurred in rod tanks which seemed to have a lag phase at the start (see Tank R2, Fig 3.5).

The first order model was found to fit the oxygen limited tanks if only the data before oxygen limitation were used. Therefore, additional linear regressions using only the data from start to 5.5 hours were run on all tanks in which oxygen fell below 1 mg/l by T3. These were found to fit the first order model reasonably well.

The k rate constants without oxygen limitation were combined and analyzed.

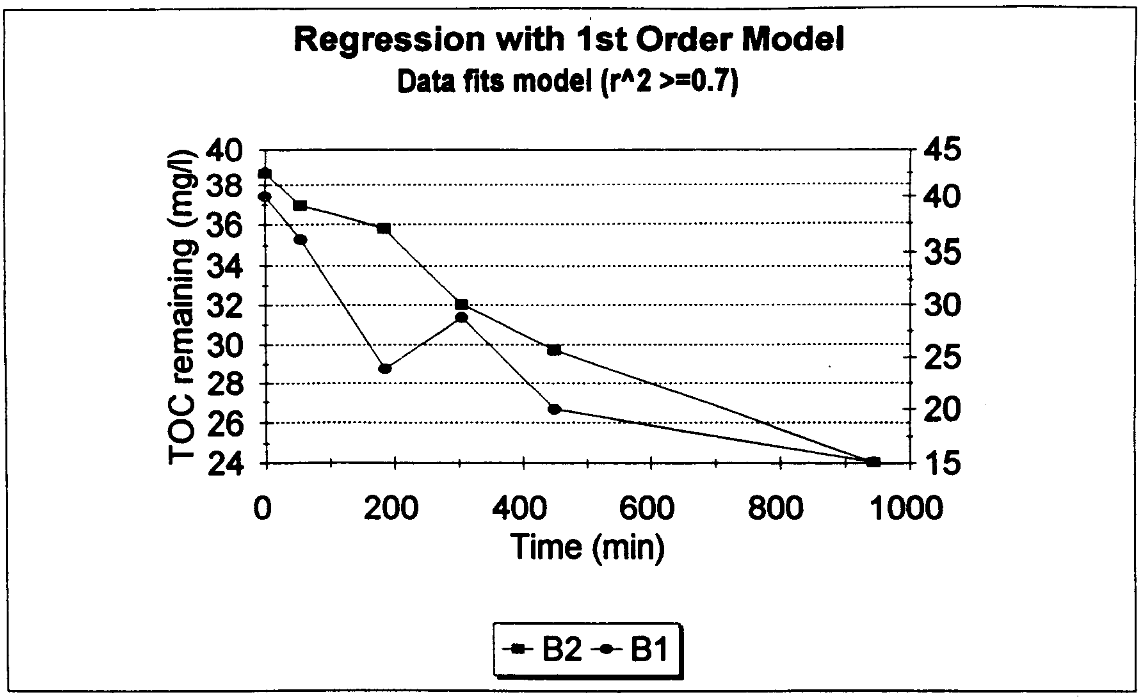


FIGURE 3.4 Typical data fitting 1st order model

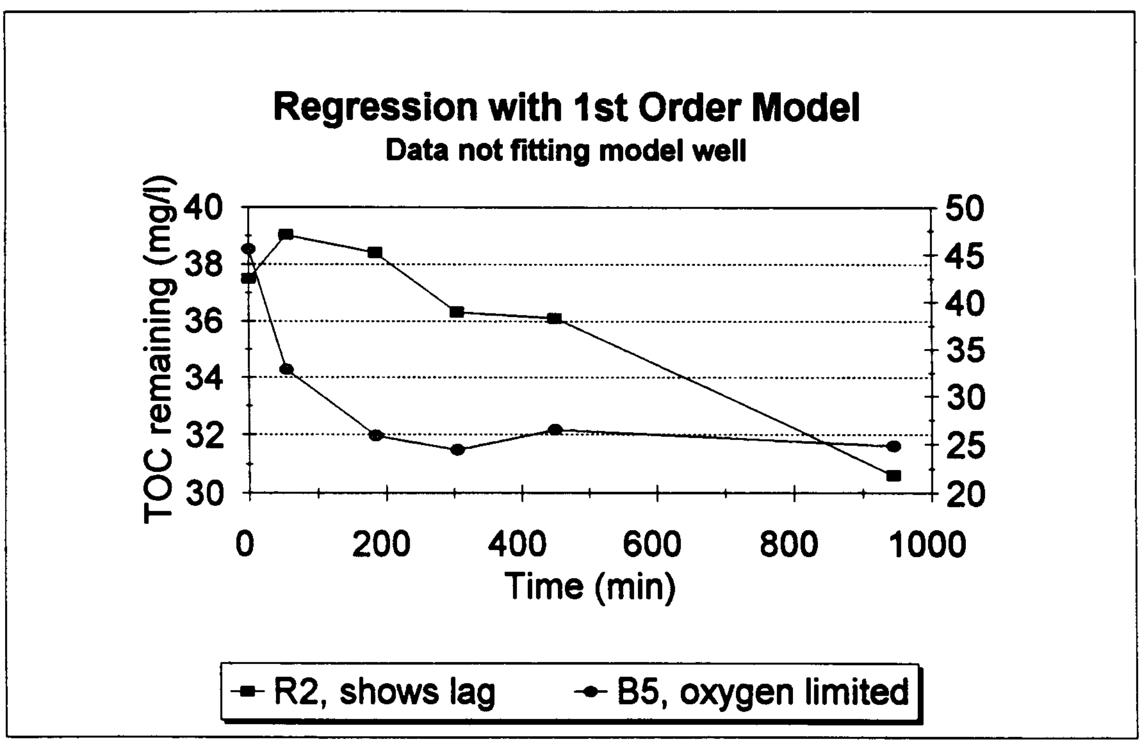


FIGURE 3.5 Oxygen limited bins

3.6.2. ANALYSIS OF FIRST ORDER, K RATES PRIOR TO OXYGEN LIMITATION

Using the first order rate constants estimated from data for which oxygen was not limiting, rates were graphed for each density and each configuration of load/light conditions. Figures 3.6 through 3.9 illustrate these data. Negative values with greater magnitudes indicate higher treatment rates.

For each type (RODS HIGH starting at 25%, RODS LOW starting at 0%, MATURE BULRUSH, YOUNG BULRUSH), some of the data show a trend to faster treatment rates with increasing stem/rod density, at least up to 15%. However, the data shows considerable variation, especially for the rods beginning at high density and for the three measurements of young bulrushes at 7.5%. Bulrush rate constants are generally much faster than rod rate constants.

As a further illustration of these trends, mean densities by type are presented in Figure 3.10. The mature bulrush and young bulrush each show a trend for faster treatment rate with higher density. However, the young bulrush treat more quickly than the mature bulrush at the same density. Rods also have faster treatment rates for higher densities but the trend drops off at 20% and reverses at 25%.

The water-only tanks are an average of the unacclimatized sterilized dirt tank and two acclimatized tanks that never had anything except water in them. One of the water tanks had a very thick algal mat that yielded high treatment rates and this tank accounts for the water rate being faster than the rod rate. The other water-only tank and the dirt tank degraded much slower than the rods.

In summary, a graphical review of the data indicates that density may be a significant factor in the variations in treatment rates when tanks are not oxygen limited.

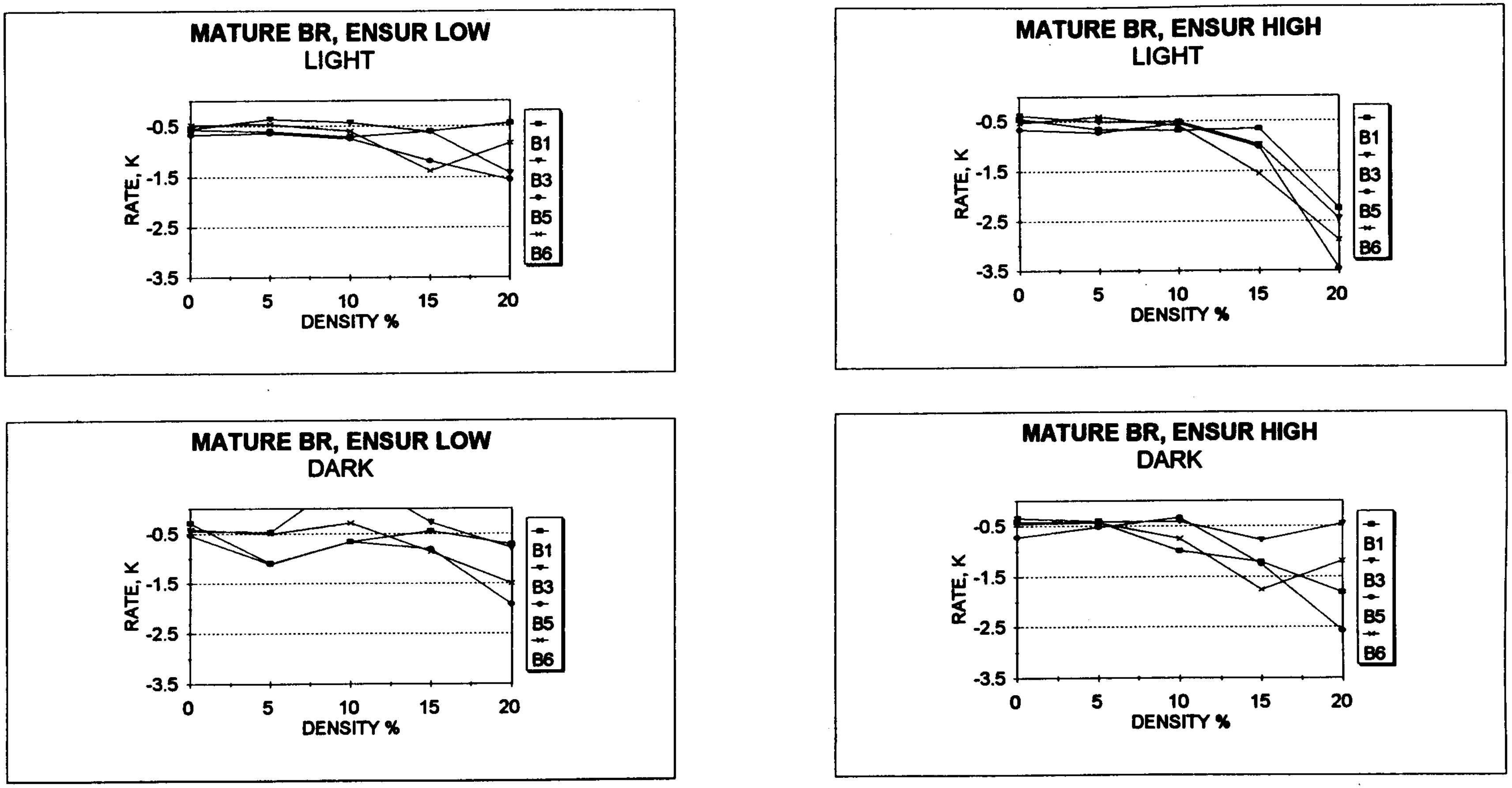


FIGURE 3.6 Mature Bulrush Bins performance

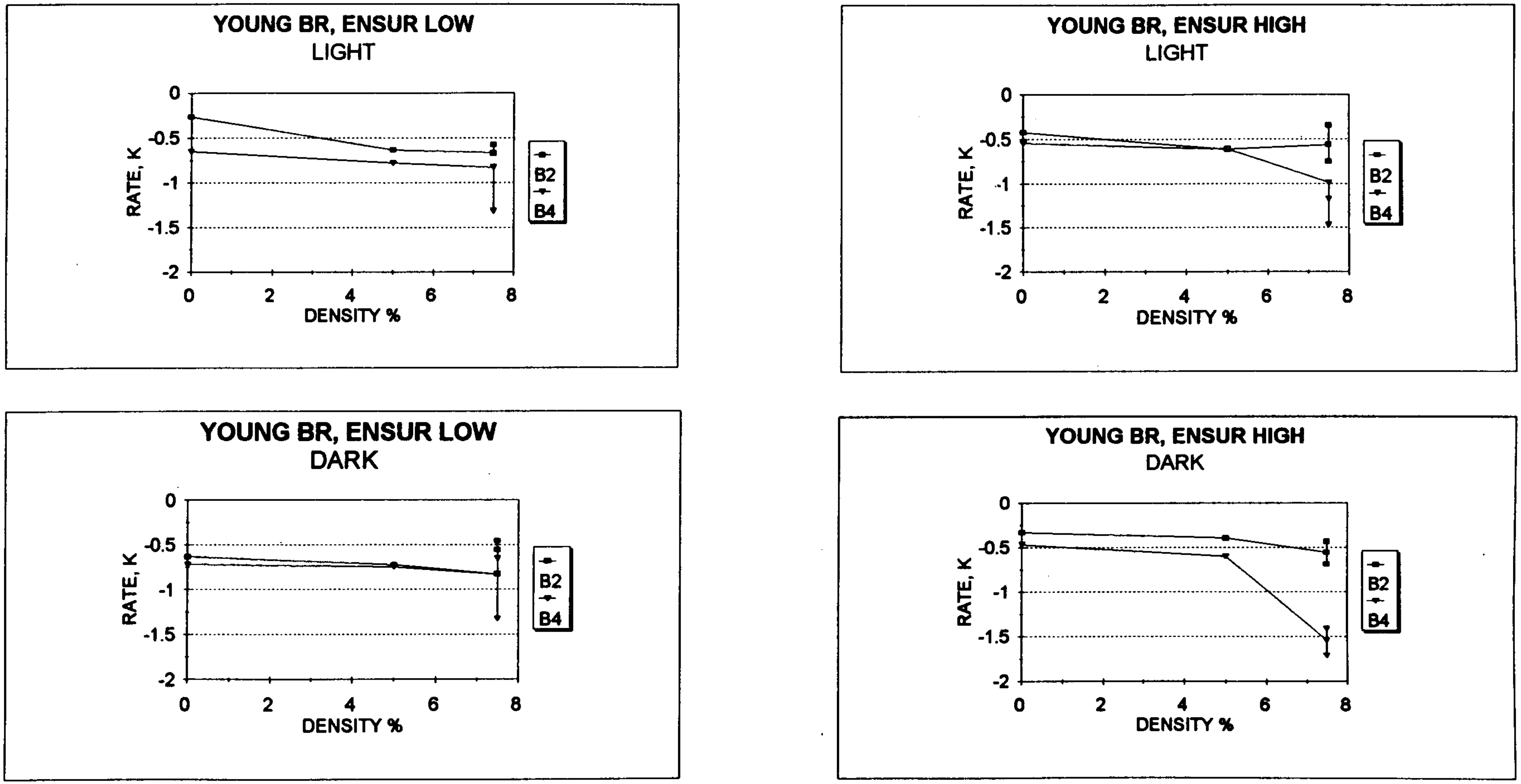


FIGURE 3.7 Young Bulrush Bins performance

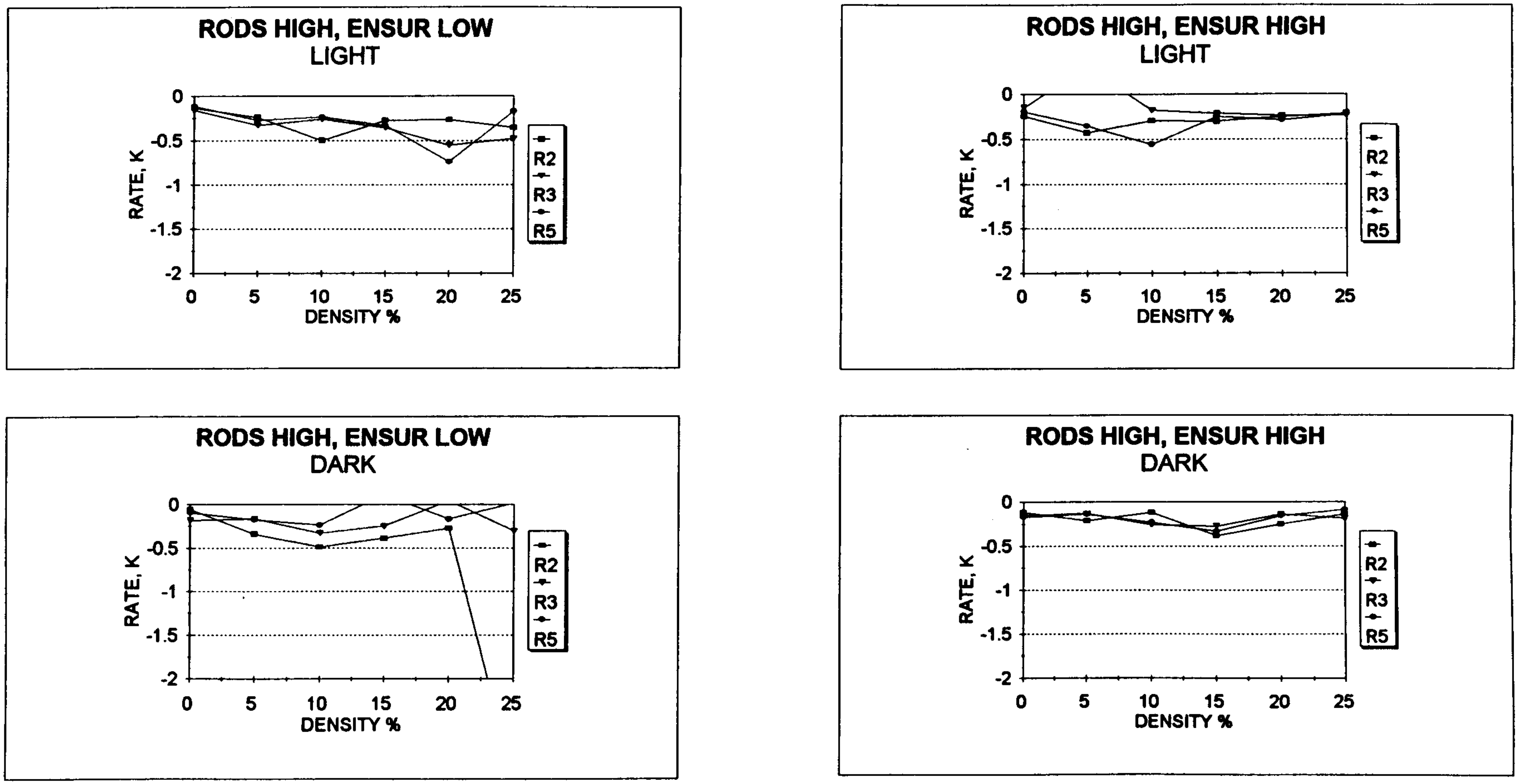


FIGURE 3.8 Rod High performance
(rods starting at 25 % density)

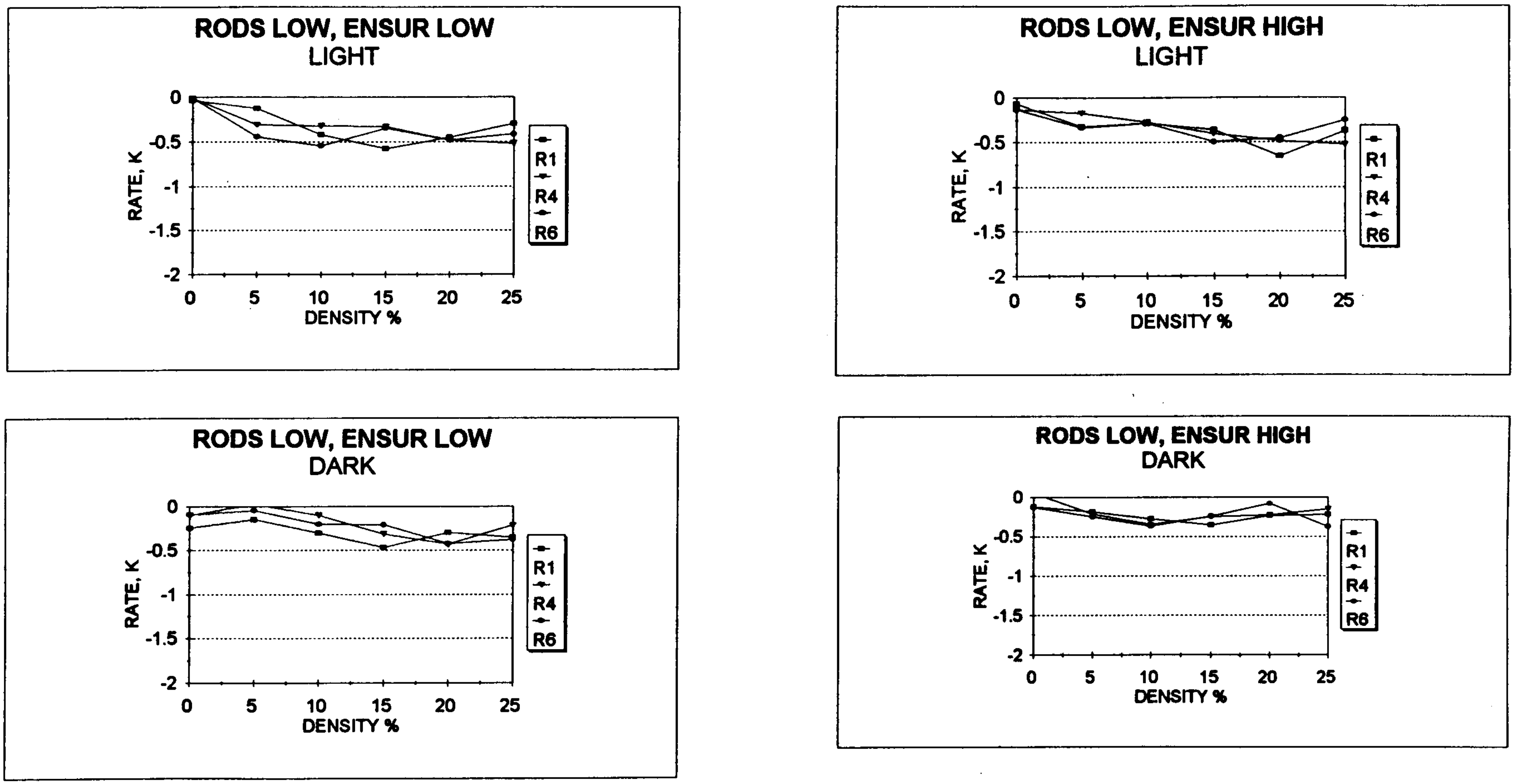


FIGURE 3.9 Rod Low performance
(rods starting at 0% density)

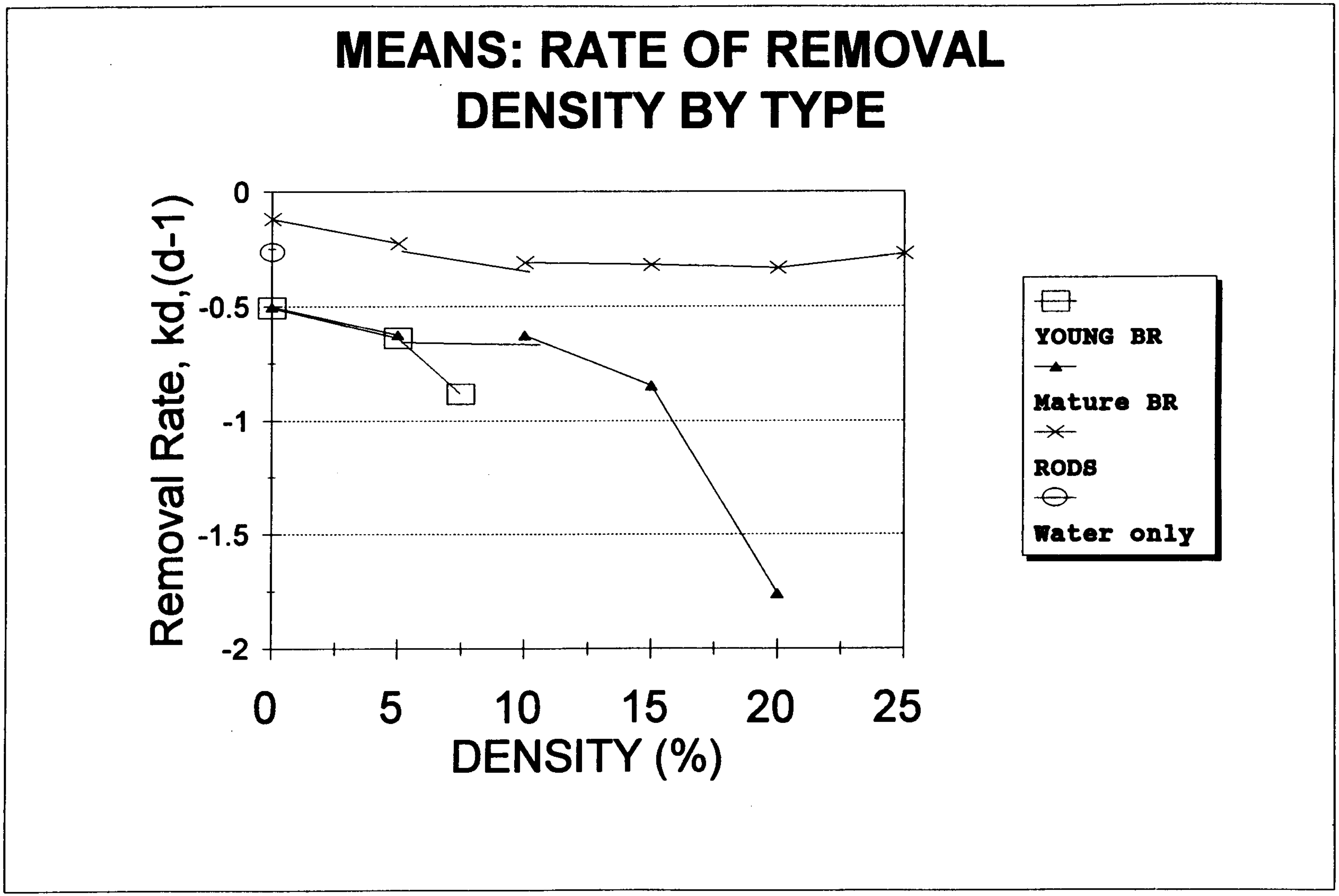


FIGURE 3.10 Rate of removal, density by type

3.6.3. SPLIT-SPLIT-SPLIT-PLOT STATISTICAL ANALYSIS

The experimental design does not fit a completely randomized model and so a standard factorial analysis is not appropriate to establish statistical significance of effects. Instead, a split (density) - split (ENSUR) - split (light) plot analysis was used. The non-random variables included tanks, density, and ENSUR level. The tanks were not randomly varied since the bulrushes and soil could not be moved from tank to tank in a random fashion. The density had to be tested in descending order since it was possible to lower density by cutting but not to raise it. The ENSUR was always tested with low load first, followed by high load, to ensure microbial populations were acclimated in the same pattern at each density.

Two other significant statistical problems exist in the design. First, it was not possible to test the mature bulrush at 25% or the young bulrush above 7.5%. As a result, there was an unbalanced design (Table 3.1). Second, density is confounded with time. It was not possible to run all tests at once. Testing took place over 2 months. Thus, any time related effects such as changes in the microbial community in the tanks could not be differentiated from density effects. However, by cutting down the bulrush one would expect treatment rates to go down while maturation of microbes would be expected to create steady state or faster treatment rates. The time effect should be conservative. In addition, three rod tanks were decreasing in density and three tanks were increasing in density in time which provides a check for the time effect.

For all the analyses described, significance was considered to be at the 95% level with $p <= 0.05$. Means tests used this criteria.

3.6.4. MAIN EFFECTS: DENSITY, TYPE, LIGHT, ENSUR

The split-split-split plot analysis was run on the balanced portion of Table 3.1, in SAS, using the k rates developed with data prior to oxygen limitation. For this analysis, density was treated as category variable. The model would be:

Removal rate = f(type, density, ensur,light)

This included all the rods and the three mature bulrush tanks starting at 20%. The error for the split plot portions were pooled and the new F values with the pooled error calculated. The results are shown in Table 3.2.

Main effects due to type (2 types rods, mature bulrush), density (within type), ENSUR and light are very significant (Type, $p = 0.0006$; Density, $p < 0.0001$; ENSUR, $p < 0.0008$; Light, $p < 0.0001$). This reflects the trends noted in the graphical analysis. The effects are highly significant despite the variation shown in Figures 3.6-3.9. Bulrushes provide faster treatment than rods. In general, higher densities have faster treatment rates than lower densities. In addition, the light condition provides faster treatment rates than the dark condition. For ENSUR loading the treatment rate is faster at the higher ENSUR loading rate in bulrushes and varies in rods.

A second analysis was run on the balanced data treating density as both a linear (continuous) variable and as a category variable, yielding the following model:

Removal rate = f(type,ENSUR,light) + f(density continuous) + f(density as category)

This model indicates the proportion of the variation resulting from density that can be explained as a linear

TABLE 3.2 TREATMENT RATE ANOVA FOR BALANCED CASE

ANOVA For Balanced Split-Split-Split Plot

TREATMENT RATES, k
data from rods high, rods low and bulrush bins B1, B3, B5
0-20% density

main effects (outlined box)
significant interactions (shaded box)

from SAS printout

Note: SS = Type III

Source:	DF	SS	MS	Pooled Layout	Pooled df	Pooled MS	F	p(**)
Type	2	14.8593985	7.4296993		2	7.429699	32.07	0.0006
Bin(Type)	6	1.3899829	0.2316638	error a	6	0.231664		
Density	4	6.4213633	1.6053408		4	1.605341	19.07	0.0000
Density * Type	8	7.0328838	0.8791105		8	0.879111	10.45	0.0000
Density*Bin (Type)	24	2.0199341	0.0841639	error b	24	0.084164		
Ensur	1	0.3145032	0.3145032		1	0.314503	13.75	0.0008
Ensur * Density	4	0.9688761	0.2422190		4	0.242219	10.59	0.0000
Ensur * Type	2	0.8579987	0.4289994		2	0.428999	18.76	0.0000
Ensur*Density*Type	8	3.0138277	0.3767285		8	0.376729	16.47	0.0000
Ensur*Density*Bin (Type)	30	0.6860139	0.0228671	error c	30	0.022867		
Light	1	0.3217677	0.3217677		1	0.321768	19.84	0.0000
Light*Ensur	1	0.0034217	0.0034217		1	0.003422	0.21	0.6484
Light*Density	4	0.3614016	0.0903504		4	0.090350	5.57	0.0007
Light*Ensur*Density	4	0.3150060	0.0787515		4	0.078752	4.86	0.0018
Light*Type	2	0.0224122	0.0112061		2	0.011206	0.69	0.5055
Light*Ensur*Type	2	0.0290568	0.0145284		2	0.014528	0.90	0.4120
Light*Density*Type	8	0.1847406	0.0230926		8	0.023093	1.42	0.2069
Light*Ensur*Density*Type	8	0.7954352	0.0994294		8	0.099429	6.13	0.0000
remaining Error	60	0.9732179	0.0162203	error d	60	0.016220		

** p values < 0.0001 show as 0

relationship. About 88% of the variation attributable to density can be explained by the linear density.

A split-split-split-plot was run in SAS for the unbalanced design (see Table 3.1) including the 25% rod data and all the mature bulrush tank data but not the young bulrush data. While interpretation is more difficult with unbalanced data, the trends of significance for main effects were all the same as in the balanced group.

Significant interactions were found for:

density X type,
ENSUR X density,
ENSUR X type,
light X density,
ENSUR X density X type, and
light X ENSUR X density X type

in all three analyses cited above. While these significant interactions could qualify the interpretation of the main effects, a more detailed analysis by each type shows that interactions do not invalidate the effects of density. However, rods, mature bulrushes, and young bulrushes behave quite differently in relation to density, light and ENSUR which accounts for the interactive effects related to type. For example, higher ENSUR loads are associated with better treatment rates in dense bulrush while low ENSUR loads are associated with better treatment rates in dense rods. The nature of the interactive effects with density will be analyzed further in the discussion section.

3.6.5. <u>TOC REMOVAL EFFICIENCY</u>

In addition to the rate values for carbon removal, an efficiency measure was developed. The batches ran for an average of 16.5 hours +/- 0.6 hr (4%). The efficiency measure was calculated as:

$$\text{Efficiency } (\%) = \frac{(\text{Influent TOC} - \text{End TOC})}{\text{Influent TOC}} \times 100 \qquad \text{(Eq. 3.3)}$$

where Infl TOC = average value of influent for batch
End TOC = value of last reading for each tank

The measure yields a percentage TOC removal value. Since the total TOC removal will be affected by oxygen limitation, this provides a comparison of the effectiveness of the treatment when oxygen limitation is included. The efficiency values were analyzed for the balanced portion of the split-split-split plot design.

The results are presented in Table 3.3. For removal efficiency, overall type effects are not significant ($p = 0.0583$) in contrast to type effect for rates ($p = 0.0006$). Density is significant ($p=0.005$) but less significant than was true for the non-oxygen limited case. ENSUR and light effects are very significant ($p < 0.0001$).

Figure 3.11 shows that the efficiency of bulrushes is greater than the efficiency of the rods, consistent with findings for the removal rates. The young bulrush (which are less oxygen limited) perform better than the mature bulrush even at a density of 20%. The analyses run for a model including density as a linear variable showed that linear density accounted for 83% of the total density variation.

Analysis of the unbalanced model followed the same trends seen in the balanced model; significance levels are similar (for type, $p = 0.03$; for density, $p =0.0018$) to the balanced model.

For all three statistical analyses of efficiency data, interactions still occur but are of lesser significance. The interaction of ENSUR and density is not significant for removal efficiency ($p = 0.8779$ balanced model, $p = 0.9635$ unbalanced model).

TABLE 3.3 EFFICIENCY OF REMOVAL ANOVA FOR BALANCED CASE

ANOVA For Balanced Split-Split-Split Plot

EFFICIENCY
data from rods high, rods low and bulrush bins B1, B3, B5
0-20% density

main effects (open box)
significant interactions (shaded box)

SAS printout

Note: SS = Type III

Source:	DF	SS	MS	Pooled Layout	Pooled df	Pooled MS	F	p(**)
Type	2	0.2234460	0.1117230		2	0.111723	4.73704	0.0583
Bin(Type)	6	0.1415100	0.0235850	error a	6	0.023585		
Density	4	0.1790019	0.0447505		4	0.044750	5.04256	0.0043
Density * Type	8	0.1554654	0.0194332		8	0.019433	2.18976	0.0658
Density*Bin (Type)	24	0.2129895	0.0088746	error b	24	0.008875		
Ensur	1	0.1673779	0.1673779		1	0.167378	27.59198	0.0000
Ensur * Density	4	0.0071933	0.0017983		4	0.001798	0.29645	0.8779
Ensur * Type	2	0.0484319	0.0242159		2	0.024216	3.99196	0.0290
Ensur*Density*Type	8	0.2017465	0.0252183		8	0.025218	4.15720	0.0019
Ensur*Density*Bin (Type)	30	0.1819853	0.0060662	error c	30	0.006066		
Light	1	0.1527694	0.1527694		1	0.152769	20.14000	0.0000
Light*Ensur	1	0.0005707	0.0005707		1	0.000571	0.26000	0.6120
Light*Density	4	0.0184912	0.0046228		4	0.004623	5.58000	0.0007
Light*Ensur*Density	4	0.1353647	0.0338412		4	0.033841	5.05000	0.0014
Light*Type	2	0.0218605	0.0109302		2	0.010930	0.61000	0.5467
Light*Ensur*Type	2	0.0024775	0.0012387		2	0.001239	0.94000	0.3963
Light*Density*Type	8	0.1364048	0.0170506		8	0.017051	1.47000	0.1874
Light*Ensur*Density*Type	8	0.0493423	0.0061678		8	0.006168	6.33000	0.0000
remaining Error	60	0.1968928	0.0032816	error d	60	0.003282		

** p values < 0.0001 show as 0

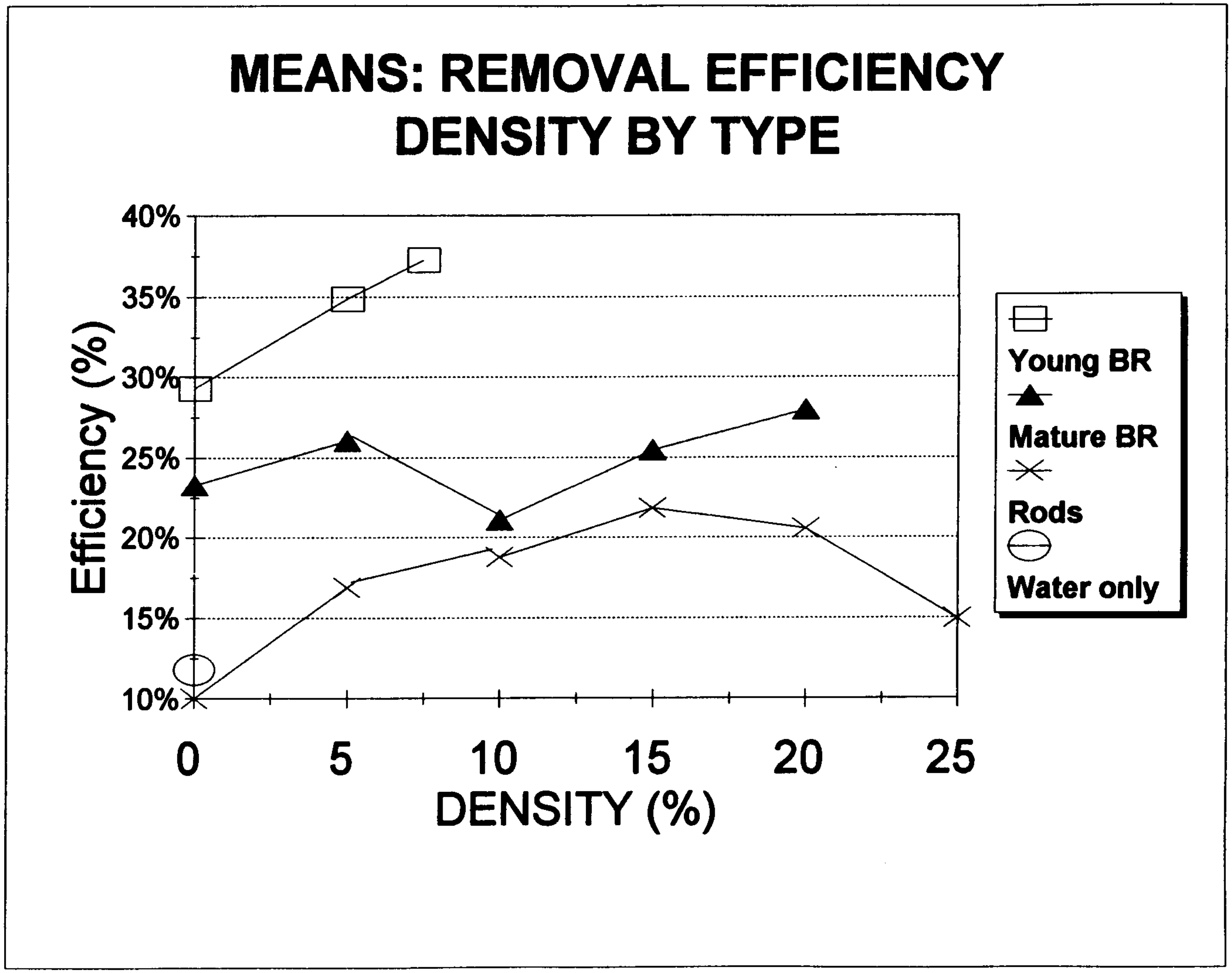


FIGURE 3.11 Efficiency of Removal, Density by Type

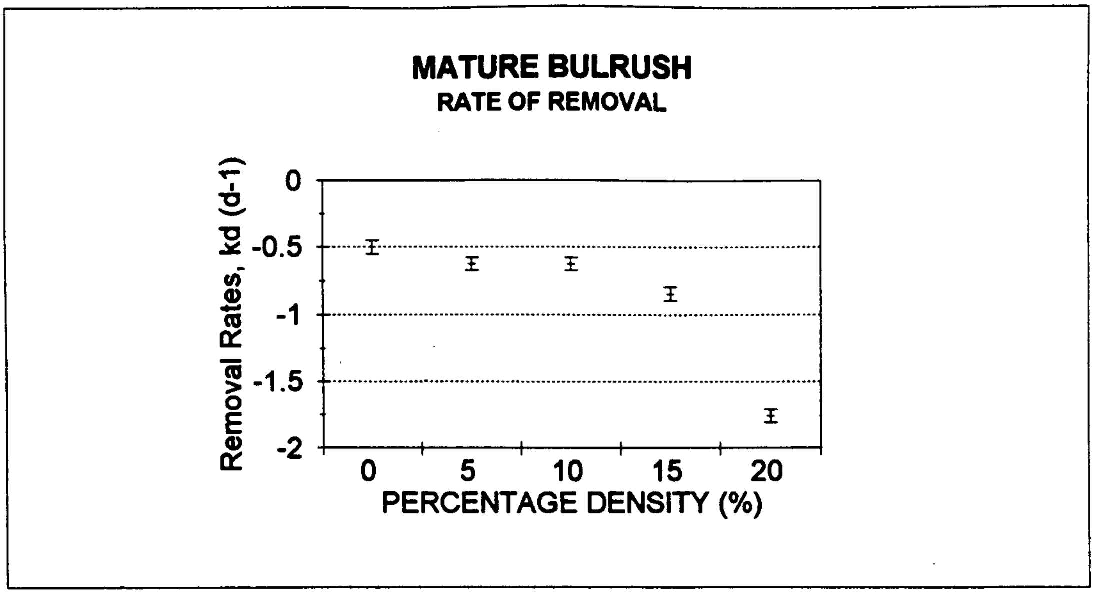
Providing light yields greater treatment efficiency in mature bulrushes but not higher treatment rates. Significant interactions in the statistical analysis of the combined data set primarily reflect differing behavior in the rods and bulrushes, and variant behavior at very low density (0-5%).

3.6.6. DETAILED RESULTS BY TYPE

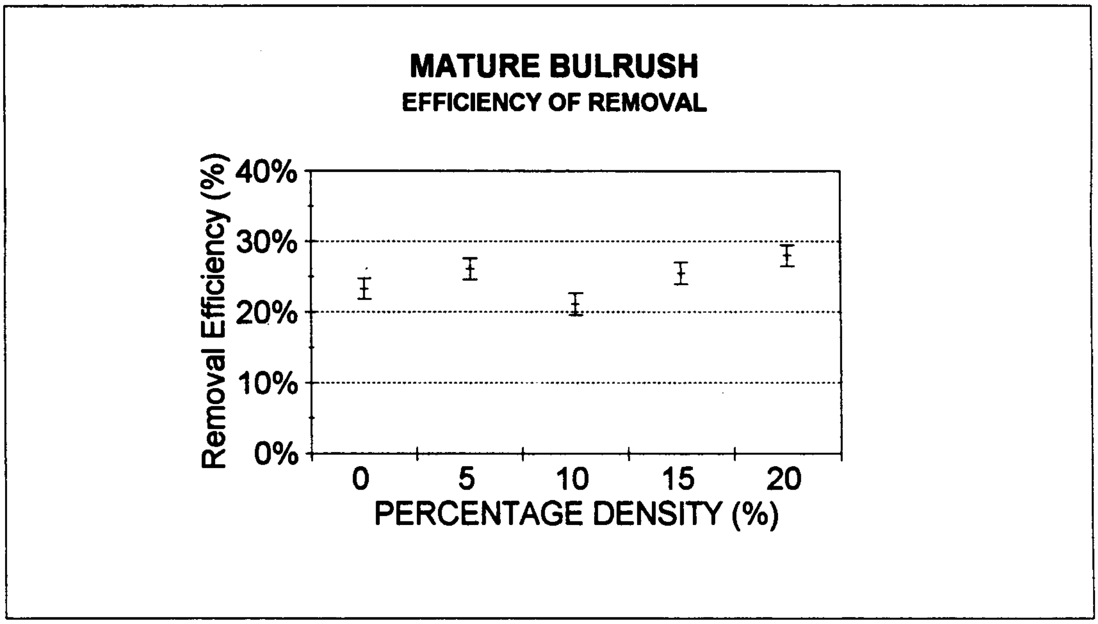
3.6.6.1. MATURE BULRUSH

Since understanding the behavior of mature wetland systems was a major objective of this study, a similar statistical analysis was run using just the mature bulrush data, leaving type out of the model. The means for removal rates and efficiency are shown in Figure 3.12. One would expect that higher treatment rates at increasing densities would be mirrored by greater removal efficiencies at increasing densities but this does not occur. The increase of treatment rate with density is a very strong effect ($p = 0.0018$). The rates of treatment at 15% and 20% densities are significantly different from each other and from 0-10% densities ($p < 0.0001$). The linear relationship of density with removal rate had an $r^2 = 0.72$. In contrast, density is not a significant factor for efficiency of treatment ($p < 0.85$). The rates represent behavior before oxygen limitation while the efficiency includes a period of oxygen limitation.

Light is not a significant factor in the removal rates ($p = 0.24$) when only the mature bulrush are considered. However, it is significant ($p = 0.009$) when efficiency is considered. This suggests that photosynthesis contributes some factor (perhaps oxygen or greater uptake) which improves performance in mature bulrush tanks over a longer time.



a)



b)

FIGURE 3.12
a) Mature bulrush rates of removal;
b) Mature bulrush efficiency of removal

Higher ENSUR loadings are associated with higher treatment rates and efficiencies ($p = 0.0004$).

3.6.6.2. YOUNG BULRUSH

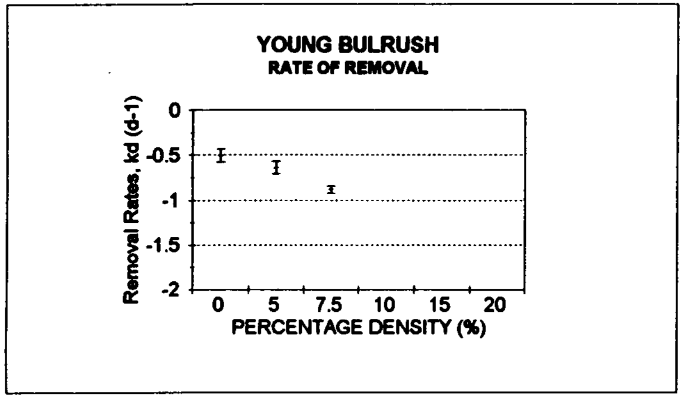
The data for the young bulrush were not included in either the balanced or unbalanced combined models. This data set constitutes the smallest data set and the 7.5% data shows high variability. Because young bulrushes are only occasionally oxygen limited, as expected, removal rates increase with density, efficiency increases relatively linearly (Fig. 3.13). The trends are similar to those of mature bulrush but none of the effects proved to be significant for rates or for efficiency.

3.6.6.3. RODS

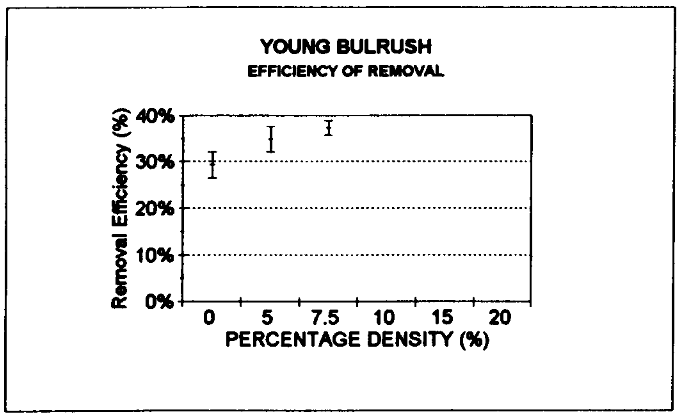
The mean removal rates and efficiencies for rods starting at low density are shown in Figure 3.14. As with the young bulrush, the efficiencies mirror the removal rates as would be expected. There was only rare oxygen limitation in the rod tanks.

A nearly linear relationship between density and rate exists for densities of 0-15%. At 20% the rate still increases with density but not as quickly, at 25% density the trend reverses. The ROD HIGH and the ROD LOW tanks performed differently. Their interaction will be detailed in the discussion and may account for reduction at 25%. In addition, light strongly effects performance in the rods ($p < 0.0001$). At 25% density, many rods were touching so light may not have penetrated.

Twice, microbial populations on the rods and bulrushes were checked qualitatively. The rods began with considerable pale green algae and bacteria, and later,

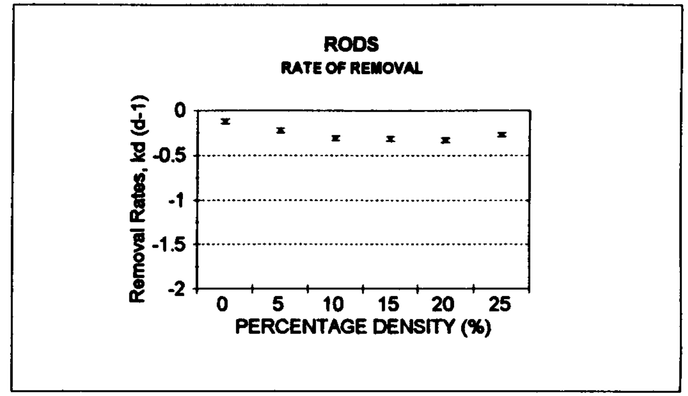


a)

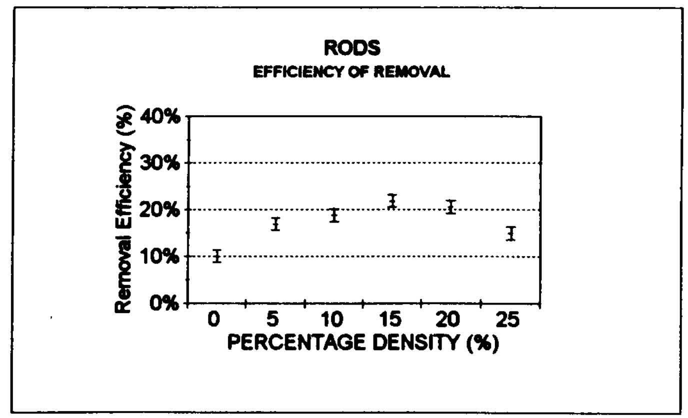


b)

FIGURE 3.13
a) Young bulrush rates of removal;
b) Young bulrush efficiency of removal



a)



b)

FIGURE 3.14
a) Rod rates of removal;
b) Rod efficiency of removal

developed dark green filamentous algae. The bulrushes had a much more diverse community with rotifers, worms, but very few algae.

3.7. Discussion

3.7.1. SURFACE AREA

The primary objective in this experiment was to assess whether treatment rates were proportional to surface area (plant density) as in conventional biofilm reactors. The experiment confirmed that treatment rates and treatment efficiencies would increase with increasing surface area (rod/stem density). A linear model relating removal rates and removal efficiencies to increasing density yielded $r^2 = 0.88$ and $r^2 = 0.83$, respectively, for the balanced, combined data. However, there are several limitations to these conclusions for each type of microbial attachment surface studied.

3.7.2. OXYGEN LIMITATION

The theory that treatment rates are proportional to surface area in biofilm reactors assumes that there is an adequate supply of electron acceptors to transform the waste. In a constructed wetland, one would expect that removal rates and removal efficiencies for organic carbon would be proportional to surface area only if sufficient oxygen was present. If oxygen was depleted one would expect removal rates to become erratic or drop off (Williamson and McCarty Jan 1976).

During the experiments, oxygen readings were taken at three points (at the start, at 5.5 hours and at 16.5 hours). Oxygen levels ranged from 10-12 mg/l in the influent water.

Within minutes of filling, the oxygen concentration had often already dropped 2-3 mg/l from the influent value.

By the third TOC sampling period (about 5.5 hours later), the oxygen in most mature bulrush tanks was depleted below 1 mg/l for densities greater than 10%, even at low ENSUR loadings. By 16.5 hours, the oxygen in all mature bulrush tanks was depleted below 1 mg/l. In many tanks, oxygen concentration was less than 0.1 mg/l (effectively zero).

The rod tanks still contained a typical 2-3 mg/l of oxygen after 5.5 hours, even in tanks with 25% density rods. Less oxygen remained in the tanks with high ENSUR loading than with low ENSUR loading. After 16.5 hours, the oxygen concentration in all rod tanks fell to below 1 mg/l at high ENSUR loading but not at low ENSUR loading.

The oxygen concentration in the young bulrush tanks was similar to that of the rods at 5.5 hours but was depleted below 1 mg/l in all tests after 16.5 hours.

From this oxygen data, one would predict that, if constructed wetlands act as biofilm reactors, there would be a decrease in removal rate after 5.5 hours in the mature bulrush tanks but not in the young bulrush and rod tanks. One might also expect a drop off in removal rate in the young bulrush tanks after 16.5 hours.

The data confirmed these predictions. For mature bulrush, removal rates <u>before</u> oxygen depletion increased with plant density, but once oxygen was depleted, density was not a significant factor in removal efficiency. During the batch tests the removal of carbon was not significantly greater in the tanks with plant density of 15% than it was in the 0%, 5%, or 10% tanks.

In two experiments, tanks were tested after a total of 24 hours, (eight hours after oxygen depletion occurred in the young bulrush tanks). No additional carbon removal was observed in the mature or young bulrush tanks. Continued removal occurred only in rod tanks exposed to light (with significant populations of epiphytes for photosynthesis).

Oxygen supply may also limit the total amount of waste degraded. Assuming that ENSUR is a reasonable surrogate for municipal waste, one would anticipate an oxygen demand of about 0.4-0.6 mg of oxygen per mg ENSUR (Tchobanoglous 1987). In these experiments, mature and young bulrush tanks typically removed 5-8 mg/l TOC at low loading and 13-20 mg/l TOC at high loading. The high loading removal is within range of the maximum removal anticipated with such an oxygen ratio. The removals are lower than expected for the low loading rates but this is consistent with the information reported by Knight et al (1993) that efficiency is less when the loading rate is low.

The final TOC values of 9-12 mg/l TOC (<= 20 mg/l BOD) found in most of the mature bulrush tanks at low loading rate is similar to the values reported for constructed wetlands. Given the very short retention period the results represent reasonable performance. The removal of carbon in the bulrush tanks was in the 30-60% range within 16.5 hours. The removals are within the same range reported by Gearheart (1992) (40-65%) over 4-8 days retention time. This suggests that in full-scale wetlands, little additional removal is occurring once oxygen is depleted and that wetland plants do not contribute significant oxygen.

3.7.3. PLANTS VS. RODS

Do plant surface areas perform similarly to inert surfaces? The literature suggested that acrylic rods would host similar but more extensive microbial communities than bulrushes. In contrast, the results of this experiment suggest that bulrushes perform better than rods and host quite different microbial communities.

Mature bulrushes reacted at higher rates and were more efficient at carbon removal than rods at similar densities. The community of bacteria in the bulrush tanks was very diverse as compared with the rods, including rotifers and worms but few epiphytes. Rods hosted large epiphytic communities, some bacteria but little else. Moreover, there may be symbiotic effects of plants and microbes. The bulrush tanks also contained grazing snails and there is evidence that a snail/microbial/macrophyte system is highly efficient, with snails maintaining very healthy biofilms (Bronmark 1989).

Plant uptake of carbon may play a role in increasing removal rates as compared with rods although this has not been quantified. Finally, the bulrush may have greater actual surface area than the stem densities suggest. When the tanks were cut back it was found that plant roots with many fine root hairs occupied a large portion of the top "soil layer" resulting in additional surface area for treatment. However, the number of root hairs and roots in the upper layer of soil in the young bulrush tanks was small and yet they performed better than the mature bulrush. This suggests that the other factors mentioned above are more important.

3.7.4. OTHER FINDINGS: YOUNG BULRUSH

None of the main effects were significant when young bulrush data were analyzed separately but the data set is very small and has relatively high variability. Young bulrush at 7.5% reacted similarly to the dense mature bulrush in that they were more effective at high ENSUR loadings and in light.

The performance trends for young bulrushes are similar to those of mature bulrushes but young bulrushes are less oxygen limited and have greater overall efficiency of carbon removal. A young bulrush tank at 7.5% density is more efficient than a mature bulrush tank at 20% density. The difference in behavior between the young bulrush and the mature bulrush could be caused by several factors: young bulrush may pump more oxygen to the roots and stems, reducing oxygen depletion (Brix, #41 1993). Detritus and sediments can produce oxygen demand. The lack of detritus in the tanks may reduce the additional oxygen demand. The younger plants may have greater carbon uptake although all tanks grew new young stems during the experiment in similar numbers except mature tank B3 which did not regrow. Wetzel (1993) suggests maintaining plants in a growth phase to aid in maximizing removal of carbon. There is not enough information to determine which effect caused the greater treatment efficiency in the young tanks.

3.7.5. OTHER FINDINGS: RODS

The rod data clearly demonstrate the trend of increasing treatment rates and greater treatment efficiency up to 15% density. However, 20% density does not improve treatment as much as might be expected, and 25% shows a falling off. It would appear that the optimum density for treatment by the rods was between 10-20%. More than one factor may contribute to this effect.

The rods were tested in six tanks, with three tanks increasing in density and three decreasing in density during the study. The tanks with increases in density showed less variability of performance and more consistent trends (Fig. 3.15). The microbial population was assessed qualitatively twice during the experiments. The microbial population found on the rods did change over time. Filamentous dark green algae was not present in tanks early in the testing but was present in all rod tanks for the later batch tests (appearing when ROD HIGH tanks were at 15% and ROD LOW tanks were at 10)%. Thus, there was a time-dependent effect in

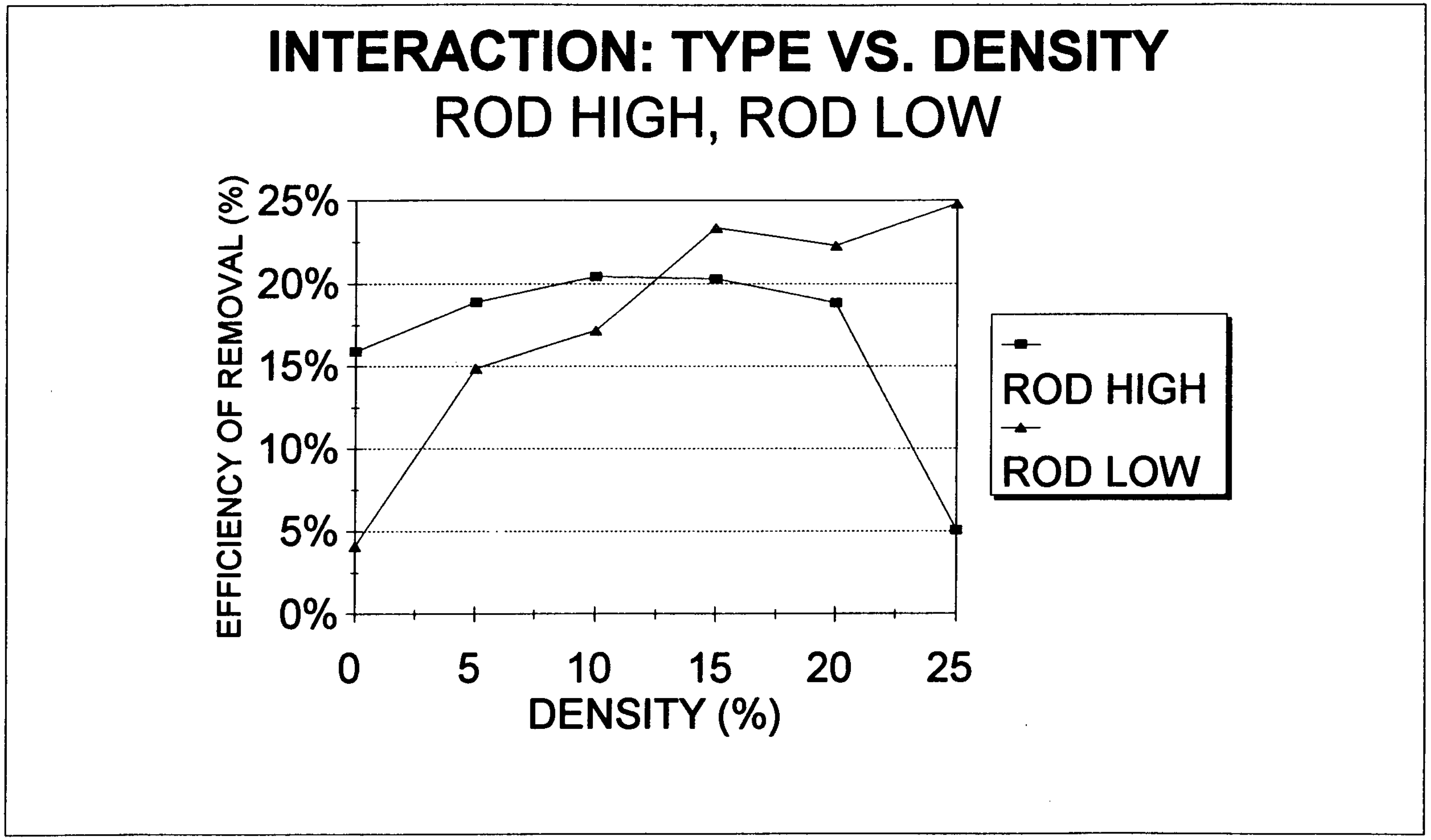


FIGURE 3.15 Interaction of type with density for ROD HIGH and ROD LOW bins

the experiment, perhaps due to the microbial population maturation. This factor accounts for much of interaction with density and type in the combined data set (Table 3.2).

Light has a very significant effect in the rods with light producing more effective treatment than darkness. However, light and density interact in the rods. Light has a much stronger effect in the 10%-20% range than at low or higher densities. The rods were clear and grew microbial communities with a high proportion of epiphytic algae but at densities of 20-25% relatively little light would be able to reach the inner areas of the tank even through the clear rods.

3.7.6. OTHER FINDINGS: ENSUR, LIGHT, INTERACTIONS

Significant interactions were found in the combined data sets for several interactions, particularly those involving ENSUR and light. These effects are partly the result of the differing behavior found for rods and bulrushes. For mature bulrush but not for rods, ENSUR loading rate is a significant factor for both rates and efficiency ($p = 0.0004$) with higher ENSUR loads producing better performance as is anticipated in the literature. Conversely, light is not a significant factor ($p = 0.24$) for mature bulrush rate of removal but is significant ($p = 0.009$) for efficiency and is significant in the rods.

Usually high ENSUR and light are correlated with better performance although the magnitude of the effect is quite varied. These trends are reversed for mature bulrush only at 5% density. Thus, the main effects of density, ENSUR and light in bulrush are not invalidated. Though the main effects were not significant in young bulrush, they also showed reversed trends at 5% density. The behavior at 5% density could be related to altered physical conditions such as greater light reaching the soil or could be an artifact of some unknown variation in experimental conditions.

3.8. Implications for Wetland Design

The results of this experiment could be interpreted to show that current designs waste the major potential of wetland plants in treating wastewater. The bulrush degrade the carbon at very fast rates until they become oxygen limited. After oxygen depletion, the apparent treatment rate decreases as oxygen limitation slows the decay rate to a virtual stop.

Because oxygen is limiting, the actual total carbon removal over 16 hours does not significantly increase with density in the mature bulrush above 5%, despite the fact that the rates of carbon removal do increase with higher plant densities.

When the EPA (1991) determined that specific surface was not a significant factor and then used specific surface (Av) as a constant 15.7 m^2/m^3 in their design equation (EPA 1991), they tested the equation sensitivity only for specific surfaces corresponding to plant densities of 3.8-5.1%.

Comparing the data from this experiment with the WPCF design equation we find:

first order model used for analyzing data from this experiment with equation in exponential form:

$$(Ce/Co) = e^{(-kt)} \qquad \text{(Eq. 3.2)}$$

using from WCPF:

$$Ce/Co = F \times e^{(0.7 \times k_t \times Av^{1.75} \times n \times HRT)}$$

(Eq. 3.1)

Then, with t = HRT, and F = 1.0 since ENSUR does not readily settle, the "k" constant from equation 3.2 (the first order equation used to analyze the data from this experiment), is equivalent to the expression in the exponent in Eq. 3.1 (the equation used by WPCF) without the HRT term, as shown below:

$$\underset{\text{Eq. 3.2}}{k} = \underset{\text{Eq. 3.1}}{0.7 \times k_t \times Av^{1.75} \times n}$$

Letting k_t = 0.0057 d^-1 and n = 0.75 as suggested by WPCF, projections were calculated for the WPCF equation in two ways: 1) letting Av vary with density, and, 2) keeping Av = 15.7 m^2/m^3 as suggested in the EPA sensitivity analysis. These projections are shown in Figure 3.16.

In Figure 3.16, the WPCF line is the line calculated by varying Av with density. The 15.7 m^2/m^3 line assumes that specific surface is relatively constant as assumed by EPA in its sensitivity analysis. These two lines mark the range of performance one might expect from wetlands. The WPCF line represents the maximum performance expected if treatment was proportional to plant density. The 15.7 m^2/m^3 line could represents the performance observed by the researchers testing the model for the EPA. The other lines demonstrate the data from this experiment. The young bulrush follow the WPCF line, the k rate increasing with plant density as predicted. The mature bulrush at 5.5 hours, prior to oxygen limitation show rates somewhat less than those predicted by the WPCF equation but increasing with density. Mature bulrush Tank B1 at 16.5 hours, which was severely oxygen limited, shows a flattening out toward the 15.7 m^2/m^3 EPA line which assumes constant specific surface. Thus, when oxygen is limited, plant systems with higher plant density, and potential for very fast reaction rates, perform as if they had only about 5% plant density. This may explain why

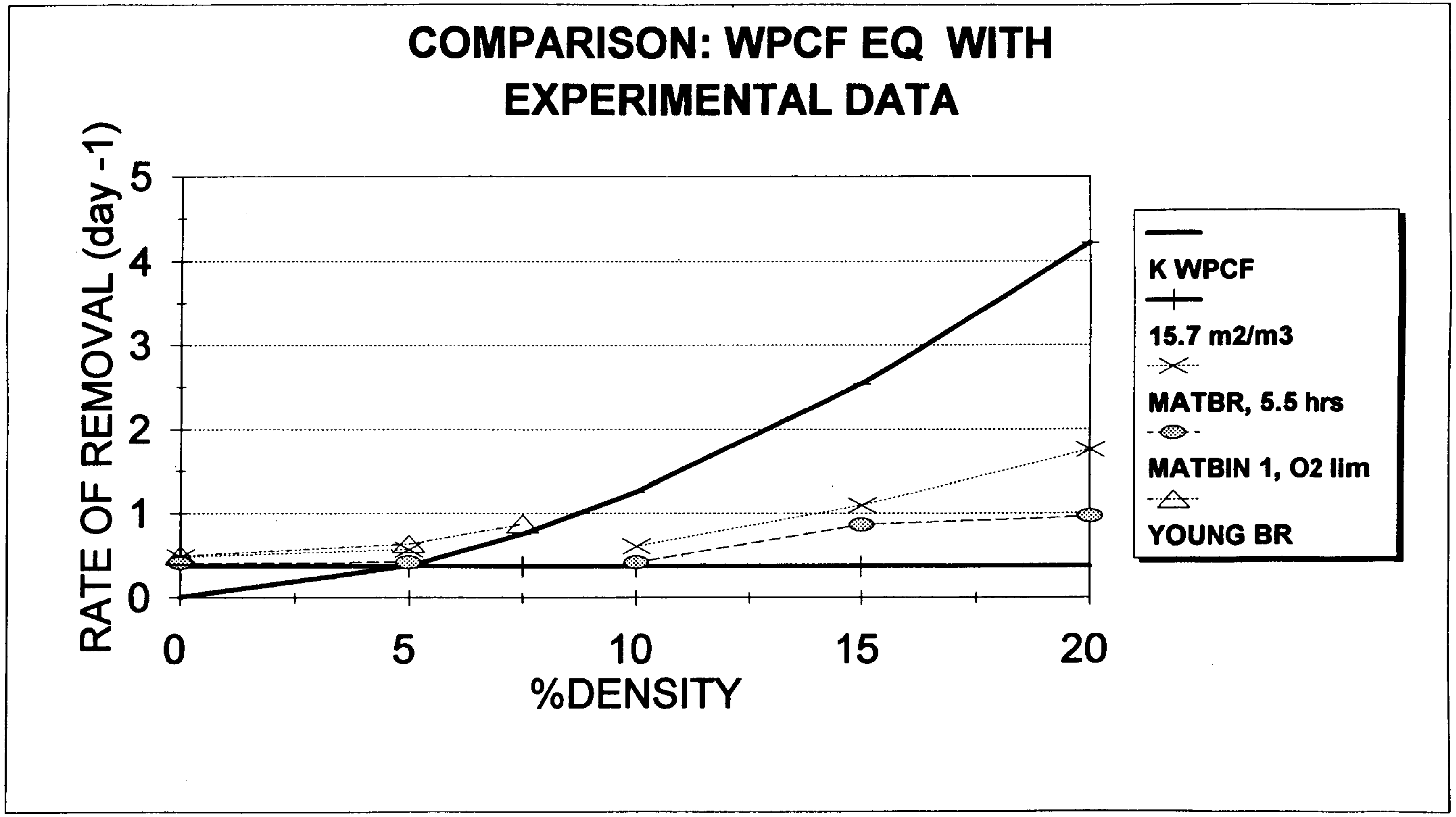


FIGURE 3.16 Data vs. WPCF Design Equation

the EPA analysis could fit a constant specific surface value to data from numerous wetland systems even though the specific surface areas probably varied.

The EPA (1991) analysis assumed that oxygen was not limiting unless very high organic loading rates were applied. In this experiment, young and mature bulrush always depleted the oxygen within 16.5 hours. This experiment differed from a typical constructed wetland in that the water was not flowing, but reaeration in the quiescent waters in most constructed wetlands is very slow. This experiment thus supports the conclusions of Brix (41, 1993) and Wetzel (1993) that wetland plants transfer relatively little oxygen to the root zone in excess of that required for their own survival, or that the excess that is transported is used up by the oxygen demand created in the wetland and the sediments.

Constructed wetlands are currently designed to use very large land areas. If oxygen is significantly limited after a few hours in densely planted systems, as was found in this experiment, then the designs are not taking advantage of the high rates of carbon removal possible in these wetland plant systems. Since larger wetlands reportedly remove from 40% to 60% BOD in 4-8 days and in this experiment 30-60% BOD was removed in 16.5 hours, these results suggest that large areas of wetland may function primarily as reaeration zones and add little to treatment efficiency. Gearheart (1992) actually suggests designing in this manner by providing open zones.

If designs provided more oxygen, it might be possible to use significantly smaller wetland areas since the plant/biofilms systems provide high rates of treatment. Brix (#2, 1993) has recently proposed combinations of wetland cells with designs that provide more oxygen using techniques such as intermittent loading. Reed and Brown (1992) propose adding an overland flow area while Danzig and Watkins (1993) propose a sand filter to provide more oxygen.

These suggestions were made primarily for nitrogen treatment but Reed and Brown acknowledge that carbon removal could also be enhanced. Many FWS wetland systems use between 5 and 10 m^2 /person to achieve BOD reductions to less than 10 mg/l while Brix (#2, 1993) describes a system using only 1 m^2/person that removes 98% of carbon plus nitrogen and phosphorous.

Aeration is not inexpensive but may cost less than conventional tertiary treatment systems. The Metropolitan Water District of Greater Chicago (MWRDGC) set up a sidestream aeration system which can reaerate 775 MGD from 2-3 mg/l to dissolved oxygen saturation using waterfalls of 12 feet (in 3 four foot sections). The major cost of the system is for pumping, but this is about 25% of the cost of the in-stream reaeration used previously (Macaitis), and was estimated to cost about 15% of the projected cost of conventional tertiary treatment (Robison 1994). High treatment levels could be obtained using far less area without exorbitant cost if terrace waterfalls were used to add oxygen to the system.

3.9. Conclusions

1. The results of this experiment support the hypothesis that higher plant densities in constructed wetlands can provide faster treatment rates, if oxygen is not limiting. For mature bulrush, increased treatment rates for carbon removal were found with increasing density. This is contrary to the assumptions used in the current design methodology.

2. For mature bulrush, treatment efficiency (carbon removal) did not increase with density. Evidence suggests that the effect is the result of oxygen limitation.

3. Oxygen depletion is a major limiting factor, occurring within only 5.5 hours in mature bulrush tanks. Oxygen limitation should be considered in optimizing future wetland designs. It should be possible to design wetlands using much smaller areas if more oxygen is provided. Such designs would take advantage of the ability of the wetland plants to provide high treatment rates.

4. This experiment does not support the assumption that wetland plants provide significant oxygen for wastewater treatment. This also contradicts current design assumptions.

5. Young bulrush tanks showed higher removal efficiencies than the mature bulrush tanks. Factors that might contribute to this are increased oxygen transport in young stems, lower detrital oxygen demand, and variations in plant/microbial systems.

6. The bulrush reaction rates are much faster than those for the artificial rod substrates.

7. Higher ENSUR loading results in higher removal rates and efficiencies. The presence of light increased treatment rates for mature bulrushes and rods, but the effect was much more significant for rods. Light may provide oxygen and energy (through epiphytic algae) and plant photosynthesis.

CHAPTER 4: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

4.1. Summary

Constructed wetlands have proven to be effective for advanced treatment of wastewater, especially for the removal of suspended solids and biochemical oxygen demand (BOD) (Reed 1992, Gearheart 1992). Early designs were based on trial and error. Most subsequent studies have been made on a "black box" basis, measuring influent and effluent values for the parameters of interest. Internal processes have seldom been studied. Nonetheless, most researchers believe that constructed wetlands act as biofilm reactors in which most water treatment occurs through interaction with attached microbial biofilms (Reed 1988).

In a biofilm reactor, the treatment rate should be proportional to the surface area, with the important proviso that there is a sufficient supply of the required chemicals for the reaction. For example, for aerobic degradation of carbon one would expect removal of carbon to be proportional to the biofilm surface area providing oxygen is present in stoichiometric proportions.

While the currently recommended design equation (WPCF 1990) for constructed wetlands includes a term for specific surface (equivalent to surface area per given volume), this parameter is not thought to be important. When the EPA (1991) conducted its analysis of data from existing constructed wetlands and concluded that specific surface was not an important parameter for constructed wetland performance, it only looked at a very narrow range of values. The literature suggests that densities of plants can result in very high specific surface values, much higher than those studied by the EPA, and that these do affect treatment efficiencies (Gearheart 1992, Lakshman 1992).

In its analysis, the EPA (1990) also assumed that oxygen was not limited unless the organic loading rate was very high because it is known that wetland plants transport oxygen through their tissues to the root zone. The evidence for the magnitude of the effect is contradictory. Some researchers find high rates (Reed 1988, Reddy and DeBusk 1987) while other researchers believe that most of the oxygen is used by the plants for survival and little excess is available for wastewater treatment (Brix #41 1993, Wetzel 1993). Moreover, as researchers have tried to apply constructed wetland technology to the treatment of nitrogen, they have found that nitrification is the limiting step, indicating an oxygen limitation (Gearheart 1992, Reed 1992, Knight et al 1993, Watson and Danzig 1993).

The main objective of this study was to examine the relationship of plant surface area (expressed as density) to treatment rates and treatment efficiency in constructed wetlands. In addition, oxygen was measured to see if it became limiting. The performance of bulrush was compared with the performance of a neutral surface (acrylic rods) thought to be a reasonable surrogate for bulrush (Goldsborough and Hickman 1991).

It was expected that the data would fit a first order degradation model. Much of the data did fit such a model, but many tanks became oxygen limited after only 5.5 hours. Carbon degradation rates were then greatly reduced.

Before oxygen became limited, removal rates for the combined data from rods and mature bulrushes were linearly related to the density of plants or rods tested. Removal efficiencies showed a similar relationship. However, several interactions in the analysis were also significant. When the data was analyzed by type of stem (or rod), it was found that bulrushes and rods did not respond in the same manner.

4.1.1. MATURE BULRUSH

Mature bulrush showed a significant linear relationship between increasing plant density (surface area) and higher treatment rates ($p = 0.0001$) until oxygen became limited. However, efficiency of removal once oxygen was limiting was not related to plant density. This supports the hypothesis that constructed wetlands are biofilm reactors able to treat wastewater at high rates, but that they are very susceptible to oxygen limitation.

These results showed higher removal rates with higher organic loadings, confirming other reports (Knight et al 1993). The presence of light was not significant for removal rates but was significant for removal efficiencies.

4.1.2. YOUNG BULRUSH

Young bulrush reflected similar trends to the mature bulrush but were less oxygen limited. The young bulrush may be less oxygen limited due to greater oxygen transport rates to their roots or due to lower sediment detrital oxygen demand, or some other factor.

4.1.3. RODS

Rods removed carbon at much slower rates and had lower overall efficiencies than the bulrush. In this study, the microbial communities on the rods consisted of many algae and some bacteria, while those on the bulrush were highly diverse including little algae but significant populations of fungi and rotifers as well as bacteria. Rods showed a linear relationship of removal to density increasing up to 15% but removal showed a drop off at 20% and 25%. Two factors are known to contribute to this effect. Rod tanks starting at 25% density showed lower treatment rates at high density than did rod tanks that started with no rods. Changes in the microbial population with time are probably responsible for this effect. Light could not penetrate effectively at 25% density and since light boosted the treatment effectiveness in the rods, this could account for poorer performance at 25%.

4.1.4 IMPLICATIONS

The results of this study support the hypothesis that constructed wetlands act as biofilm reactors in which treatment rates and efficiencies are proportional to plant surface area (density), as long as oxygen does not become depleted. However, high density constructed wetlands contain such large and effective biofilm surface areas that influent oxygen is used up within 5.5 hours of the start of reaction. Current wetlands are commonly designed with four to eight day retention times. This experiment suggests that most of the degradation is occurring in the first day and that the remaining retention time contributes little or primarily provides reaeration. The results do not support the EPA assumption that wetland plants are contributing significant excess oxygen for wastewater treatment.

A major drawback to the expanded use of constructed wetlands is that current designs require large land areas. The results of this study suggest that land area for constructed wetlands could be reduced substantially if more oxygen were provided. Researchers have suggested using multiple cells with alternate loadings, large open water areas, or sand filters for reaeration. This study supports the conclusion that future wetland design should include some mechanism for adding oxygen if optimal performance is to be achieved. Current designs waste significant potential for wastewater treatment by wetland plants.

4.2. Conclusions

This study supports the following specific conclusions:

1. The rate of removal of organic carbon in constructed wetlands is proportional to plant surface area (density) provided that oxygen is not limiting. This contradicts an assumption of the standard design equation that surface area is not an important parameter.

2. Influent oxygen was exhausted within 5.5 hours in mature bulrush tanks with plant densities of 10% or greater. Oxygen was exhausted in all bulrush tanks within 16.5 hours. Oxygen is a limiting factor in the treatment potential of constructed wetlands.

3. This study does not support the assumption, made in the current wetland design manuals, that excess amounts of oxygen are supplied by wetland plants for wastewater treatment. Treatment rates were severely reduced after influent oxygen was depleted. Oxygen concentrations did not increase in the duration of the experiment.

4. Bulrush remove organic carbon better than the same amount of inert surface area.

5. Constructed wetlands could be designed with significantly less land area if oxygen supply was considered in design.

4.3. Recommendations

Future studies that could substantiate or extend the findings of this research include:

- Evaluation of a wetland system to which additional oxygen supply is provided. This would improve understanding of potential for optimizing performance.

- Evaluation of young and mature plant systems to understand in what way young stems perform better than mature ones, or whether detritus acts as an extra oxygen demand on the system.

- Assessment of ways to provide additional oxygen at reasonable cost using appropriate technology. Currently, constructed wetlands are a low cost, low maintenance option and this advantage should be preserved in new designs.

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APPENDICES

APPENDIX 1: SPECIFIC SURFACE CALCULATION

PLANT ATTACHMENT SURFACE AREA

SURFACE AREA OF ONE PLANT = 2*PI*R*H

VOLUME OF ONE PLANT = PI*R^2*H

SPECIFIC SURFACE =

$$\frac{\text{surface area of plant}}{\text{volume of plant}} = \frac{2*PI*R*H}{PI*R^2*H} = 2/R$$

SPECIFIC SURFACE AT A GIVEN PLANT DENSIT = 2/R x % VOL OCCUPIED BY PLANTS

SAMPLE CALCULATION of SPECIFIC SURFACE, SS

IF DIAMETER OF STEM = 1.27 cm (0.5 in)
R = 0.00635 m

then
SS = 2/0.00635 x 0.05 = 15.7 m2/m3

SPECIFIC SURFACE AS RELATED TO PLANT DENSITY (% VOLUME)

ASSUMING STEM DIAMETER OF 1.27 cm (0.5 in)

% VOLUME OCCUPIED BY PLANTS	SPECIFIC SURFACE (m2/m3)
1%	3.1
2%	6.3
3%	9.4
4%	12.6
5%	15.7
10%	31.5
15%	47.2
20%	63.0
25%	78.7

APPENDIX 2: ENSUR COMPOSITION

ANALYSIS:

	Grams/Qt	% by Weight
Protein	35.2	3.5
Fat	35.2	3.5
Carbohydrate	137.2	13.6
Water	798.0	

INGREDIENTS:

Water
Corn syrup
Sucrose
Sodium and calcium caseinates
Soy protein isolate
Potassium citrate
Magnesium chloride
Soy lecithin
Calcium phosphate tribasic
Sodium citrate
natural and artificial flavor
Potassium chloride
Ascorbic acid
Choline chloride
Carrageenan
Zinc sulfate
Ferrous sulfate
Alpha-tocopheryl acetate
Niacinamide
Calcium pantothenate
Manganese sulfate
Thiamine schloride hydrochloride
Pyridoixne hydrochloride
Riboflavin
Cupric sulfate
Vitamin A palmitate
Folic acid
Biotin
Sodium molybdate
Chromium chloride
Potassium iodide
Sodium selenite
Phylloquinone
Cyanocobalamin
Vitamin D

TABLE 3.1 Oxygen Levels at T3 (about 5.5 hours)

	BATCHES	ENSUR	LIGHT	DENSITY	MATURE BULRUSH				YOUNG BULRUSH	
					B1	B3	B5	B6	B2	B4
LOW ENSUR	1	1	1	25						
LIGHT	3	1	1	20	2	0.86	0.6	0.78	5.28	5.21
	12	1	1	15	1.78	0.88	0.78	0.72	6.05	2.19
	14	1	1	10	2.44	2.06	2.82	1.74	5.35	2.44
	17	1	1	5	2.16	4.1	3.26	2.76	5.25	3.55
	22	1	1	0	3.54	3.88	2.42	3.02	4.91	3.46
LOW ENSUR	2	1	2	25						
DARK	4	1	2	20	1.76	0.28	0.24	0.47	4.21	4.03
	11	1	2	15	1.03	0.37	0.25	0.38	3.84	1.02
	13	1	2	10	1.05	1.1	0.77	0.66	2.76	0.64
	18	1	2	5	0.71	3.47	0.63	1.14	3.57	2.32
	21	1	2	0	4.34	4.29	2.05	2.89	4.61	4.63
HIGH ENSUR	5	2	1	25						
LIGHT	7	2	1	20	0.48	0.21	0.18	0.22	1.47	1.38
	10	2	1	15	1.78	0.44	0.35	0.3	1.56	0.64
	15	2	1	10	0.84	1.05	2.1	1.05	3.28	1.05
	19	2	1	5	2.56	3.57	2.86	2.56	3.71	3.85
	24	2	1	0	3.67	3.56	2.38	2.52	3.77	2.71
HIGH ENSUR	6	2	2	25						
DARK	8	2	2	20	0.45	0.12	0.2	0.1	2.54	0.64
	9	2	2	15	0.58	0.13	0.23	0.21	2.46	0.44
	16	2	2	10	0.43	0.95	1.09	0.49	2.44	0.24
	20	2	2	5	1.35	3.53	1.33	1.95	2.05	2.41
	23	2	2	0	2.11	1.25	0.75	1.85	3.15	2.83

TABLE 3.1 Continued

OXYGEN LEVELS AT T3 (ABOUT 5.5 HOURS)

	BATCHES	ENSUR	LIGHT	DENSITY	RODS STARTING AT 25%			RODS STARTING AT 0%			WATER ONLY		
					R2	R3	R5	R1	R4	R6	W1	W2	D1
LOW ENSUR	1	1	1	25	9.26	8.64	6.53	9.93	10.8	9.4		10.59	
LIGHT	3	1	1	20	8.67	8.32	7.44	8.78	9.43	8.59			
	12	1	1	15	8.76	7.53	7.8	8.23	9.4	8.24			
	14	1	1	10	6.79	6.54	8.65	6.61	8.08	7.56			
	17	1	1	5	7.67	7.25	7.97	7.55	7.25	6.31			
	22	1	1	0	7.73	7.83	7.84	6.33	6.43	5.65	8.96	8.55	9.74
LOW ENSUR	2	1	2	25	8.42	8.37	6.74	8.95	9.22	8.61	8.36	9.57	
DARK	4	1	2	20	7.55	7.19	6.13	7.5	7.29	6.47			
	11	1	2	15	8.17	6.42	6	7.2	6.73	5.55			
	13	1	2	10	6.91	6.2	6.09	5.71	5	4.59			
	18	1	2	5	6.41	7.3	7.13	5.93	4.47	4.84			
	21	1	2	0	7.9	8.17	8.26	5.41	2.78	3.62	8.53	7.14	
HIGH ENSUR	5	2	1	25	3.09	2.39	3.45	4.3	4.67	3.89	3.4		
LIGHT	7	2	1	20	6.92	4.81	2.88	6.5	7.05	6.81			
	10	2	1	15	7.1	6.75	5.52	7.4	7.08	6.34			
	15	2	1	10	6.62	4.68	4.53	5.87	3.97	4.43			
	19	2	1	5	8.32	7.04	8.72	7.39	6.26	6.46			
	24	2	1	0	7.39	8.32	5.8	4.16	3.89	3.01	5.59	7.03	7.31
HIGH ENSUR	6	2	2	25	2.07	1.62	3.74	3.62	3.77	3.13	3.58		
DARK	8	2	2	20	6.56	4.45	1.7	5.71	6.24	4.34			
	9	2	2	15	6.11	5.03	2.4	6.18	5.69	4.93			
	16	2	2	10	5.39	4.91	4.58	5.22	1.73	2.45			
	20	2	2	5	8.4	7.73	7.37	6	3.22	3.19			
	23	2	2	0	7.15	7.65	7.45	3.74	2.54	3.31	7.47	6.97	7.95

TABLE 3.2 Oxygen Levels at T5 (avg. 16.5 hours)

	BATCHES	ENSUR	LIGHT	DENSITY %	MATURE BULRUSH				YOUNG BULRUSH	
					B1	B3	B5	B6	B2	B4
LOW ENSUR	1	1	1	25						
LIGHT	3	1	1	20	0.92	0.42	0.27	0.32	0.68	0.49
	12	1	1	15	0.27	0.13	0.14	0.19	1.46	0.12
	14	1	1	10	0.16	0.08	0.06	0.11	0.34	0.14
	17	1	1	5	0.24	0.11	0.12	0.14	0.45	0.17
	22	1	1	0	0.08	0.07	0.10	0.04	0.04	0.00
LOW ENSUR	2	1	2	25						
DARK	4	1	2	20	0.71	0.12	0.11	0.12	0.16	0.1
	11	1	2	15	0.19	0.09	0.07	0.09	0.18	0.06
	13	1	2	10	0.11	0.07	0.06	0.09	0.24	0.54
	18	1	2	5	0.11	0.1	0.05	0.1	0.14	0.03
	21	1	2	0	0.13	0.14	0.09	0.06	0.08	0.05
HIGH ENSUR	5	2	1	25						
LIGHT	7	2	1	20	0.38	0.08	0.12	0.1	0.09	0.1
	10	2	1	15	0.27	0.16	0.12	0.17	0.16	0.09
	15	2	1	10	0.23	0.13	0.13	0.14	0.2	0.13
	19	2	1	5	0.06	0.04	0.07	0.06	0.13	0.07
	24	2	1	0	0.17	0.17	0.13	0.08	0.11	0.03
HIGH ENSUR	6	2	2	25						
DARK	8	2	2	20	0.28	0.11	0.15	0.12	0.04	0.04
	9	2	2	15	0.07	0.09	0.15	0.04	0.08	0.05
	16	2	2	10	0.14	0.05	0.03	0.06	0.05	0.01
	20	2	2	5	0.18	0.11	0.06	0.12	0.15	0.1
	23	2	2	0	0.08	0.05	0.02	0.04	0.04	0.03

TABLE 3.2 Continued

OXYGEN LEVELS AT T5 (AVG. 16.5 HOURS)

	BATCHES	ENSUR	LIGHT	DENSITY	RODS STARTING AT 25%			RODS STARTING AT 0%			WATER ONLY		
					R2	R3	R5	R1	R4	R6	W1	W2	D1
LOW ENSUR LIGHT	1	1	1	25	5.45	0.94	2.97	7.11	8.89	6.15			
	3	1	1	20	5.56	4.04	1.42	4.94	7.01	5.15			
	12	1	1	15	4.18	3.4	2.23	4.76	4.6	3.12			
	14	1	1	10	0.37	0.16	5.61	0.84	3.08	3.31			
	17	1	1	5	3.16	3.41	4.98	3.72	2.64	1.41			
	22	1	1	0	4.52	4.77	4.86	1.62	1.6	1.23	6.73	6.45	9.6
LOW ENSUR DARK	2	1	2	25	4.59	3.69	1.24	5.09	5.51	4.41			
	4	1	2	20	4.47	2.78	1.96	3.82	4.24	2.88			
	11	1	2	15	3.27	2.18	1.38	3.71	1.5	1.6			
	13	1	2	10	0.97	1.46	2.65	0.86	0.78	0.75			
	18	1	2	5	0.77	3.34	2.72	0.85	0.7	0.65			
	21	1	2	0	4.14	4.77	5.18	0.5	0.22	0.25	5.56	3.42	
HIGH ENSUR LIGHT	5	2	1	25	0.14	0.11	0.17	0.21	1.33	0.14			
	7	2	1	20	0.99	0.19	0.12	1.09	2.47	0.05			
	10	2	1	15	0.54	0.6	0.11	1.69	0.88	0.24			
	15	2	1	10	0.22	0.2	0.1	0.29	0.17	0.12			
	19	2	1	5	2.06	0.06	2.52	0.53	0.23	0.25			
	24	2	1	0	1.11	2.69	0.19	0.2	0.13	0.15	0.13	1.2	0.12
HIGH ENSUR DARK	6	2	2	25	0.2	0.19	0.24	0.3	0.24	0.25			
	8	2	2	20	0.07	0.11	0.09	0.16	0.22	0.09			
	9	2	2	15	0.18	0.08	0.07	0.29	0.19	0.17			
	16	2	2	10	0.11	0.08	0.04	0.14	0.08	0.04			
	20	2	2	5	2.18	2.13	1.27	0.24	0.22	0.11			
	23	2	2	0	2.05	2.8	2.28	0.09	0.07	0.07	1.27	1.97	3.89

APPENDIX 4: SUMMARY DATA FOR RATES AND EFFICIENCIES

TABLE 4.1 Summary Data Table of Rates and Efficiencies

KEY:

REACTION RATES: kd
CARBON REMOVAL EFFICIENCY: at 5.5 and 16.5 hours

Bin Type:
1 = mature bulrush
2 = young bulrush
3 = rods starting at 25% density
4 = rods starting at 0% density
5 = water only bins

ENSUR Level:
1 = low
2 = high

TOC:
Total organic carbon (mg/l)

Light Level:
1 = lights on
2 = lights off

Reaction Rates:

k	min (-1)
kd	day (-1)

Times of efficiency calculation:

T3	5.5 hours (average) into testing
T5	16.5 hours (average) into testing

Efficiency: [Initial TOC - (T3 or T5 TOC)]/Initial TOC

TABLE 4.1, Continued

BIN TYPE	BATCH	ENSUR LEVEL	LIGHT LEVEL	BIN #	PLANT DENSITY	k (min -1)	kd (days-1)	INITIAL TOC (mg/l)	T T (	T3 (5.5 hrs) EFFIC. (%)	T5 (16.5 hrs) TOC (mg/l)	T5 (16.5 hrs) EFFIC. (%)
MATURE BULRUSH BINS												
1	22	1	1	B1	0	-0.00039	-0.5602	19.67	*	9.7%	15.50	21.2%
1	17	1	1	B1	5	-0.00042	-0.6019	16.78	*	16.9%	12.25	27.0%
1	14	1	1	B1	10	-0.00049	-0.7070	17.25	*	-5.5%	12.73	26.2%
1	12	1	1	B1	15	-0.00042	-0.5990	17.45	*	22.2%	13.67	21.7%
1	3	1	1	B1	20	-0.00030	-0.4369	17.42	*	-5.9%	14.18	18.6%
1	21	1	2	B1	0	-0.00020	-0.2880	16.78	*	2.1%	15.53	7.4%
1	18	1	2	B1	5	-0.00076	-1.0872	16.67	*	24.3%	12.00	28.0%
1	13	1	2	B1	10	-0.00046	-0.6581	17.18	*	5.1%	15.12	12.0%
1	11	1	2	B1	15	-0.00031	-0.4507	17.40	*	2.1%	13.73	21.1%
1	4	1	2	B1	20	-0.00050	-0.7171	17.36	*	1.8%	10.83	37.6%
1	24	2	1	B1	0	-0.00031	-0.4450	44.77	*	13.8%	33.54	25.1%
1	19	2	1	B1	5	-0.00045	-0.6523	40.19	*	15.9%	26.78	33.4%
1	15	2	1	B1	10	-0.00047	-0.6768	40.92	*	22.4%	29.73	27.3%
1	10	2	1	B1	15	-0.00045	-0.6523	41.14	*	22.8%	26.05	36.7%
1	7	2	1	B1	20	-0.00156	-2.2412	41.00	*	29.7%	15.10	63.2%
1	23	2	2	B1	0	-0.00029	-0.4147	45.23	*	14.1%	34.58	23.5%
1	20	2	2	B1	5	-0.00029	-0.4234	40.64	*	17.2%	32.79	19.3%
1	16	2	2	B1	10	-0.00069	-1.0005	40.27	*	21.1%	29.51	26.7%
1	9	2	2	B1	15	-0.00084	-1.2102	41.77	*	23.3%	25.55	38.8%
1	8	2	2	B1	20	-0.00126	-1.8187	41.64	*	42.4%	21.71	47.9%
1	22	1	1	B3	0	-0.00038	-0.5458	19.67	*	5.7%	14.35	27.0%
1	17	1	1	B3	5	-0.00025	-0.3557	16.78	*	4.2%	13.80	17.8%
1	14	1	1	B3	10	-0.00030	-0.4277	17.25	*	9.3%	14.34	16.9%
1	12	1	1	B3	15	-0.00042	-0.6078	17.45	*	10.8%	14.61	16.3%
1	3	1	1	B3	20	-0.00099	-1.4278	17.42	*	-9.0%	18.83	-8.1%
1	21	1	2	B3	0	-0.00031	-0.4522	16.78	*	-10.5%	14.72	12.3%
1	18	1	2	B3	5	-0.00033	-0.4680	16.67	*	9.7%	12.68	23.9%
1	13	1	2	B3	10	-0.00045	-0.6538	17.18	*	2.0%	14.89	13.3%
1	11	1	2	B3	15	-0.00019	-0.2750	17.40	*	-1.1%	17.97	-3.3%
1	4	1	2	B3	20	-0.00055	-0.7989	17.36	*	-14.3%	15.79	9.0%
1	24	2	1	B3	0	-0.00027	-0.3830	44.77	*	14.6%	33.60	24.9%
1	19	2	1	B3	5	-0.00035	-0.5054	40.19	*	15.4%	30.57	23.9%
1	15	2	1	B3	10	-0.00035	-0.5011	40.92	*	10.7%	31.46	23.1%
1	10	2	1	B3	15	-0.00068	-0.9783	41.14	*	15.2%	30.65	25.5%
1	7	2	1	B3	20	-0.00170	-2.4422	41.00	*	33.5%	29.95	27.0%
1	23	2	2	B3	0	-0.00024	-0.3456	45.23	*	3.2%	34.45	23.8%

TABLE 4.1, Continued

BIN TYPE	BATCH	ENSUR LEVEL	LIGHT LEVEL	BIN #	PLANT DENSITY	k	kd	INITIAL TOC	T T	T3 (5.5 hrs) EFFIC.	T5 (16.5 hrs) TOC	T5 (16.5 hrs) EFFIC.
1	20	2	2	B3	5	-0.00028	-0.4046	40.64	*	8.6%	32.24	20.7%
1	16	2	2	B3	10	-0.00042	-0.6042	40.27	*	11.1%	31.18	22.6%
1	9	2	2	B3	15	-0.00077	-1.1081	41.77	*	17.4%	28.41	32.0%
1	8	2	2	B3	20	-0.00118	-1.7050	41.64	*	31.1%	33.72	19.0%
1	22	1	1	B5	0	-0.00046	-0.6595	19.67	*	17.4%	13.73	30.2%
1	17	1	1	B5	5	-0.00045	-0.6408	16.78	*	13.2%	10.71	36.2%
1	14	1	1	B5	10	-0.00051	-0.7402	17.25	*	9.1%	12.19	29.3%
1	12	1	1	B5	15	-0.00082	-1.1851	17.45	*	-1.1%	11.54	33.9%
1	3	1	1	B5	20	-0.00108	-1.5621	17.42	*	8.2%	16.33	6.3%
1	21	1	2	B5	0	-0.00037	-0.5386	16.78	*	3.2%	13.02	22.4%
1	18	1	2	B5	5	-0.00077	-1.1068	16.67	*	19.1%	13.00	22.0%
1	13	1	2	B5	10	-0.00046	-0.6627	17.18	*	4.0%	15.45	10.1%
1	11	1	2	B5	15	-0.00056	-0.8097	17.40	*	4.9%	14.64	15.9%
1	4	1	2	B5	20	-0.00133	-1.9181	17.36	*	26.9%	12.08	30.4%
1	24	2	1	B5	0	-0.00046	-0.6595	44.77	*	20.7%	27.51	38.6%
1	19	2	1	B5	5	-0.00050	-0.7128	40.19	*	13.7%	25.97	35.4%
1	15	2	1	B5	10	-0.00038	-0.5400	40.92	*	11.3%	30.66	25.1%
1	10	2	1	B5	15	-0.00071	-1.0190	41.14	*	21.2%	27.77	32.5%
1	7	2	1	B5	20	-0.00240	-3.4561	41.00	*	40.3%	24.84	39.4%
1	23	2	2	B5	0	-0.00050	-0.7233	45.23	*	16.6%	34.89	22.9%
1	20	2	2	B5	5	-0.00036	-0.5227	40.64	*	17.6%	30.39	25.2%
1	16	2	2	B5	10	-0.00023	-0.3341	40.27	*	14.5%	31.94	20.7%
1	9	2	2	B5	15	-0.00087	-1.2542	41.77	*	21.9%	27.34	34.5%
1	8	2	2	B5	20	-0.00179	-2.5733	41.64	*	37.2%	22.67	45.6%
1	22	1	1	B6	0	-0.00033	-0.4723	19.67	*	13.2%	14.89	24.3%
1	17	1	1	B6	5	-0.00032	-0.4594	16.78	*	13.9%	12.24	27.1%
1	14	1	1	B6	10	-0.00042	-0.5990	17.25	*	5.7%	12.88	25.3%
1	12	1	1	B6	15	-0.00096	-1.3795	17.45	*	25.7%	13.01	25.4%
1	3	1	1	B6	15	-0.00058	-0.8358	17.42	*	11.6%	12.39	28.9%
1	21	1	2	B6	0	-0.00029	-0.4170	16.78	*	-0.8%	13.84	17.5%
1	18	1	2	B6	5	-0.00035	-0.5083	16.67	*	8.5%	12.81	23.2%
1	13	1	2	B6	10	-0.00020	-0.2873	17.18	*	0.3%	14.12	17.8%
1	4	1	2	B6	15	-0.00060	-0.8669	17.36	*	17.4%	13.17	24.1%
1	11	1	2	B6	15	-0.00104	-1.4933	17.40	*	20.9%	13.49	22.5%
1	24	2	1	B6	0	-0.00036	-0.5242	44.77	*	15.9%	31.05	30.6%
1	19	2	1	B6	5	-0.00028	-0.3974	40.19	*	11.0%	29.84	25.8%
1	15	2	1	B6	10	-0.00041	-0.5846	40.92	*	13.4%	27.65	32.4%
1	10	2	1	B6	15	-0.00108	-1.5566	41.14	*	31.0%	29.72	27.8%
1	7	2	1	B6	15	-0.00200	-2.8735	41.00	*	36.0%	29.99	26.9%
1	23	2	2	B6	0	-0.00032	-0.4579	45.23	*	11.5%	32.97	27.1%

TABLE 4.1, Continued

BIN TYPE	BATCH	ENSUR LEVEL	LIGHT LEVEL	BIN #	PLANT DENSITY	k	kd	INITIAL TOC	T T	T3 (5.5 hrs) EFFIC.	T5 (16.5 hrs) TOC	T5 (16.5 hrs) EFFIC.
1	20	2	2	B6	5	-0.00030	-0.4320	40.64	*	10.8%	31.31	23.0%
1	16	2	2	B6	10	-0.00052	-0.7446	40.27	*	16.4%	27.15	32.6%
1	8	2	2	B6	15	-0.00122	-1.7542	41.64	*	24.8%	24.18	41.9%
1	9	2	2	B6	15	-0.00083	-1.1966	41.77	*	24.5%	22.59	45.9%

TABLE 4.1, Continued

BIN TYPE	BATCH	ENSUR LEVEL	LIGHT LEVEL	BIN #	PLANT DENSITY	k	kd	INITIAL TOC	T T	T3 (5.5 hrs) EFFIC.	T5 (16.5 hrs) TOC	T5 (16.5 hrs) EFFIC.
YOUNG BULRUSH BINS												
2	22	1	1	B2	0	-0.00018	-0.2650	19.67	*	17.4%	14.38	26.9%
2	17	1	1	B2	5	-0.00044	-0.6336	16.78	*	11.7%	10.12	39.7%
2	12	1	1	B2	7.5	-0.00047	-0.6725	17.45	*	1.5%	11.54	33.9%
2	14	1	1	B2	7.5	-0.00046	-0.6667	17.25	*	11.3%	11.39	34.0%
2	3	1	1	B2	7.5	-0.00040	-0.5787	17.42	*	13.7%	12.76	26.8%
2	21	1	2	B2	0	-0.00044	-0.6322	16.78	*	8.6%	14.62	12.9%
2	18	1	2	B2	5	-0.00050	-0.7214	16.67	*	17.8%	10.14	39.2%
2	13	1	2	B2	7.5	-0.00058	-0.8294	17.18	*	16.0%	10.56	38.5%
2	11	1	2	B2	7.5	-0.00039	-0.5573	17.40	*	-5.5%	12.81	26.4%
2	4	1	2	B2	7.5	-0.00032	-0.4565	17.36	*	19.0%	12.96	25.3%
2	24	2	1	B2	0	-0.00030	-0.4262	44.77	*	19.7%	32.43	27.6%
2	19	2	1	B2	5	-0.00043	-0.6178	40.19	*	18.4%	25.78	35.9%
2	10	2	1	B2	7.5	-0.00039	-0.5564	41.14	*	16.7%	25.83	37.2%
2	15	2	1	B2	7.5	-0.00024	-0.3413	40.92	*	8.7%	31.13	23.9%
2	7	2	1	B2	7.5	-0.00052	-0.7531	41.00	*	21.9%	24.05	41.3%
2	23	2	2	B2	0	-0.00023	-0.3283	45.23	*	8.2%	34.17	24.5%
2	20	2	2	B2	5	-0.00027	-0.3931	40.64	*	3.2%	33.43	17.7%
2	16	2	2	B2	7.5	-0.00039	-0.5558	40.27	*	15.7%	26.76	33.5%
2	8	2	2	B2	7.5	-0.00030	-0.4319	41.64	*	21.3%	28.10	32.5%
2	9	2	2	B2	7.5	-0.00048	-0.6854	41.77	*	17.3%	26.20	37.3%
2	22	1	1	B4	0	-0.00045	-0.6494	19.67	*	18.1%	13.35	32.1%
2	17	1	1	B4	5	-0.00054	-0.7776	16.78	*	15.7%	9.56	43.0%
2	12	1	1	B4	7.5	-0.00091	-1.3162	17.45	*	27.3%	8.71	50.1%
2	14	1	1	B4	7.5	-0.00057	-0.8251	17.25	*	12.3%	11.03	36.1%
2	3	1	1	B4	7.5	-0.00058	-0.8294	17.42	*	11.2%	9.75	44.0%
2	21	1	2	B4	0	-0.00050	-0.7171	16.78	*	3.8%	14.20	15.4%
2	18	1	2	B4	5	-0.00052	-0.7445	16.67	*	18.2%	10.29	38.3%
2	4	1	2	B4	7.5	-0.00045	-0.6509	17.36	*	13.7%	14.83	14.5%
2	11	1	2	B4	7.5	-0.00092	-1.3248	17.40	*	24.2%	9.21	47.1%
2	13	1	2	B4	7.5	-0.00058	-0.8395	17.18	*	13.6%	10.94	36.3%
2	24	2	1	B4	0	-0.00038	-0.5458	44.77	*	22.2%	29.79	33.5%
2	19	2	1	B4	5	-0.00043	-0.6120	40.19	*	15.2%	26.58	33.9%
2	10	2	1	B4	7.5	-0.00102	-1.4666	41.14	*	26.8%	20.13	51.1%
2	7	2	1	B4	7.5	-0.00082	-1.1759	41.00	*	29.2%	25.53	37.7%
2	15	2	1	B4	7.5	-0.00069	-0.9893	40.92	*	25.7%	22.17	45.8%
2	23	2	2	B4	0	-0.00032	-0.4637	45.23	*	16.9%	32.25	28.7%
2	20	2	2	B4	5	-0.00042	-0.5990	40.64	*	18.7%	27.83	31.5%

TABLE 4.1, Continued

BIN TYPE	BATCH	ENSUR LEVEL	LIGHT LEVEL	BIN #	PLANT DENSITY	k	kd	INITIAL TOC	T T	T3 (5.5 hrs) EFFIC.	T5 (16.5 hrs) TOC	T5 (16.5 hrs) EFFIC.
2	8	2	2	B4	7.5	-0.00107	-1.5437	41.64	*	29.5%	21.97	47.2%
2	16	2	2	B4	7.5	-0.00098	-1.4098	40.27	*	28.6%	25.12	37.6%
2	9	2	2	B4	7.5	-0.00119	-1.7110	41.77	*	34.1%	17.88	57.2%

TABLE 4.1, Continued

BIN TYPE	BATCH	ENSUR LEVEL	LIGHT LEVEL	BIN #	PLANT DENSITY	k	kd	INITIAL TOC	T T	T3 (5.5 hrs) EFFIC.	T5 (16.5 hrs) TOC	T5 (16.5 hrs) EFFIC.
ROD HIGH BINS												
3	22	1	1	R2	0	-0.00009	-0.1318	19.67	*	-5.3%	17.94	8.8%
3	17	1	1	R2	5	-0.00017	-0.2390	16.78	*	2.4%	13.61	18.9%
3	14	1	1	R2	10	-0.00035	-0.4997	17.25	*	13.2%	12.25	29.0%
3	12	1	1	R2	15	-0.00019	-0.2739	17.45	*	-1.9%	14.54	16.7%
3	3	1	1	R2	20	-0.00019	-0.2664	17.42	*	2.6%	15.32	12.1%
3	1	1	1	R2	25	-0.00026	-0.3745	17.97	*	-0.4%	15.09	16.0%
3	21	1	2	R2	0	-0.00004	-0.0566	16.78	*	6.1%	14.70	12.4%
3	18	1	2	R2	5	-0.00024	-0.3398	16.67	*	-3.8%	14.04	15.8%
3	13	1	2	R2	10	-0.00034	-0.4897	17.18	*	-0.2%	12.34	28.2%
3	11	1	2	R2	15	-0.00027	-0.3902	17.40	*	4.8%	13.76	20.9%
3	4	1	2	R2	20	-0.00019	-0.2722	17.36	*	2.6%	15.28	12.0%
3	2	1	2	R2	25	-0.00023	-0.3302	17.75	*	-0.1%	15.70	11.5%
3	24	2	1	R2	0	-0.00017	-0.2419	44.77	*	11.5%	35.11	21.6%
3	19	2	1	R2	5	-0.00030	-0.4277	40.19	*	13.8%	29.52	26.5%
3	15	2	1	R2	10	-0.00020	-0.2909	40.92	*	5.7%	34.82	14.9%
3	10	2	1	R2	15	-0.00021	-0.3021	41.14	*	12.1%	30.31	26.3%
3	7	2	1	R2	20	-0.00017	-0.2477	41.00	*	11.4%	30.63	25.3%
3	5	2	1	R2	25	-0.00015	-0.2088	45.22	*	9.4%	43.51	3.8%
3	23	2	2	R2	0	-0.00008	-0.1145	45.23	*	4.8%	35.73	21.0%
3	20	2	2	R2	5	-0.00015	-0.2131	40.64	*	7.2%	33.52	17.5%
3	16	2	2	R2	10	-0.00008	-0.1178	40.27	*	7.8%	34.96	13.2%
3	9	2	2	R2	15	-0.00027	-0.3816	41.77	*	9.8%	30.08	28.0%
3	8	2	2	R2	20	-0.00017	-0.2462	41.64	*	9.2%	33.97	18.4%
3	6	2	2	R2	25	-0.00009	-0.1344	44.93	*	12.8%	40.06	10.8%
3	22	1	1	R3	0	-0.00011	-0.1627	19.67	*	-0.5%	17.72	9.9%
3	17	1	1	R3	5	-0.00023	-0.3298	16.78	*	12.7%	13.23	21.2%
3	14	1	1	R3	10	-0.00018	-0.2592	17.25	*	12.9%	12.15	29.6%
3	12	1	1	R3	15	-0.00025	-0.3571	17.45	*	-0.5%	13.45	22.9%
3	3	1	1	R3	20	-0.00038	-0.5501	17.42	*	9.2%	13.26	23.9%
3	1	1	1	R3	25	-0.00033	-0.4712	17.97	*	1.2%	15.42	14.2%
3	21	1	2	R3	0	-0.00013	-0.1800	16.78	*	3.1%	14.37	14.4%
3	18	1	2	R3	5	-0.00012	-0.1670	16.67	*	6.4%	15.23	8.6%
3	13	1	2	R3	10	-0.00023	-0.3283	17.18	*	1.7%	13.98	18.6%
3	11	1	2	R3	15	-0.00017	-0.2506	17.40	*	12.0%	14.08	19.1%
3	4	1	2	R3	20	0.00003	0.0425	17.36	*	-7.6%	13.91	19.9%
3	2	1	2	R3	25	-0.00022	-0.3204	17.75	*	-0.6%	15.39	13.3%
3	24	2	1	R3	0	-0.00010	-0.1454	44.77	*	7.8%	36.81	17.8%

TABLE 4.1, Continued

BIN TYPE	BATCH	ENSUR LEVEL	LIGHT LEVEL	BIN #	PLANT DENSITY	k	kd	INITIAL TOC	T T	T3 (5.5 hrs) EFFIC.	T5 (16.5 hrs) TOC	T5 (16.5 hrs) EFFIC.
3	19	2	1	R3	5	0.00000	0.0000	40.19	*	14.2%	28.43	29.3%
3	15	2	1	R3	10	-0.00012	-0.1742	40.92	*	11.5%	34.87	14.8%
3	10	2	1	R3	15	-0.00015	-0.2131	41.14	*	11.0%	32.50	21.0%
3	7	2	1	R3	20	-0.00016	-0.2347	41.00	*	15.9%	30.25	26.2%
3	5	2	1	R3	25	-0.00016	-0.2275	45.22	*	8.3%	42.02	7.1%
3	23	2	2	R3	0	-0.00010	-0.1483	45.23	*	6.2%	36.94	18.3%
3	20	2	2	R3	5	-0.00009	-0.1320	40.64	*	2.6%	34.94	14.0%
3	16	2	2	R3	10	-0.00018	-0.2549	40.27	*	8.3%	32.58	19.1%
3	9	2	2	R3	15	-0.00019	-0.2707	41.77	*	4.9%	34.08	18.4%
3	8	2	2	R3	20	-0.00010	-0.1377	41.64	*	9.9%	35.22	15.4%
3	6	2	2	R3	25	-0.00013	-0.1892	44.93	*	8.6%	44.08	1.9%
3	22	1	1	R5	0	-0.00008	-0.1152	19.67	*	1.2%	17.20	12.6%
3	17	1	1	R5	5	-0.00019	-0.2750	16.78	*	8.7%	13.14	21.7%
3	14	1	1	R5	10	-0.00016	-0.2362	17.25	*	-6.7%	15.39	10.8%
3	12	1	1	R5	15	-0.00023	-0.3298	17.45	*	1.6%	13.47	22.8%
3	3	1	1	R5	20	-0.00051	-0.7373	17.42	*	6.9%	13.69	21.4%
3	1	1	1	R5	25	0.00013	0.1836	17.97	*	-42.1%	21.30	-18.5%
3	21	1	2	R5	0	-0.00007	-0.0953	16.78	*	-0.2%	14.62	12.9%
3	18	1	2	R5	5	-0.00012	-0.1786	16.67	*	4.0%	14.73	11.6%
3	13	1	2	R5	10	-0.00017	-0.2376	17.18	*	2.3%	15.13	11.9%
3	11	1	2	R5	15	0.00008	0.1143	17.40	*	-0.5%	16.55	4.9%
3	4	1	2	R5	20	-0.00011	-0.1655	17.36	*	0.4%	13.67	21.2%
3	2	1	2	R5	25	0.00001	0.0104	17.75	*	-10.0%	20.33	-14.5%
3	24	2	1	R5	0	-0.00013	-0.1901	44.77	*	7.5%	35.91	19.8%
3	19	2	1	R5	5	-0.00024	-0.3485	40.19	*	12.4%	29.49	26.6%
3	15	2	1	R5	10	-0.00038	-0.5530	40.92	*	9.1%	26.85	34.4%
3	10	2	1	R5	15	-0.00017	-0.2477	41.14	*	14.0%	32.15	21.9%
3	7	2	1	R5	20	-0.00020	-0.2822	41.00	*	16.9%	29.25	28.7%
3	5	2	1	R5	25	-0.00015	-0.2146	45.22	*	3.3%	40.52	10.4%
3	23	2	2	R5	0	-0.00012	-0.1685	45.23	*	9.6%	35.50	21.5%
3	20	2	2	R5	5	-0.00009	-0.1352	40.64	*	8.5%	34.52	15.1%
3	16	2	2	R5	10	-0.00016	-0.2275	40.27	*	11.0%	31.89	20.8%
3	9	2	2	R5	15	-0.00023	-0.3298	41.77	*	9.1%	33.07	20.8%
3	8	2	2	R5	20	-0.00011	-0.1526	41.64	*	7.2%	40.86	1.9%
3	6	2	2	R5	25	-0.00006	-0.0850	44.93	*	7.1%	42.70	5.0%

TABLE 4.1, Continued

BIN TYPE	BATCH	ENSUR LEVEL	LIGHT LEVEL	BIN #	PLANT DENSITY	k	kd	INITIAL TOC	T T	T3 (5.5 hrs) EFFIC.	T5 (16.5 hrs) TOC	T5 (16.5 hrs) EFFIC.
ROD LOW BINS												
4	1	1	1	R1	0	-0.00003	-0.0425	17.97	*	4.3%	16.34	9.1%
4	3	1	1	R1	5	-0.00009	-0.1247	17.42	*	1.1%	15.05	13.6%
4	12	1	1	R1	10	-0.00029	-0.4205	17.45	*	3.1%	14.40	17.5%
4	14	1	1	R1	15	-0.00040	-0.5774	17.25	*	13.7%	11.28	34.6%
4	17	1	1	R1	20	-0.00031	-0.4507	16.78	*	11.7%	12.74	24.1%
4	22	1	1	R1	25	-0.00021	-0.2981	19.67	*	10.8%	16.02	18.6%
4	2	1	2	R1	0	-0.00018	-0.2616	17.75	*	0.8%	16.21	8.7%
4	4	1	2	R1	5	-0.00010	-0.1498	17.36	*	-0.5%	15.12	12.9%
4	11	1	2	R1	10	-0.00021	-0.3030	17.40	*	-3.9%	14.93	14.2%
4	13	1	2	R1	15	-0.00033	-0.4680	17.18	*	-1.0%	11.82	31.2%
4	18	1	2	R1	20	-0.00021	-0.2952	16.67	*	7.0%	13.80	17.2%
4	21	1	2	R1	25	-0.00025	-0.3542	16.78	*	8.9%	12.81	23.7%
4	5	2	1	R1	0	-0.00005	-0.0698	45.22	*	-4.9%	48.61	-7.5%
4	7	2	1	R1	5	-0.00022	-0.3197	41.00	*	12.9%	31.14	24.0%
4	10	2	1	R1	10	-0.00020	-0.2851	41.14	*	7.8%	32.07	22.0%
4	15	2	1	R1	15	-0.00025	-0.3586	40.92	*	8.4%	30.49	25.5%
4	19	2	1	R1	20	-0.00046	-0.6552	40.19	*	11.7%	27.43	31.7%
4	24	2	1	R1	25	-0.00026	-0.3701	44.77	*	15.7%	32.41	27.6%
4	6	2	2	R1	0	-0.00008	-0.1210	44.93	*	5.5%	44.61	0.7%
4	8	2	2	R1	5	-0.00013	-0.1843	41.64	*	17.4%	33.66	19.2%
4	9	2	2	R1	10	-0.00019	-0.2750	41.77	*	13.9%	32.28	22.7%
4	16	2	2	R1	15	-0.00025	-0.3557	40.27	*	10.6%	32.04	20.4%
4	20	2	2	R1	20	-0.00016	-0.2318	40.64	*	3.3%	39.30	3.3%
4	23	2	2	R1	25	-0.00016	-0.2232	45.23	*	12.1%	34.46	23.8%
4	1	1	1	R4	0	-0.00001	-0.0155	17.97	*	-5.4%	17.89	0.4%
4	3	1	1	R4	5	-0.00022	-0.3125	17.42	*	0.7%	15.68	10.0%
4	12	1	1	R4	10	-0.00022	-0.3226	17.45	*	1.0%	13.03	25.3%
4	14	1	1	R4	15	-0.00023	-0.3326	17.25	*	-6.5%	13.97	19.0%
4	17	1	1	R4	20	-0.00033	-0.4810	16.78	*	19.0%	11.03	34.3%
4	22	1	1	R4	25	-0.00036	-0.5170	19.67	*	1.0%	13.80	29.8%
4	2	1	2	R4	0	-0.00007	-0.1059	17.75	*	-4.4%	17.64	0.6%
4	4	1	2	R4	5	-0.00002	-0.0288	17.36	*	-2.2%	15.99	7.9%
4	11	1	2	R4	10	-0.00007	-0.0936	17.40	*	-41.3%	23.54	-35.3%
4	13	1	2	R4	15	-0.00022	-0.3154	17.18	*	2.6%	14.81	13.8%
4	18	1	2	R4	20	-0.00030	-0.4349	16.67	*	10.3%	12.44	25.4%
4	21	1	2	R4	25	-0.00015	-0.2160	16.78	*	5.5%	14.90	11.2%
4	5	2	1	R4	0	-0.00009	-0.1302	45.22	*	-7.7%	46.30	-2.4%

TABLE 4.1, Continued

BIN TYPE	BATCH	ENSUR LEVEL	LIGHT LEVEL	BIN #	PLANT DENSITY	k	kd	INITIAL TOC	T T	T3 (5.5 hrs) EFFIC.	T5 (16.5 hrs) TOC	T5 (16.5 hrs) EFFIC.
4	7	2	1	R4	5	-0.00012	-0.1676	41.00	*	12.7%	31.91	22.2%
4	10	2	1	R4	10	-0.00019	-0.2722	41.14	*	11.4%	30.47	25.9%
4	15	2	1	R4	15	-0.00028	-0.4003	40.92	*	16.8%	29.56	27.8%
4	19	2	1	R4	20	-0.00034	-0.4824	40.19	*	10.5%	25.32	37.0%
4	24	2	1	R4	25	-0.00036	-0.5213	44.77	*	15.7%	29.96	33.1%
4	6	2	2	R4	0	0.00004	0.0521	44.93	*	2.2%	44.32	1.4%
4	8	2	2	R4	5	-0.00015	-0.2102	41.64	*	6.2%	36.47	12.4%
4	9	2	2	R4	10	-0.00024	-0.3499	41.77	*	5.3%	32.28	22.7%
4	16	2	2	R4	15	-0.00017	-0.2477	40.27	*	17.5%	32.00	20.5%
4	20	2	2	R4	20	-0.00016	-0.2275	40.64	*	3.2%	36.04	11.3%
4	23	2	2	R4	25	-0.00010	-0.1498	45.23	*	5.8%	37.12	17.9%
4	1	1	1	R6	0	-0.00001	-0.0166	17.97	*	2.6%	16.42	8.6%
4	3	1	1	R6	5	-0.00031	-0.4450	17.42	*	10.4%	16.59	4.8%
4	12	1	1	R6	10	-0.00038	-0.5472	17.45	*	7.4%	11.74	32.7%
4	14	1	1	R6	15	-0.00024	-0.3470	17.25	*	0.5%	14.22	17.6%
4	17	1	1	R6	20	-0.00033	-0.4810	16.78	*	18.3%	11.35	32.4%
4	22	1	1	R6	25	-0.00029	-0.4147	19.67	*	4.2%	14.36	27.0%
4	2	1	2	R6	0	-0.00007	-0.1028	17.75	*	-0.4%	17.32	2.4%
4	4	1	2	R6	5	-0.00003	-0.0454	17.36	*	3.2%	16.12	7.1%
4	11	1	2	R6	10	-0.00014	-0.2045	17.40	*	3.9%	15.94	8.4%
4	13	1	2	R6	15	-0.00015	-0.2117	17.18	*	-1.1%	15.02	12.6%
4	18	1	2	R6	20	-0.00030	-0.4262	16.67	*	1.0%	13.56	18.7%
4	21	1	2	R6	25	-0.00026	-0.3773	16.78	*	13.1%	12.38	26.2%
4	5	2	1	R6	0	-0.00009	-0.1333	45.22	*	13.0%	36.56	19.2%
4	7	2	1	R6	5	-0.00023	-0.3326	41.00	*	10.8%	31.67	22.8%
4	10	2	1	R6	10	-0.00020	-0.2837	41.14	*	24.1%	30.25	26.5%
4	15	2	1	R6	15	-0.00034	-0.4939	40.92	*	9.1%	27.10	33.8%
4	19	2	1	R6	20	-0.00031	-0.4493	40.19	*	18.0%	27.17	32.4%
4	24	2	1	R6	25	-0.00018	-0.2520	44.77	*	12.4%	31.25	30.2%
4	6	2	2	R6	0	-0.00009	-0.1253	44.93	*	10.1%	41.23	8.2%
4	8	2	2	R6	5	-0.00017	-0.2491	41.64	*	14.5%	32.55	21.8%
4	9	2	2	R6	10	-0.00026	-0.3715	41.77	*	13.8%	32.01	23.4%
4	16	2	2	R6	15	-0.00017	-0.2405	40.27	*	17.2%	30.69	23.8%
4	20	2	2	R6	20	-0.00006	-0.0827	40.64	*	0.5%	40.63	0.0%
4	23	2	2	R6	25	-0.00026	-0.3744	45.23	*	17.0%	32.23	28.7%

TABLE 4.1, Continued

BIN TYPE	BATCH	ENSUR LEVEL	LIGHT LEVEL	BIN #	PLANT DENSITY	k	kd	INITIAL TOC	T T	T3 (5.5 hrs) EFFIC.	T5 (16.5 hrs) TOC	T5 (16.5 hrs) EFFIC.
WATER ONLY BINS												
5	22	1	1	D1	0	-0.00004	-0.0513	19.67	*	-10.9%	22.71	-15.5%
5	24	2	1	D1	0	-0.00013	-0.1869	44.77	*	10.1%	38.47	14.1%
5	23	2	2	D1	0	-0.00012	-0.1771	45.23	*	11.0%	37.99	16.0%
5	22	1	1	W1	0	-0.00012	-0.1757	19.67	*	3.2%	18.97	3.6%
5	21	1	2	W1	0	-0.00007	-0.0971	16.78	*	3.5%	14.82	11.7%
5	24	2	1	W1	0	-0.00014	-0.1973	44.77	*	5.7%	39.58	11.6%
5	23	2	2	W1	0	-0.00018	-0.2606	45.23	*	12.6%	36.44	19.4%
5	22	1	1	W2	0	-0.00025	-0.3643	19.67	*	3.8%	17.88	9.1%
5	21	1	2	W2	0	-0.00036	-0.5155	16.78	*	3.8%	14.20	15.4%
5	24	2	1	W2	0	-0.00029	-0.4190	44.77	*	11.5%	33.93	24.2%
5	23	2	2	W2	0	-0.00029	-0.4118	45.23	*	13.6%	36.15	20.1%

TABLE 5.1 Table of Means and Standard Error by Stem Type

	COMBINED HIGH/LOW RODS		MATURE BULRUSH		YOUNG BULRUSH		WATER ONLY	
RATES DENSITY	kd(days^-1)	se	kd(days^-1)	se	kd(days^-1)	se	kd(days^-1)	se
0	-0.1176097	0.0278	-0.5013	0.04915	-0.5035	0.0708	-0.2597	0.0445
5	-0.223146	0.0278	-0.6235	0.04915	-0.6373	0.0708		
7.5					-0.882	0.0409		
10	-0.308238	0.0278	-0.6255	0.04915				
15	-0.315879	0.0278	-0.8458	0.04915				
20	-0.3311643	0.0278	-1.7581	0.04915				
25	-0.2679066	0.0278						
EFFICIENCY DENSITY	efficiency %	se	efficiency %	se	efficiency %	se	efficiency %	se
0	10.01%	0.0208	23.28%	0.015	29.35%	0.0347	11.79%	0.0321
5	16.89%	0.0208	26.06%	0.015	34.89%	0.0781		
7.5					37.31%	0.0981		
10	18.80%	0.0208	21.11%	0.015				
15	21.84%	0.0208	25.46%	0.015				
20	20.58%	0.0208	27.98%	0.015				
25	14.95%	0.0208						

se = standard error