USE OF CONSTRUCTED WETLANDS TO IMPROVE WATER QUALITY IN FINFISH POND CULTURE, PHASE II

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ABSTRACT

Use of constructed wetlands in finfish pond culture water recirculation was studied to evaluate their effectiveness in improving water quality, determine optimal design and operating criteria and assess the associated benefits and costs in finfish pond production. Sixteen quarter-water acre ponds and 13 constructed wetlands of varying sizes and retention times were used in the experiment. Of the 13 wetlands used in the experiment, eight were two-year-old marsh systems originally planted with *Juncus effusus* and *Sagittaria lancifolia* at equal densities. Subsequently, *Juncus effusus* showed poor survival in all but one wetland and its use was discontinued. These plants were initially planted on 1-ft centers in September 1993. Additional *Sagittaria lancifolia* were planted in these wetlands in November 1995 to replace those plants which did not survive and increase vegetative coverage (1/2-ft centers). Phase II *Ictalurus punctatus* fingerlings were stocked at a rate of 2,000 fingerlings/pond.

Except for salinity and pH, wetlands were shown to significantly reduce levels of most parameters at the following rates: total ammonia (2-63%), nitrite (29-97%), nitrate (28-80%), total phosphorus (52-95%), total suspended solids (2-76%) and pH (0.5-10%). In general, wetlands of standard size and flow rate showed the highest levels of reduction for most parameters. Vegetative characteristics of wetlands also indicate that wetlands of standard size and flow rate were optimal in assimilating available nutrients. Results of pond monitoring showed that ponds with wetlands had dampened daily fluctuations in dissolved oxygen and reduced levels of photosynthetic pigments compared to control ponds. These ponds also required less aeration than control ponds. Levels of nutrients within ponds with wetlands were highly variable among treatments and were not less than those in control ponds, but were within tolerable ranges for fish production.

The added benefits and costs associated with the use of constructed wetlands in intensive and recirculating catfish pond production were estimated by applying the experimental results to a multi-enterprise commercial farm in the Mississippi Black Belt area. The initial investment requirements for six 8-water-surface acre catfish ponds on a multi-enterprise farm in the Mississippi Black Belt area were $3,527/acre. With six 1.2, 2.0 and 2.8-water-surface-acre wetlands built adjacently to the catfish ponds, total initial investment requirements rose by $2,656, $4,160 and $5,665/acre, respectively. Total specified operating and ownership costs of the 48-acre Mississippi Black Belt catfish enterprise without constructed wetlands amounted to $184,074/year, averaging $3,835/acre or $0.57/lb. When six 1.2, 2.0 and 2.8-acre constructed wetlands were added to the catfish enterprise, total costs rose by $0.052, $0.059 and $0.079/lb, respectively. In the short-run, the use of six 1.2, 2.0 and 2.8-acre constructed wetlands in a 48-water-acre catfish farm in a multi-enterprise Mississippi Black Belt farm area would be acceptable to farmers if the annual yield of marketable catfish would increase by 7, 5 and 7%, respectively.

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I. INTRODUCTION

Water quality is a primary concern for the pond culture of all finfish species. Parameters such as dissolved oxygen, ammonia, nitrite concentrations and turbidity limit stocking densities and production capabilities, contribute to off-flavor problems, and increase risks of mortality and disease. With approximately 525 million pounds of catfish harvested for processing (USDA, 1998) from more than 163,000 water surface acres in the U.S. (USDA, 1997), the economic consequences of fish loss and off-flavor to the industry can be very significant. For off-flavor alone, the social welfare costs was estimated at about 12 percent of industry revenues (Kinnucan et al., 1988). Heikes and Killian (1997) reported survival rate in commercial catfish ponds averaging 65% during yield verification studies conducted in Arkansas.

Three principal water quality problems occur in fish culture ponds: 1) excessive phytoplankton production, 2) low dissolved oxygen, and 3) toxic metabolite accumulation (Kleinholz, 1987). Poor water quality often leads to health problems in stocked fish including parasite incidence, bacterial incidence, fungal infections, nitrite toxicity and ammonia toxicity. Methods commonly used in the finfish pond culture industry to treat the causes and effects of poor water quality include water exchange, aeration, and application of chemicals. There are significant production costs associated with these treatment methods as well as environmental impacts. The estimated operating costs of chemical requirements and water quality analysis for various size fish farms (160, 320 and 640-water acres) in the Mississippi Delta range from $485 to $4,000 annually per farm, while electricity and fuel costs for aeration and pumping range from $19 to $76 thousand annually per farm (Engle and Kouka, 1996). Posadas and Dillard (1997) estimated that in the Mississippi Black Belt Area, the annual costs of chemicals and electricity for aeration for a 48-acre catfish farm were $3,000 and $6,000 per farm, respectively. In the case of water exchange, however, the efficacy of this practice has been questioned. A study of fish culture ponds in Israel showed that despite the high rate of water exchange (five to 10 times the pond volume a day), high concentrations of metabolites and low concentrations of oxygen were occasionally detected (Rijn and Shilo, 1989). This study demonstrated the necessity for a biological breakdown of accumulating organic matter, together with the biological transformation of metabolites.

From the standpoint of environmental impact, fish farm effluents are currently being closely scrutinized as non-point pollution sources and for possible inclusion in the National Pollutant Discharge Elimination System (NPDES) Wastewater Permit process. In Mississippi, a permit is not required unless the fish farm discharges wastes at least 30 days per year and has an annual production exceeding 100 thousand pounds of aquatic animals. Permits are also required for groundwater use, and in some cases, surface water diversion (McLaughlin et al., 1992). Mississippi law closely mirrors the regulatory framework of other states where fish culture activities exist. Use of groundwater and surface water for water exchange in fish ponds is constrained in many areas of the country due to limits on water supplies. More stringent regulations on pond effluents may improve water quality, but the added cost may raise the price of pond-raised fish relative to other products.

There is, therefore, a need for new cost-effective and environmentally-compatible techniques to reduce the effects of water quality degradation in pond culture systems as well as reducing the impact of nutrient release into the environment. Under the current regulatory scheme concerning fish farm effluents, pond culturists faced with marginal profit margins most likely would not voluntarily adopt this technology solely for the purpose of environmental protection. Research activities to develop technology to improve water quality are typically beyond the capability of producers operating on small profit margins. With higher fish stocking densities, the added costs associated with the construction and operation of mature constructed wetlands must be compared with the benefits in avoiding crop loss, disease, or off-flavor.

This research project is a continuation of the initial experiment conducted in 1993-95 using newly constructed wetlands and stocking density of 5,000 fingerlings per acre (Posadas and LaSalle, 1997). During the initial experiment, substantial improvements and less variations in many water quality variables were observed among ponds with standard wetlands as compared to control ponds. Significant differences in many water quality variables were also noted among ponds with variable wetlands sizes and retention times. Due to the relatively young age and incomplete vegetative coverage in constructed wetlands, there were no definitive trends in the effects of wetland sizes and retention times on water quality. At this stage of determining the effectiveness of using constructed wetlands in finfish pond production, the significant improvements in pond water quality did not lead to significantly observable benefits, namely: higher yields and less incidence of off-flavor. Marked differences, however, were observed in pond aeration time and wetland pumping time. The application of the initial experimental results to a 48-acre commercial catfish farming enterprise in the Mississippi Black Belt indicated that the observed additional costs more than offset any limited economic benefits derived. Total revenues from the catfish enterprise with or without constructed wetlands (25% of pond size) remained at $174,720 per year, $3,640 per production acre or $0.70 per pound. Annual specified costs for the catfish enterprise without constructed wetlands amounted to $146,912 per year, averaging $3,060 per production acre or $0.59 per pound harvested. When constructed wetlands were added to the catfish enterprise, total costs rose by $18,930 annually, $394 per production acre or $0.075 per pound.

It was expected that as constructed marsh systems mature, they became more effective in reducing pond water quality problems and associated risks to production. The limits of the constructed wetlands effectiveness to improve pond water quality could be evaluated by increasing fish stocking densities beyond current industry practices. The overall goals of this project were to evaluate the use of constructed wetlands in improving water quality and assess the associated benefits and costs in intensive finfish pond production. Specifically, this project aimed to achieve the following objectives:

1) evaluate the effectiveness of constructed marsh systems toward improving water quality in aquaculture ponds;

2) determine optimal design and operating criteria for constructed marsh systems used in pond culture;

3) determine the concomitant reductions in risk of crop loss, incidence of off-flavor, and release of nutrient-laden effluent into the environment;

4) determine the improvement in fish growth and feed conversion arising from the new technology;

5) document the costs versus benefits of using this technology in pond culture; and

6) provide information and technology transfer to the pond culture industry.

II. MATERIALS AND METHODS

The experiment was conducted at the Mississippi State University-Coastal Aquaculture Unit (MSU-CAU) located at Mississippi Power Company's Plant Watson power generating station in Gulfport, Mississippi. Sixteen quarter-water acre ponds were used during the experiment. Each pond was about 125 ft long, 85 ft wide and 4 ft deep. Six of the ponds were used in a replicated fashion to evaluate the effectiveness of constructed marshes toward improving water quality while the remaining 10 ponds were used in a range testing fashion to determine optimal wetland design criteria and operation parameters.

Experimental Design

The 16 quarter-water acre ponds used during the experiment were randomly assigned to four sets of ponds in the following experimental design:

Wetland Effectiveness:

Set A: Control Ponds (no marsh, simulated water flow in three ponds).

Set B: Treatment Ponds (with marshes of a "standard" size and flow rate in three ponds).

Optimal Design/Operation:

Set C: Wetland Size Variations [two variations of relative marsh to pond size (not including the "standard" size), using the "standard" flow rate in two ponds for each wetland size].

Set D: Wetland Flow Rate Variations [three variations of the flow rate through the marsh (not including the "standard" flow rate), using the "standard" marsh size in two ponds for each flow rate].

Wetland Design and Construction

The standard marsh size was set as 25% of the surface area of the pond (Figure 1), with the length set equal to the pond margin along which it is located (85 ft). For the size variation portion of the study, the width was adjusted to achieve the following marsh/pond ratios:

Small: 15% or 12.75 ft,
Standard: 25% or 21.25 ft,
Large: 35% or 29.75 ft.

The standard flow rate was 6.5 gal/min which, based on the volume of the standard marsh system, equated to an exchange rate of 3% of the pond volume per day and a retention time of two days. Flow rate, retention time or exchange rate levels for the rate variation portion of the study included the following:

Slow: 3.25 gal/min, 3-day retention or 1.5% exchange rate,
Regular: 6.5 gal/min, 2-day retention or 3% exchange rate,
Fast: 13 gal/min, 1-day retention or 6.25% exchange rate,
Very fast: 26 gal/min, ½-day retention or 12.5% exchange rate.

Marshes were constructed by raising a 3-4 ft high levee around the specified area to achieve the desired size. Water was gravity-fed from the pond into the marsh and returned to the pond via a sump pump. To facilitate circulation, water was drawn from the pond via a 2 to 3-inch diameter PVC pipe placed halfway across the width of the pond, 5 ft from the pond edge, and positioned 1 ft off the pond bottom. Water was siphoned into the intake side of the marsh across the top of the pond levee and into a 2 to 3-inch diameter PVC pipe. Water flowed from two openings of this pipe which was positioned at the middle of the intake side of the marsh. Flow rate was set by altering the size of an orifice drilled into an end cap placed on the feeder pipe. A sump (55-gal) and sump pump (**a** to ½ HP) on the discharge side of the marsh distributed water back into the pond through a 2 to 3-inch diameter pipe that was laid out in a similar manner as that of the intake pipe. The pump was set to maintain water level in the marsh at the design depth of 1 ft, which allowed for adequate growth of the vegetative coverage.

Of the 13 wetlands used in the experiment, eight were two-year-old marsh systems originally planted with *Juncus effusus* (soft rush) and *Sagittaria lancifolia* (duck potato) at equal densities. Subsequently, soft rush showed poor survival in all but one wetland and its use was discontinued. These plants were initially planted on 1-ft centers in September 1993. Additional *Sagittaria lancifolia* were planted in these

Figure 1. Catfish pond and constructed wetland system at MSU-Coastal Aquaculture Unit, July 1997.

wetlands in November 1995 to replace those plants which did not survive and increase vegetative coverage. In order to increase vegetative coverage to simulate mature wetlands, planting rate was increased to 1/2-ft centers. The other five wetlands were constructed and planted at the same rate with *Sagittaria lancifolia* in November 1995.

Control ponds were fitted with influent and effluent pipes with water pumped through an interconnecting pipe run along the levee. This arrangement simulated the water flow conditions of those ponds with marshes, without the actual marsh. This should control for any variations due solely to water circulation by the pumping systems.

Fish Species and Stocking Density

Phase II (7-8 in) channel catfish (*Ictalurus punctatus*) fingerlings were stocked in the ponds during the experiment. The experimental ponds were stocked with 8,000 fingerlings per acre or 2,000 fingerlings per pond. Fish were stocked in late March 1997 in order to reduce the effects of bird predation (primarily double-crested cormorant) on the fish population. The catfish fingerlings were raised to marketable size (≥ 1.25 pounds) for one growing season according to accepted industry practices. The phase II fingerlings used in this study were purchased from commercial hatchery operators in order to insure adequate supply and uniform size during stocking time.

Feeds and Feeding

Sinking catfish feeds (32% protein) were used due to the presence of large populations of sea gulls observed near the vicinity of the ponds. The fish were fed daily except during winter months and bad weather. Limited feeding was undertaken during winter months. Daily feed rations were adjusted weekly depending on the temperature and estimated fish biomass in each pond. Fish biomass in each pond was estimated from fish sampling conducted at the beginning and end of summer. The same feeding rate as recommended by Robinson and Li (1996) was applied to all experimental ponds.

Monitoring

Water quality parameters were monitored on both daily and weekly schedules and included factors assessed as part of standard pond management practice (e.g., dissolved oxygen, temperature, pH, total ammonia nitrogen, nitrite) as well as additional factors (e.g., nitrate and total phosphorous) and parameters (e.g., total suspended solids, chlorophyll *a* concentration) that were needed for a more detailed assessment of nutrient removal. Dissolved oxygen (DO) and temperature were measured twice per day (early morning, mid-afternoon). For management purposes, DO levels were monitored at dawn during summer months. Salinity, pH, total ammonia, nitrate, nitrite, total phosphorus, total suspended solids, and photosynthetic pigments (chlorophyll *a* and phaeophytin) were measured on a weekly basis.

All measurements and water samples were taken from three locations in each pond/marsh system. A "pond" sample, that should reflect the general water quality condition of each pond, was taken near the pond edge at a point midway between the effluent and influent pipes for the marsh and on the opposite bank from the marsh. Samples were also taken at the points where water entered (inlet pipe) and left (sump) the marsh in order to assess the level of water quality improvement by the marsh itself. The pond sample served as a measure of the effect of the marsh on overall pond water quality. Only the pond water sample was taken in control ponds. Water quality parameters were measured using a combination of meters and standard analytical testing procedures (APHA, 1989).

The growth of fish was monitored by collecting fish samples at four different periods during each growing season. A sample of 100 fingerlings was measured during stocking to determine initial weight and length. Fish samples were collected from each pond by using cast nets at the beginning and end of summer. The final samples of 100 fish per pond were taken during harvest time. The standard length and wet weight of each fish were individually measured during each sampling period.

Fish growth was measured by taking the absolute increase in weight from stocking to harvesting time. Hopkins (1992) stated that either final size or growth rate can be used if treatments have equal experimental periods and initial sizes are to be compared and intermediate data points ignored. Earlier sampling attempts using cast net or seine did not provide enough fish samples. Seine sampling is widely recognized by aquaculturists to produce upwardly-biased estimates of size (Hopkins and Yakupitiyage 1991). The results of the intermediate fish sampling were used to adjust feeding rates. By comparing the absolute growth rate of the fish, the treatment effects of the experiment were measured. Food conversion was assessed at harvest time by comparing the quantity of feed used with fish production.

The condition of the plant population in each wetland was assessed after fish harvest. The number of stems and biomass of plants were measured in each of three 0.25 m^2 plots haphazardly located at both the influent and effluent ends of each wetland, for a total of six samples per wetland. Plants were oven-dried to constant weight at 105 °C.

Delta Pride Catfish, Inc., a large catfish processing plant located in Indianola, Mississippi conducted the organoleptic testing for off-flavor using standard industry protocol. Testing was conducted by the processing plant at the end of summer (fish size $\geq$ 1 lb) and before final harvest. The fish samples were delivered to Delta Pride in whole and fresh form the following day the fish were harvested. The flavor scale used by the processing plant was from 0 to 5, where 0 is on flavor and 5 is worst off-flavor.

Each pond/marsh system was metered for electric power consumption. Individual weekly readings of electric consumption of each pond were recorded. Water flow rates were monitored weekly both at the influent and effluent ends of the marsh cells to account for variances in seepage and evapotranspiration throughout the production cycle. Checking and cleaning of the inlet and outlet pipes were conducted on a weekly basis.

Statistical Analysis

Analysis of variance was performed using General Linear Model (GLM) procedure (SAS, 1989) in order to determine the effects of wetland size and flow rate on water quality variables in ponds and wetlands, vegetative characteristics of wetlands, and critical biological and economic variables. The means of variables were compared by using the Student-Newman-Keuls (SNK) multiple range test (SAS, 1989). All tests were conducted at a significance level of 0.05. Data on water quality within ponds (pond samples) and wetlands (inlet and outlet samples) were used to address two basic questions: a) what is the effectiveness of wetlands of different configurations themselves in changing water quality, and b) what effect do wetlands of different configurations have on the water quality within ponds? In order to address the issue of wetland effectiveness, values of percent difference between inlet and outlet samples within each wetland were used to allow for comparisons across treatments (i.e., the single value allows for direct comparison between treatments). Under this approach, it is assumed that percent change in each parameter reflects the relative effectiveness of the system to alter the parameter in question. Water quality parameters from pond samples were used to address the second question in a standard comparison of data across treatments.

In the case of water quality parameters, three sets of statistical comparisons were made. For wetland data, including vegetative characteristics, comparisons were made between: a) wetlands of standard water flow rate (6.5 gpm) and variable sizes (15, 25 and 35%), and b) wetlands of standard size (25%) and variable flow rates (3.25, 6.5, 13.0 and 26.0 gpm). For daily and weekly pond sample data, comparisons were made between: a) control ponds and ponds with standard wetlands (25% and 6.5 gpm); b) ponds with standard water flow rate and variable wetland sizes; and c) ponds with standard wetland size and variable water flow rates. For each of the above listed comparisons (except vegetation), data were also compared for each of three designated seasons monitored (spring, summer, fall).

Economic Analysis

Engle (1989) stated that at the early stages of technology development, economic analysis provides methods to estimate both fixed and variable costs associated with the new technology. Cost estimation provides information on the production efficiency of the new technology. Careful assessment of benefits arising from the new technology leads to the estimation of potential revenues. In evaluating the use of constructed wetlands in finfish pond production, experimental data were used to extrapolate the associated added benefits and costs of commercial catfish production.

The benefits and costs associated with the use of constructed wetlands in catfish pond production were estimated by applying the results of the experiment conducted at

MSU-Coastal Aquaculture Unit to a multi-enterprise commercial farm in the Mississippi Black Belt area. A mixed integer linear programming model adapted from Posadas (1998) was used to determine the points of entry of constructed wetlands in the optimal enterprise mix.

III. RESULTS AND DISCUSSION

Effects of Constructed Wetlands on Pond Effluents

The effectiveness of wetlands in changing water quality of pond effluents was evaluated by comparing weekly values of percent difference between inlet and outlet samples for: a) ponds with variable wetland sizes, and; b) ponds with variable retention times. The following discussions focus on values of percent change of parameters across each wetland and not directly on measured values. Starting values for each parameter (i.e., inlet values) are reflected in reported values for pond water quality (next section). It was assumed that the combined effects of rainfall and other extraneous environmental factors on wetland water quality were similar among all wetlands. The following discussions also cover seasonal patterns of each parameter considered. Additionally, the vegetative characteristics of wetlands were also assessed by comparing differences in parameters between inlet and outlet portions of each wetland at the end of the experimental period.

Weekly Wetland Water Quality Parameters (Chemical Parameters)

Average levels of percent change of the chemical parameters monitored in wetlands on a weekly basis are provided in Table 1 for comparisons of wetlands of variable sizes and Table 2 for comparisons of wetlands of variable flow rates. The patterns for each variable across all treatments are discussed below.

Salinity. Salinity levels were reduced across all wetland treatments (i.e., negative values for % change), but were also minimal, ranging from 0 to -8%. There was somewhat of a trend for greater reduction in salinity from small to larger wetlands, but this trend was not statistically significant. There was no apparent trend in values across wetlands with variable flow rate.

pH. Wetland pH was reduced across all wetland treatments, although the level of change was typically under 5%. For wetlands of varying size, there was an obvious and statistically significant trend (overall and for spring and summer) for greater change in pH with greater size of wetlands with large wetlands showing the greatest level of change, at times representing a threefold difference above small and standard wetlands. There was also a trend for reduction of pH across wetlands of varying flow rate, although the level of change was small (2.0-2.5%). Overall, slow and standard flow wetlands showed less reduction in pH compared to fast and very fast wetlands, significantly so overall and in summer and fall. Overall, large wetlands and wetlands with fastest flow rates appear to provide greatest reduction in pH, although the overall levels of change were relatively small.

Total Ammonia. Ammonia levels were reduced across all wetland treatments, at times representing greater than 60% reduction in this compound. For wetlands of varying size, standard size and large wetlands showed significantly greater levels of reduction (overall and during summer and fall) compared to small wetlands, at times representing a two to three fold difference above small wetlands. Although not significantly different, standard wetlands showed slightly greater levels of reduction for ammonia (ranging from 3-12%) compared to larger wetlands. There was also a trend for reduction of ammonia across wetlands of varying flow rate, although the level of change among treatments (10-30%) was relatively smaller than for wetlands of different sizes. Although highest values of reduction were recorded for wetlands with standard flow, they were significantly higher only during summer months and were higher along with slow wetlands overall. Overall, it appears that standard size wetlands and standard flow wetlands provided the greatest levels of reduction for ammonia.

Nitrite. Patterns of nitrite change across wetlands were similar to those for ammonia, with levels of change reaching as high as 97% reduction. Standard size and large wetlands showed significantly greater levels of reduction of nitrites compared to small wetlands overall and for summer and fall months, while small and larger wetlands had higher levels for spring months. Although not significantly different, standard wetlands showed slightly greater levels of reduction for nitrites (as much as 7%) compared to larger wetlands. There was also a trend for reduction of nitrites across wetlands of varying flow rate. Slow and standard flow wetlands tended to have highest values of reduction compared to fast and very fast wetlands, significantly so overall and for all seasons, with highest levels of reduction attributed to standard flow wetlands (93 - 97%). Overall, it appears that standard size and large wetlands and standard flow and slow wetlands provided the greatest levels of reduction for nitrite.

Nitrate. Patterns of nitrate change across wetlands were also similar to those for nitrites and ammonia, with levels of change reaching as high as 80%. Standard size wetlands had significantly higher levels of reduction overall and in summer compared to both small and large wetlands. Standard and slow rate wetlands had significantly higher levels of reduction compared to fast and very fast wetlands overall while standard flow wetlands had significantly higher (and the highest level of reduction) levels of reduction in summer. Overall standard size and standard flow rate wetlands appeared to provide the greatest level of reduction for nitrates.

Phosphorous. Phosphorous levels followed similar trends as those for ammonia, nitrites and nitrates. Standard size and large wetlands showed significantly higher levels of reduction overall and during fall months, with highest values recorded for standard wetlands. Standard and slow rate wetlands had significantly higher levels of reduction overall, with mixed results across seasons. In general, levels of reduction increased as flow rate decreased. Overall, standard size and large wetlands and standard flow and slow wetlands provided the greatest levels of reduction for phosphorous.

Total Suspended Solids. Levels of total suspended solids reductions were similar overall for wetlands of varying sizes, ranging from 14 to 76%. Slow rate wetlands had significantly lower levels of reduction compared to standard and fast rate wetlands overall, with similar but non-significant trends in each season. Standard and fast wetlands appeared to have provided for the largest levels of reduction in suspended solids.

The results of the present study compare well to those of Schwartz and Boyd (1995) who evaluated the use of constructed wetlands for treatment of channel catfish pond effluents in Hale County, Alabama. Water from a 6.9-hectare channel catfish production pond was passed through a constructed wetland consisting of two 84 x 14 meter cells, one planted with California bulrush and giant cutgrass and one planted with Halifax maidencane. The constructed wetland was effective in reducing potential pollutants since concentrations in wetland effluent were much lower than in influent from the channel catfish pond. The removal of potential pollutants was determined for 1 to 4-d hydraulic residence times (HRT, days) with hydraulic rates of 77-91 L/m^2 of wetland per day. The overall performance of the constructed wetland was at its peak when operated with a 4-d HRT in the vegetative season. When the vegetation was dormant, however, shorter HRTs resulted in good removal of potential pollutants. The ranges of reported levels of reductions from both studies were similar for common parameters and were as follows:

Parameter	Schwartz and Boyd (1995)	Present Study
Total ammonia nitrogen	1-81 percent	2-63 percent
Nitrite-nitrogen	43-98 percent	29-97 percent
Nitrate-nitrogen	51-75 percent	28-80 percent
Total Kjeldahl nitrogen	45-61 percent	-
Total phosphorus	59-84 percent	52-95 percent
Biochemical oxygen demand	37-67 percent	-
Suspended solids	75-87 percent	2-76 percent
Volatile suspended solids	68-91 percent	-
Settleable solids	57-100 percent	-
pH	-	0.5-10 percent

Vegetation

The vegetative characteristics of constructed wetlands varied between treatments (i.e., wetland size and flow rate) and between the inlet and outlet areas of each system. Each plant variable was compared for the inlet and outlet portions of wetlands between treatments directly as well as expressed as percentage change. Average values for total dry weight biomass, numbers of stems and calculated average biomass per stem for inlet and outlet portions of wetlands are provided for treatments of varying sizes in Table 3 and for varying flow rates in Table 4. Values of percentage change of these parameters between inlets and outlets within each treatment are also provided. Overall, biomass of plants at the inlet portion of wetlands was greater compared to outlet areas, suggesting that plants near the inlets remove and utilize a larger proportion of available nutrients as these compounds flow through these wetlands.

For wetlands of variable sizes and fixed retention times, plant biomass was significantly greater for the inlets of standard size wetlands and for the outlets of small size wetlands compared to the same sample points in other configurations (Table 3). This pattern suggests that the standard size wetlands at this flow rate resulted in optimal uptake of available nutrients, at least near the inlet, as reflected in greater biomass of plants compared to smaller and larger wetlands. The greater biomass of plants at the outlet end of the smallest wetland used suggests that nutrients may be transported farther along the length of this size wetland. This latter pattern is supported by the similar values of average biomass per stem between the inlet and outlet portions of small wetlands (2.2 and 2.0 g/0.25m^2, respectively) and the relatively small value for percent change for this parameter (2.4%). Values for number of stems were similar across all wetlands for both the inlet and outlet portions. The average size of plants was similar for inlet sites but greater in small wetlands for outlet sites, again suggesting greater distribution of nutrients across small wetlands. Percent changes in all three parameters were significantly different, with standard size wetlands having the highest levels of change and small wetlands the lowest. These patterns also suggest that standard size and large wetlands assimilate most nutrients near inlet compared to outlet areas, while nutrients appear to be distributed more evenly across small wetlands.

For wetlands of fixed size and variable flow rates, plant biomass was not significantly different across flow rates for either inlet or outlet portions of wetlands (Table 4), although a trend for greater biomass is evident for the inlet portion of wetlands with a standard flow rate and for the outlet portion of slow rate wetlands. As with observed trends for fixed-rate wetlands, these patterns suggest that the standard flow wetlands (2-day retention time) resulted in optimal uptake of available nutrients near the inlet, while wetlands with the slowest rate (3-day retention time) may allow for a larger proportion of uptake at the outlet end of the wetland. Numbers of stems were significantly greater for standard wetlands compared to very fast wetlands for inlet areas and significantly greater for slow wetlands compared to all others for outlet areas. This trend also suggest that the standard wetland allowed for optimal growth of plants near the inlet and that the slowest rate treatment allowed for greater proportional growth of plants near the outlet of wetlands across treatments. The average size of plants was similar for inlet sites but varied somewhat for outlet sites, with a trend for greater average size for fast and slow wetlands. No apparent reason for this latter pattern is evident. Percent changes in plant biomass and average stem biomass were significantly different, with fast wetlands showing positive change in these parameters, suggesting that nutrients were being transported further along within these wetlands prior to their assimilation by plants. Slow rate wetlands had the smallest change in plant biomass and average stem biomass, suggesting that, as with the case of small wetlands, this treatment may have allowed for a more even distribution of nutrients across these wetlands.

Effects of Constructed Wetlands on Pond Water Quality

The effects of using constructed wetlands on pond water quality were evaluated by comparing the daily and weekly values for: a) control ponds versus ponds with standard wetland size and retention time; b) ponds with variable wetland sizes, and; c) ponds with variable retention times. It was assumed that the effects of rainfall and other extraneous environmental factors on pond water quality were similar among all ponds. The following discussions also cover seasonal patterns of each parameter considered.

Daily Pond Water Quality Parameters (Water Temperature, Dissolved Oxygen, and Aeration)

The optimal range of dissolved oxygen (DO) for catfish pond culture is between 5 and 15 ppm (Tucker and Boyd 1985, Boyd and Frobish 1990). At concentrations below 4 ppm, fish may survive but slow growth occurs when fish are exposed for prolonged periods, while the lethal level is about 1 ppm (Boyd and Frobish 1990, Wellborn 1987). In order to maintain the optimal range, daily DO concentrations in each pond were monitored three times during summer months (dawn, morning, afternoon) and twice (morning, afternoon) during cooler months. When the DO level in a pond was expected to fall below the critical range, an aerator was turned on until such time when the DO level reached the desired range. These decisions were usually based on patterns of both morning and afternoon readings that showed a high range of DO and aerators were usually turned on after afternoon readings were taken.

Average daily levels for morning and afternoon DO and temperature and aeration time are provided in Table 5 for comparisons of control ponds and ponds with standard wetlands, Table 6 for comparisons of wetlands of variable sizes and Table 7 for comparisons of wetlands of variable flow rates. Overall, morning DO levels and morning and afternoon temperature levels were similar and not significantly different between ponds for any of the three pond sets compared.

Afternoon DO levels and aeration times among treatments were at times, however, significantly different with the following trends among treatments. Control ponds had significantly higher levels of afternoon DO compared to ponds with standard wetlands. Among wetlands of varying sizes, small and large wetlands had higher levels of DO compared to standard wetlands and among wetlands of varying flow rates slow, fast and very fast wetlands had significantly higher values compared to standard wetlands. Similarly, the ranges between morning and afternoon levels of DO were also higher for these same treatments compared to standard wetlands (Table 8). Both of these trends may, in part, be related to higher levels of algal production in each of these treatments compared to standard wetlands (see following section on chlorophyl and phaeophytin) that would contribute to both higher afternoon DO levels and a greater daily range of DO.

Although not as consistent, the patterns for daily aeration times may also be related to daily ranges of DO. Control ponds required higher daily aeration times (significantly so in summer) compared to standard wetlands. Standard size wetlands, however, had significantly higher aeration times compared to small and large wetlands, while fast rate wetlands had higher aeration times compared to slow, standard and very fast rate wetlands.

Overall, these patterns suggest that wetlands had the effect of dampening fluctuations in daily DO within ponds compared to ponds without wetlands (controls) and that ponds with wetlands of standard size (25%) and flow rate (2-day retention time) appear to be most effective in minimizing daily fluctuations in DO compared to other combinations of wetland size and flow rate.

Weekly Pond Water Quality Parameters (Chemical Parameters and Photosynthetic Pigments)

Average levels of the chemical, physical and biological parameters monitored on a weekly basis are provided in Table 9 for comparisons of control ponds and ponds with standard wetlands, Table 10 for comparisons of wetlands of variable sizes and Table 11 for comparisons of wetlands of variable flow rates. The patterns for each variable across all treatments are discussed below.

Salinity. Channel catfish are freshwater fish (Wellborn, 1987) and achieve optimal growth rates at salinity levels ranging from 0.5 to 3 ppt (Tucker and Boyd, 1985). This fish species also thrives in brackish water (Wellborn, 1987) and tolerates salinity ranging from 0.1 to 8 ppt. Overall, pond water salinity (ppt) was typically below 2.0 ppt across most treatments and seasons, with values as high as 3.2 ppt with lowest values in the spring and highest values in the fall. Although average values were significantly different between treatments at times of the year (spring and fall), the differences were relatively small (generally less than 0.5 ppt, upwards of 1.0 ppt) and within the range for optimal growth for catfish (< 3.0 ppt). These levels for salinity are not, therefore, suspected of affecting other results.

pH. The optimal range of pH for fish culture is between 6.5 and 9 (Tucker and Boyd, 1985; Wellborn, 1987) although channel catfish can tolerate as low as 5 or as high as 10. When pH reaches 4 or 11, acid or alkaline death occurs (Boyd and Frobish, 1990). Slow grow occurs if fish are exposed to pH below 6.5, while no reproduction takes place when pH is between 4 and 5 (Boyd and Frobish, 1990). Pond water pH readings during the entire experiment ranged between 6.7 and 7.4 across all treatments, with lowest values in summer and highest values in the fall. As with salinity, average values were significantly different between treatments at times. However, the differences were relatively small (generally less than 0.3, upwards of 0.7) and within the range for optimal growth. Because of the small absolute differences between treatments for this parameter, they are not suspected to have any affect on other parameters.

Total Ammonia. When proteins in the feed are digested by fish, ammonia is excreted through the gills and in feces (Tucker and Boyd, 1985; Durborow et al., 1992b). Ammonia also enters into the ponds from bacterial decomposition of organic matter, e.g., excess feed, dead algae and aquatic plants (Durborow et al., 1992b). Total ammonia nitrogen is composed of un-ionized ammonia and ionized ammonia (Durborow et al., 1992b). Un-ionized ammonia is considered toxic to aquatic animals (Boyd and Frobish 1990; Durborow et al., 1992b). Short-term exposure to toxic un-ionized ammonia of about 0.6 mg/l is capable of killing fish in a few days while chronic exposure to levels as low as 0.06 mg/l can cause gill and kidney damage, growth reduction, brain malfunction, and reduction in oxygen-carrying capacity (Durborow et al., 1992b). In general, total ammonia levels below 1.0 mg/l are non-toxic for fish. The standard equation used to calculate weekly total ammonia levels was as follows: Total Ammonia Nitrogen (mg/l) = 0.6334 - 0.0368 X mV, (S.E. = 0.0016; R^2 = 0.9756; n = 15).

Total ammonia levels varied significantly between treatments but remained below 1.0 mg/l throughout the experimental period. Ponds with standard wetlands had significantly higher levels of ammonia compared to control ponds overall and during summer months. For wetlands of varying sizes, small wetlands tended to have higher values (significantly so overall and during fall months) followed by standard wetlands, with smallest levels in large wetlands. For wetlands of varying flow rates, levels were highest (significantly so overall and for all seasons) for standard flow rate, followed by slow, fast and very fast wetlands. These patterns suggest that wetlands did not appear to reduce levels of ammonia and in fact had significantly higher levels of the compound compared to control ponds, although levels remained below that considered toxic. These results also suggest that larger wetlands and wetlands with very fast flow rates were better at reducing levels of ammonia. These trends should be viewed with caution, however, given the highly volatile nature of ammonia. The observed trend for lower levels of ammonia with increasing size of wetlands may be related to the concomitant increase in surface area across which ammonia may exit the wetland and, therefore, lead to reduced levels within ponds.

Nitrite. Total ammonia nitrogen is first converted to nitrite which, under normal conditions, is quickly converted to nonionic nitrate by naturally occurring bacteria (Durborow et al., 1992a). When nitrite concentrations exceed that which the pond's bacterial populations can rapidly transform to nitrate, brown blood disease may occur due to the rapid accumulation of nitrite in the pond (Durborow et al., 1992a). Fish tolerance to nitrites, however, depends on chloride concentrations in the ponds (Tucker and Boyd, 1985). A standard curve estimated before the start of the experiment was used to measure weekly nitrite concentrations [Nitrite (mg/l) = 0.3061 X % absorbance, (S.E. = 0.0008; R^2 = 0.9999; n = 12)].

As with ammonia levels, nitrite levels varied significantly between treatments, with similar trends among treatments. Ponds with standard wetlands had significantly higher levels of nitrite compared to control ponds in summer months. For wetlands of varying sizes, large wetlands tended to have the lowest levels (significantly so in spring) followed by small and standard wetlands. For wetlands of varying flow rates, levels were highest (significantly so overall and during summer and fall) for standard flow rate, generally followed by slow, very fast and fast wetlands. As for ammonia, these patterns suggest that wetlands did not appear to reduce levels of nitrite compared to control ponds, although levels remained low overall. Similarly, larger wetlands and wetlands with very fast flow rates were better at reducing levels of nitrite.

Nitrate. With constructed wetlands, it is expected that the conversion of nitrites to nitrates by the bacterial populations in the ponds and wetlands is enhanced. Nitrate values were measured by using the following standard curve: Nitrate (mg/l) = 2.6374 -

0.0798 X mV, (S.E. = 0.0117; R^2 = 0.8221; n = 12). Nitrate levels followed the same patterns as for nitrite: ponds with standard wetlands tended to have higher levels compared to control ponds (although not significantly), large wetlands had lowest levels (significantly so in spring) followed by small and standard wetlands, and standard flow rate ponds had highest (significantly so overall and during summer) followed by slow, very fast and fast wetlands. As for ammonia and nitrite, these patterns suggest that wetlands did not appear to reduce levels of nitrate compared to control ponds, although levels remained low overall. Similarly, larger wetlands and wetlands with very fast flow rates were better at reducing levels of nitrate.

Phosphorus. The supply of native and added phosphorous affects the productivity of natural waters (Boyd and Frobish, 1990). During intensive feeding it is expected that phosphorous concentrations will rise steadily. The build up of phosphorous in ponds will enhance the growth of wetland plants as well as phytoplankton in ponds. The availability of natural food in ponds will also enhance fish growth. A healthy and mature population of plants will make the wetlands more effective in improving water quality. When planktonic blooms in ponds become over-abundant, however, additional culture problems are encountered (e.g., off-flavor, oxygen depletion). Weekly phosphorus levels were measured by using the following standard equation: Total Phosphorus (mg/l) = 9.1999 X % absorbance, (S.E.= 0.2226; R^2 = 0.9892; n = 15).

Phosphorous levels varied significantly between treatments at times during the experimental period. Control ponds had higher levels of phosphorous compared to ponds with standard wetlands in the spring (significantly so) and summer, but the opposite was true for the fall period (significantly so). For wetlands of varying sizes, the pattern was mixed with a trend for standard wetlands to have higher values (significantly so overall and in the fall) followed by large wetlands and small wetlands. For wetlands of varying flow rates, levels were highest (significantly so overall and for summer and fall) for slow rate wetlands, followed by standard, fast and very fast wetlands. These patterns suggest that wetlands may at times reduce levels of phosphorous compared to control ponds. These results also suggest that small wetlands and wetlands with very fast flow rates were better at reducing levels of phosphorous.

Total Suspended Solids. Total suspended solids (TSS) is a measure of the particular matter in suspension and may indicate the pollution strength of pond effluents (Boyd and Tucker, 1992). This parameter was similar for control ponds compared to ponds with standard wetlands, except for the fall period when levels were greater in control ponds. For wetlands of varying size, small wetlands tended to have higher levels of TSS (significantly so overall and for spring and fall). For wetlands of varying flow rate, standard wetlands had higher levels in general (significantly so overall and in spring), except for fall when fast and very fast wetlands had significantly higher levels. Wetlands, therefore, appear to have a minimal effect on levels of TSS compared to control ponds. Small wetlands appear to be less capable of reducing levels of TSS compared to standard and large wetlands.

Chlorophyll a. In intensive pond culture, the metabolic activities of plankton influence concentrations of dissolved oxygen, carbon dioxide, ammonia, nitrite, and other substances that affect the growth and survival of fish (Boyd and Tucker 1992). Van der Ploeg and Boyd (1991) reported that a study of *Anabaena* blooms over a period of 4-8 weeks at Auburn University Fisheries Research Station showed that changes in geosmin were correlated significantly with changes in algal abundance and chlorophyll a. A close relationship usually exists between the concentrations of chlorophyll a in water and the total abundance of phytoplankton (Boyd and Tucker 1992). Levels of chlorophyll a in control ponds tended to be greater than that in ponds with standard wetlands (significantly so overall and in summer and fall). For wetlands of varying size, ponds with small wetlands had higher levels of chlorophyll a (significantly so overall and in the fall), with standard and larger wetlands having similar levels. For wetlands of varying flow rate, fast and very fast wetlands tended to have higher levels of chlorophyll a (significantly so overall and in the fall) with standard and slow wetlands with similar levels. These trends suggest that wetlands can lead to lower levels of chlorophyll a in ponds, and may be related to the trend for higher levels and ranges of DO in control ponds compared to ponds with wetlands. It also appears that small wetlands and wetland with fast and very fast flow rates may be least effective at reducing levels of chlorophyll a in ponds.

Phaeophytin. Levels of phaeophytin in ponds followed the same trends as for chlorophyll a with control ponds tending to have greater levels than that in ponds with standard wetlands (significantly so overall and in the fall). For wetlands of varying size, ponds with small wetlands had higher levels of chlorophyll a (significantly so in spring and fall), with standard and larger wetlands having similar levels. For wetlands of varying flow rate, fast and very fast wetlands tended to have higher levels of phaeophytin (significantly so overall and in the fall) with standard and slow wetlands with similar levels. As for chlorophyll a, these trends suggest that wetlands can lead to lower levels of phaeophytin in ponds, and may be related to the trend for higher levels and ranges of DO in control ponds compared to ponds with wetlands. Similarly, it also appears that small wetlands and wetland with fast and very fast flow rates may be least effective at reducing levels of phaeophytin in ponds.

Effects of Constructed Wetlands on Catfish Production

Catfish Survival, Growth and Yield

During harvest, all the fish in each experimental pond were counted. Overall catfish survival averaged 57% as compared to 65% reported by Heikes and Killian (1997) in commercial catfish ponds during yield verification studies conducted in Arkansas. Catfish survival rates did not vary significantly between control ponds and ponds with standard wetlands (Table 12) and among ponds with variable wetland sizes (Table 13) and variable flow rates (Table 14). Since the observed fish mortality was about 1%, the low survival rate can be attributed to bird predation. Severe predation still occurred despite the delay of stocking to coincide with the departure of the migrating populations of double-crested cormorants from the area.

During harvest, a sample of 100 fish from each pond was weighed and measured. Absolute fish growth was measured by taking the difference between the final harvest weight and the initial stocking weight. Fish growth in all experimental ponds averaged 1.52 lb/fish. Statistical tests showed that catfish growth rates did not vary significantly between control and treatment ponds, among ponds with variables wetlands and among ponds with variable flow rates (Tables 12-14).

Heikes and Killian (1997) reported that among the participating Arkansas ponds, the harvested and marketed weights averaged 1.33 and 1.52 lb/fish, respectively. Overall harvested fish size from the 16 experimental ponds averaged 1.63 lb/fish. Harvested sizes did not vary significantly between control ponds and treatment ponds, among ponds with variables wetlands and among ponds with variable flow rates (Tables 12-14).

Average fish yield from the 16 experimental ponds was 1,686 lb/pond or 6,744 lb/acre with a stocking density of 8,000 fingerlings/acre. In Arkansas, Heikes and Killian (1997) reported total fish harvested averaging 5,542 lb/acre with a stocking density averaging 6,702 fish/acre. With a stocking density of 5,700 fish/acre, catfish farmers in the Mississippi Black Belt marketed about 5,200 lb/acre (Posadas and Dillard, 1997). Fish harvest did not vary significantly between control ponds and ponds with standard wetlands, among ponds with variable wetland sizes and among ponds with variable retention times (Tables 12-14).

Incidence of Off-flavor

Off-flavor occurs when catfish acquire certain flavors perceived as unacceptable by the consumer (Keenum and Waldrop, 1988; Van der Ploeg, 1989; Boyd and Frobish, 1990). Biological processes that take place in the pond environment produce odorous compounds that are absorbed by fish through the gills and accumulate in the flesh (Van der Ploeg, 1989). Boyd and Frobish (1990) suggested that water in ponds be exchanged to flush out substances responsible for off-flavor. Mississippi Cooperative Extension Service (1993) reported that studies conducted at the Delta Research and Extension Center in Stoneville, Mississippi provide new information for efficient management of the off-flavor problem, as follows:

> "It is now known that, during the summer, 75% of all off-flavors are caused by a compound called MIB (*2-methylisoborneol*). Although at least 10 species of blue-green algae are found in the Delta, only one is responsible for MIB production. This species (*Oscillatoria chalybea*) first appears in ponds during the summer when water temperatures exceed 70 ^{o}F (20 ^{o}C). It usually disappears when water temperatures fall below this level in September or October, but is has been found at temperatures as low as 60 ^{o}F (15 ^{o}C).
>
> When present in a pond, this alga releases MIB into the water. MIB is then absorbed through the gills and stored in fish flesh causing fish to become off-flavor. While research has shown that fish can purge MIB once the alga disappears, the purging process depends on water temperature and is very slow at temperatures below 60 ^{o}F. Fish exposed to MIB during summer and early fall may not be able to get rid of off-flavor due to cooler water temperatures; the off-flavor that is acquired in the summer can thus last the entire winter. In addition, the alga responsible for MIB is likely to return to the same pond summer after summer. This means that if

> fish do not purge MIB before May or June, they may be exposed to MIB once more, off-flavors will intensify.
>
> Most ongoing research is focusing on learning more about the species that produces MIB. This knowledge is necessary to develop possible treatments or control methods. As for now, the only proven option available to producers is to "manage around the problem."

The incidence of catfish off-flavor did not vary significantly between control ponds and ponds with standard wetlands, among ponds with variable wetland sizes and among ponds with variable retention times. Except for the ponds with small wetlands (15%), the fish in control and treatment ponds had some degree of off-flavor. The average off-flavor scale (0 being on flavor and 5 being the worst case of off-flavor) for the control and treatment ponds were as follows:

Control ponds without wetlands: 1.33,
Ponds with variable wetland sizes and constant retention time:
    15% & 2 days: 0.00,
    25% & 2 days: 0.50,
    35% & 2 days: 1.25,
Ponds with variable wetland retention time and fixed wetland size:
    3 days & 25%: 2.50,
    2 days & 25%: 0.50,
    1 day & 25%: 1.00,
    0.5 day & 25%: 1.25.

Feed Conversion, Electricity Consumption, Pond Aeration and Chemical Use

Heikes and Killian (1997) reported net and gross feed conversion ratios in Arkansas averaging 1.0 to 2.0 and 1.0 to 1.7, respectively. In the Mississippi Black Belt, Posadas and Dillard (1997) estimated that the gross feed conversion ratio was 1.0 to 1.8. The overall net and gross feed conversion ratios in the 16 experimental ponds were 1.0 to 2.4 and 1.0 to 2.0, respectively. Gross and net feed conversion ratios did not vary significantly between control ponds and ponds with standard wetlands (Table 12), among ponds with variable wetland sizes (Table 13) and among ponds with variable retention times (Table 14).

Electricity used by water pumps to recirculate water from wetlands to ponds varied significantly among ponds with variable wetland sizes (Table 15) and among ponds with variable retention times (Table 16). Ponds with standard wetlands (25%) used less electricity than those with smaller (15%) and larger (35%) wetlands. Ponds with wetlands having longer retention times consumed less electricity than those with shorter retention times.

Annual electric use for aeration averaged 1,424 kwh/acre or $120/acre in the Mississippi Black Belt (Posadas and Dillard, 1997). In Arkansas, the average operating cost of aeration was about $82/acre (Heikes and Killian, 1997). Average aeration time among control ponds during the entire growing season did not vary significantly with that in ponds with standard wetlands (Tables 5-7). During summer months, however, control ponds used 12% more aeration than ponds with standard wetlands.

The annual expenditures on farm chemicals (copper sulfate, lime and salt) used by Mississippi Black Belt fish farmers to deal with water quality and off-flavor problems averaged $62/acre (Posadas and Dillard, 1997). The costs of chemicals (lime, herbicides, salt) used in the 16 control and treatment ponds did not vary significantly (Tables 12-14).

Benefits and Costs of Constructed Wetlands

The benefits and costs associated with the use of constructed wetlands in catfish pond production were estimated by applying the results of the experiment conducted at MSU-Coastal Aquaculture Unit to a multi-enterprise commercial farm in the Mississippi Black Belt area. Mississippi Black Belt was selected due to the following reasons: steady increase in catfish acreage and processing capacity, lack of a cheap water supply, and dependence on surface run-off as the major source of pond water. There are about 7,000 water surface acres devoted to catfish farming in the area and three catfish processing plants with a combined daily processing capacity of about 150,000 pounds. Deep water wells used by two commercial farms in the area were dug at a depth of 1,600 ft. In areas like the Mississippi Black Belt, therefore, constructed wetlands can be used to treat and conserve pond water and surface-run-off.

The average multi-enterprise farm in the Mississippi Black Belt had 504 land acres used in crop production (corn, cotton and/or soybeans), contract swine growing operation, and six 8-water-acre-ponds catfish enterprise (Posadas, 1998). This diversified farm is typically owned and operated by the farmer with additional labor provided by other family members and occasional hired workers during peak months. The investment requirements and annual costs of the catfish enterprise were estimated with the assumption that some common farm assets (e.g., building, tractors and truck) were also used in other farm enterprises (e.g., cotton, corn soybeans).

Investment Requirements

In estimating the investment requirements for constructed wetlands, the following wetland sizes and retention times were used for each of the three wetland/pond combinations:

Small:	15% of pond size or 1.2 acres and 2-day retention time,
Standard:	25% of pond size or 2.0 acres and 2-day retention time,
Large:	35% of pond size or 2.8 acres and 2-day retention time.

The initial investment requirements for six 8-water-surface-acre catfish ponds on a multi-enterprise farm in the Mississippi Black Belt area were to $169,312 or $3,527/acre (Posadas and Dillard, 1997; Posadas, 1998). With six 1.2-water-surface-acre wetlands built adjacent to the catfish ponds, total initial investment requirements rose by $127,498 or $2,656/acre. To build six 2.0-water-surface-acre wetlands adjoining the catfish ponds, an additional initial investment amounting to $199,703 or $4,160/acre would be required (Posadas and LaSalle, 1997). Total initial investment would rise by $271,908 or $5,665/acre when six 2.8-water-surface-acre wetlands are built adjacent to the catfish ponds. The breakdown of the investment requirements ($) for the 48-acre catfish enterprise (Posadas and Dillard, 1997) and six 2.0-acre (Posadas, 1998; Posadas and LaSalle, 1997), six 1.2-acre and six 2.8-acre constructed wetlands were as follows:

	Six catfish	Six constructed wetlands		
Item	ponds	1.2-acre	2.0-acre	2.8-acre
Land	40,656	6,098	10,164	14,230
Pond/Wetland construction				
Surveying	2,904	436	726	1,016
Earth moving	58,214	8,732	14,554	20,375
Drainage structure	3,888	NA	NA	NA
Gravel	2,064	310	516	722
Vegetative cover	541	81	135	189
Plants & planting	NA	92,160	153,600	215,040
Sub-total	67,611	101,719	169,531	237,342
Electrical system	1,300	NA	NA	NA
Recycling system	NA	19,681	20,008	20,335
Equipment	59,745	NA	NA	NA
Total investment	169,312	127,498	199,703	271,907
Per water acre	3,527	2,656	4,160	5,665

About three-fourths of the total initial investment in constructing six wetlands was spent on the purchase and planting of the desired wetland vegetation. The average purchase and planting cost of 12-inch duck potato and soft rush plants was $0.40/seedling. This method of creating the desired growth of vegetative cover was necessary to allow the constructed wetlands to achieve the highest removal efficiencies during the experimental period.

A recirculating aquaculture facility located in California uses large constructed wetlands to treat water discharged from tanks (Michael J. Masingill, Kent SeaFarms Corporation, pers. comm.). This fishfarm collected plants from nearby plant nurseries to supply the plants needed in the constructed wetlands. Artificial wetlands built in Texas designed to treat pond effluents before discharge were planted with aquatic plants obtained from federal and private-sector plant nurseries (Granvil Treece, Texas Sea Grant Program, pers. comm.).

Annual Costs and Returns

Experimental results showed that at a stocking density of 8,000 seven-inch fingerlings per production acre, there were no significant differences in the yields of ponds with and without wetlands, ponds with variable wetland sizes or ponds with variable retention times. At this stocking density, therefore, the annual yield of the six

8-acre commercial catfish ponds would be 323,712 pounds or 6,744 lb/acre. At this stage of determining the effectiveness of using constructed wetlands in finfish pond production, the significant improvements in pond water quality did not lead to significantly observable benefits, namely: higher yields, faster growth, higher survival and less incidence of off-flavor. With these catfish production results, the total revenues from the 48-acre catfish enterprise with or without constructed wetlands amounted to $213,650/year or $4,451/acre, assuming a farm-gate price of $0.66/lb. Farm-gate price received by Mississippi Black Belt catfish farmers was usually five cents less than the reported industry farm-gate price. Gross receipts ($/yr), total costs ($/yr) and net returns ($/yr) of the six 8-acre catfish ponds and six 1.2-acre, six 2.0-acre and six 2.8-acre constructed wetlands are shown below:

	Six catfish	Six constructed wetlands		
Item	ponds	1.2-acre	2.0-acre	2.8-acre
Gross receipts	213,650	0	0	0
Total costs	184,074	16,776	19,225	25,412
Net returns	29,575	-16,776	-19,225	-25,412

Total specified operating (variable) and ownership (fixed) costs of the 48-acre Mississippi Black Belt catfish enterprise without constructed wetlands amounted to $184,074/year, averaging $3,835/acre or $0.57/lb. When six 1.2-acre constructed wetlands were added to the catfish enterprise, total costs rose by $16,776 annually, $350/acre or $0.052/lb. The use of six 2.0-acre constructed wetlands in the 48-acre catfish enterprise led to an increase in total costs by $19,225 annually, $401/acre or $0.059/lb. Building and operating six 2.8-acre constructed wetlands adjacent to the six 8-acre catfish ponds would increase total costs by $25,412 annually, $529/acre or $0.079/lb. Most of the increases in total costs are attributable to the higher fixed costs associated with the construction of the wetlands. The reduction in electricity consumption due to lower aeration time was more than offset by the increased use of the water pumps to recirculate treated water back to the production ponds.

Annual fixed costs. The total ownership (fixed) costs of the 48-water-surface-acre catfish operation in the Mississippi Black Belt area amounted to $25,891/year, $539/acre or $0.08/lb. The annual fixed costs associated with the construction of six 1.2, 2.0 and 2.8-acre wetlands were $9,755, $14,219 and $18,684, respectively. The major categories of annualized fixed costs ($/yr) of the six 8-acre catfish ponds and six 1.2-acre, six 2.0-acre and six 2.8-acre constructed wetlands are shown below:

	Six catfish	Six constructed wetlands		
Item	ponds	1.2-acre	2.0-acre	2.8-acre
Depreciation	14,099	2,880	3,521	4,162
Interest on investment	10,498	6,680	10,493	14,307
Taxes and insurance	1,293	195	205	215
Total fixed costs	25,891	9,755	14,219	18,684
Per water acre	539	203	296	389
Per pound	0.080	0.030	0.044	0.058

Annual operating costs. The total operating (variable) costs of the 48-water-surface-acre catfish enterprise in the Mississippi Black Belt area were $158,183/ year, $3,295/acre or $0.49/lb. The total variable costs associated with the operation of six constructed wetlands were $7,021, $5,006 and $6,728/year for the six 1.2, 2.0, and 2.8 acre wetlands, respectively. The primary components of total operating costs ($/yr) of the six 8-acre catfish ponds, and six 1.2-acre, six 2.0-acre and six 2.8-acre constructed wetlands are as follows:

	Six catfish	Six constructed wetlands		
Item	ponds	1.2-acre	2.0-acre	2.8-acre
Repair and maintenance	4,308	647	750	871
Fuel	4,536	0	0	0
Electricity	5,952	4,264	2,277	3,767
Chemicals	2,976	0	0	0
Telephone	248	0	0	0
Water quality analysis	378	0	0	0
Fingerlings	28,800	0	0	0
Feed	75,525	0	0	0
Labor	7,501	1,620	1,620	1,620
Harvesting and hauling	16,186	0	0	0
Liability insurance	300	0	0	0
Miscellaneous	800	0	0	0
Operating interest	9,849	490	349	469
Inventory interest	823	0	0	0
Total operating costs	158,183	7,021	5,006	6,728
Per water acre	3,295	146	104	140
Per pound	0.489	0.022	0.016	0.021

Cost of Delayed Sales Due to Off-Flavor

Kelly et al. (1991) reported that the ability to sell fish on time by most of the Mississippi Black Belt farmers had been adversely affected by off-flavor problems. Off-flavor lasted between 3 and 4 months and occurred in about 2 to 3 ponds of the 4 ponds stocked with catfish. When the cost of delayed sales due to off-flavor is incorporated in the costs analysis of the Mississippi Black Belt catfish enterprise, annual specified costs will rise between 0.29-2.65 cents/lb depending on the number of ponds affected and the length of the off-flavor occurrence (Posadas, 1998). In the Mississippi Delta, Keenum and Waldrop (1988) calculated the added costs due to off-flavor occurring in one (second or fourth) and two (second and fourth) quarters as 1.86 or 1.75 and 3.61 cents/lb, respectively. Using a synthesized 323-acre catfish farm, Coats et al. (1989) estimated that off-flavor occurring 16 weeks in all 16 Mississippi Delta ponds would add 4.5 cents/lb to the cost of catfish production. With a multi-period mathematical programming model, Engle et al. (1995) suggested that in order to be feasible, systems designed to purge off-flavor from catfish would need to cost less than 2.27 cents/lb (if cash flow is not a consideration) or 1.81-11.36 cents/lb (with cash flow considerations).

Since the incidence of catfish off-flavor during the experiment at MSU-CAU was not significantly different between control and standard ponds and among treatment ponds with variable wetland sizes and retention times, the cost of delayed sales due to off-flavor are considered the same for the Mississippi Black Belt catfish enterprise operated with and without constructed wetlands. For this report, the cost of delayed sales due to off-flavor was not included in the estimation of the cost of catfish production.

Optimal Enterprise Mix

Using a mixed integer linear programming (MILP) model, the points of entry and exit of catfish production and standard constructed wetlands in a multi-enterprise farm located in the Mississippi Black Belt was evaluated (Posadas, 1998). An expanded version of this MILP model was developed to evaluate the points of entry of three sizes of constructed wetlands in the short-run optimal enterprise mix. The enterprises included in the MILP model are as follows: corn, cotton, soybeans, catfish, swine and wetlands. The corn enterprise referred to corn production for grain using 8-row equipment (DAE, 1995b; Caillavet, 1996). The cotton enterprise dealt with the production of cotton with 8-row equipment under the boll weevil eradication program (DAE, 1995a; Caillavet, 1996). The soybean enterprise referred to the production of soybeans using 8-row equipment (DAE, 1995c; Caillavet, 1996). The swine enterprise was the hog finishing operation contracted by Prestage Farms, Inc. (1995) involving four houses per operation with 880 head per house. Economic and environmental implications of the ban on commercial hog farm operations in some counties were not included in the model. The size of the catfish operation was limited to the average Mississippi Black Belt catfish enterprise consisting of six ponds or 48 water acres. The wetland enterprises referred to the use of 1.2, 2.0 or 2.8-acre constructed wetland for every eight-acre pond employed in catfish production.

The objective function was assumed to maximize net returns subject to technical and resource constraints. In the short-run, farmers are expected to make production decisions based on returns above variable (operating or direct) expenses. The objective function of the MILP model during the short-run is to maximize returns above variable expenses. Whole farm revenue is the sum of the farm-gate values of crops, swine or catfish produced during the year. Farm-gate prices used in the MILP model were as follows: corn - $2.46/bushel, cotton lint - $0.04/lb, cotton seed - $0.60/lb, soybeans - $5.89/bushel and catfish - $0.66/lb. Expected yields used in the MILP model were as follows: corn - 80 bushel/acre, cotton lint - 520 lb/acre, cotton seed - 806 lb/acre, soybeans - 25 bushel/acre and catfish - 53,952 lb/pond. The expected annual contract payments for swine growers were $23,975/house or 5.27 cents/lb of weight gain.

Whole farm costs include variable costs and fixed costs for all enterprises undertaken during the year. The variable costs of producing cotton, corn and soybeans in the Black Belt area were based on the 1996 planning budgets developed by the Department of Agricultural Economics (DAE, 1995a-c). In order to simplify analysis, harvesting and hauling of crops were assumed to be done on a contractual basis. The costs of contract harvesting and hauling for corn, cotton and soybeans were imputed from estimates made by DAE (1995a-c). The variable costs of catfish production did not include any values associated with constructed wetlands. The variable costs associated with the operation of the three sizes of constructed wetlands were estimated by applying the experimental results described earlier on the procedures used in a 48-acre catfish operation in the Mississippi Black Belt (Posadas 1998; Posadas and LaSalle 1997).

For contract swine operation, the variable costs were imputed from the budgets prepared by Prestage Farms, Inc. (1995) for contract hog finishing enterprise. The annual variable costs for the contract hog finishing enterprise included in the MILP model are the following: electricity - $1,500/house and miscellaneous - $500/house. The other variable inputs used in hog finishing operation, e.g., veterinary services, medicine, and feed were provided by Prestage Farms. The costs of these variable inputs were included in the computation of the contract payments received by farmers. Operators received net contract payments amounting to $23,975/house or 5.27 cent/lb of net weight gain.

Resource constraints included availability of land, operator and family labor, tractor time and operating capital. The average farm size was 581 acres, of which 504 acres were suitable for crop or catfish production. The remaining land was either unsuitable for crop or catfish production or used for livestock production. Labor used in the farms was primarily supplied by the farmer and family members. The available monthly man-hours were computed from the number of days suitable for fieldwork in Mississippi (Spurlock et al., 1995; Bolton et al., 1968) and the availability of two full-time family workers, one part-time family worker and one part-time hired worker. Monthly tractor time available was based on the number of suitable days for fieldwork, two full-time family workers and two tractors. Operating capital used in all the enterprises included in the optimal solution of the MILP model was assumed to be available at a 10% annual interest rate.

By using General Algebraic Modelling Systems (GAMS), the objective of the MILP model was maximized subject to resource constraints. The initial optimal short-run enterprise mix consisted of 438 acres of soybeans, six 8-acre ponds of catfish and four 880-head swine houses. Total operating capital required to finance this optimal enterprise mix was about $225,000/year. Whole farm revenues, total operating costs and net returns above variable costs were $374,000, $225,000 and $149,000/year, respectively.

Initial results showed that catfish production in a multi-enterprise farm in the Mississippi Black Belt is a profitable enterprise. The use of constructed wetlands in intensive and recirculating catfish pond production assuming present technology, however, is not economically viable. In order to reduce the risks of lower production due to water shortage, fishfarmers need a supplemental source of water. Constructed wetlands can be used to treat pond effluents before discharge to the environment. These structures can also be used to improve water quality of surface runoff or pond effluent before pumping into ponds.

By using sensitivity analysis, the entry of constructed wetlands in the short-run optimal enterprise mix was determined. The use of six 2-acre constructed wetlands would be acceptable if their use in a 48-acre catfish production would lead to an increase in the annual yield of marketable catfish by 5% or 340 lb/acre. Six 1.2 or 2.8-acre constructed wetlands would be used in a 48-acre catfish farm if the annual yield of marketable catfish would increase by 7% or 470 lb/acre.

The results of experimental trials conducted at MSU-Coastal Aquaculture Unit, however, showed that at 8,000 fingerlings/water-acre stocking density, the expected increases in the marketable yields, growth rates and survival rates of catfish in ponds with constructed wetlands were not realized. The expected increases in revenues were not achieved to justify the costs associated with constructed wetlands. Further testing of this technology needs to be undertaken in order to ascertain the effects on the yields of marketable catfish or other fish species under intensive commercial scale operations. Other species now widely being cultured commercially in ponds in some southern states include white shrimp, hybrid striped bass, tilapia and freshwater prawn.

VII. SUMMARY, CONCLUSIONS AND LIMITATIONS

Summary and Conclusions

The general objective of this study was to evaluate the use of constructed wetlands in improving pond water quality and assess the associated benefits and costs in intensive finfish pond production. The experiment was conducted at the Mississippi State University-Coastal Aquaculture Unit for one catfish growing season. Each of the 16 quarter-water acre ponds was stocked with 2,000 7-8 inch catfish fingerlings. Six of the ponds were used in a replicated fashion to evaluate the effectiveness of constructed marshes toward improving water quality while the remaining 10 ponds were used in a range testing fashion to determine optimal wetland design criteria and operation parameters.

Water quality parameters were monitored on both daily and weekly schedules and included factors assessed as part of standard pond management practice (e.g., dissolved oxygen, temperature, pH, total ammonia, nitrite) as well as additional factors (e.g., nitrate and total phosphorous) and parameters (e.g., total suspended solids, chlorophyll *a* concentration) that were needed for a more detailed assessment of nutrient removal. Dissolved oxygen and temperature were measured twice per day (early morning, mid-afternoon). Salinity, pH, total ammonia, nitrate, nitrite, total phosphorus, total suspended solids, and photosynthetic pigments (chlorophyll *a* and phaeophytin) were measured on a weekly basis.

The condition of the plant population in each wetland was assessed after fish harvest. The number of stems and biomass of plants were measured in each of three 0.25 m^2 plots haphazardly located at both the influent and effluent ends of each wetland, for a total of six samples per wetland. Plants were oven-dried to constant weight at 105 °C. Each plant variable was compared for the inlet and outlet portions of wetlands between treatments directly as well as expressed as percentage change.

Fish growth was measured by taking the absolute increase in weight from stocking to harvesting time. Food conversion was assessed at harvest time by comparing the quantity of feed used with fish production. Delta Pride Catfish, Inc. conducted the organoleptic testing for off-flavor using standard industry protocol. Individual weekly readings of electric consumption of each pond were recorded. Water flow rates were monitored weekly at the influent end of the marsh cells. Checking and cleaning of the inlet and outlet pipes were conducted on a weekly basis.

Analysis of variance was performed using General Linear Model (GLM) procedure in order to determine the effects of wetland size and water flow rate on water quality variables, critical biological and economic variables and plant biomass. The means of these variables were compared by wetland size and retention time by using the Student-Newman-Keuls (SNK) multiple range test.

The benefits and costs associated with the use of constructed wetlands in intensive and recirculating catfish pond production were estimated by applying the results of the experiment conducted at MSU-Coastal Aquaculture Unit to a multi-enterprise commercial farm in the Mississippi Black Belt area. The points of entry of constructed wetlands in a multi-enterprise farm located in the Mississippi Black Belt were evaluated by using a mixed integer linear programing model.

Except for salinity and pH, wetlands were shown to significantly reduce levels of most parameters at the following rates: total ammonia nitrogen (2-63%), nitrite-nitrogen (29-97%), nitrate-nitrogen (28-80%), total phosphorus(52-95%), total suspended solids (2-76%) and pH (0.5-10%). In general, wetlands of standard size and flow rate showed the highest levels of reduction for most parameters monitored at the inlet and outlet ends.

The vegetative characteristics of constructed wetlands varied between treatments and between the inlet and outlet areas of each system. Plant biomass at the inlet portion of wetlands was greater compared to outlet areas, suggesting that plants near the inlets remove and utilize a larger proportion of available nutrients as these compounds flow through these wetlands. For wetlands of variable sizes and fixed retention times, plant biomass was significantly greater for the inlets of standard size wetlands and for the outlets of small size wetlands compared to the same sample points in other configurations. For wetlands of fixed size and variable flow rates, plant biomass was not significantly different across flow rates for either inlet or outlet portions of wetlands.

Results of pond monitoring showed that ponds with wetlands had dampened daily fluctuations in dissolved oxygen and reduced levels of photosynthetic pigments compared to control ponds. These ponds also required less aeration than control ponds. Levels of nutrients within ponds with wetlands were highly variable among treatments and were not less than those in control ponds, but were within tolerable ranges for fish production. These patterns may, in part be related to the large observed variation in rates of fish survival and production across ponds that in turn affect water quality.

Catfish survival rates averaged 57% and did not vary significantly among various treatments. There were no significant variations observed in fish growth between control and treatment ponds. The average harvested sizes in all 16 experimental ponds did not vary significantly. Average fish yield was 1,686 lb/pond or 6,744 lb/acre. Except for the ponds with small wetlands, the fish in control and treatment ponds had some degree of off-flavor. The overall net and gross feed conversion ratios in the 16 experimental ponds were 1.0 to 2.4 and 1.0 to 2.0, respectively.

Ponds with standard wetlands used less electricity to recirculate water from the wetlands to the ponds than those with smaller and larger wetlands. Ponds with wetlands having longer retention times consumed less electricity than those with shorter retention times. Average aeration time among control ponds during the entire growing season did not vary significantly with that in ponds with standard wetlands. During summer months, however, control ponds used 12% more aeration than ponds with standard wetlands. The costs of chemicals (lime, herbicides, salt) used in the 16 experimental ponds did not show any significant variation.

The initial investment requirements for six 8-water surface acre catfish ponds on a multi-enterprise farm in the Mississippi Black Belt area were $169,312 or $3,527/acre. With six 1.2-water-surface-acre wetlands built adjacent to the catfish ponds, total initial investment requirements rose by $127,498 or $2,656/acre. To build six 2.0-water-surface-acre wetlands adjoining the catfish ponds, an additional initial investment amounting to $199,703 or $4,160/acre would be required. Total initial investment would rise by $271,908 or $5,665/acre when six 2.8-water surface acre wetlands are built adjacent to the catfish ponds.

Total specified operating and ownership costs of the 48-acre Mississippi Black Belt catfish enterprise without constructed wetlands amounted to $184,074/year, averaging $3,835/acre or $0.57/lb. When six 1.2-acre constructed wetlands were added to the catfish enterprise, total costs rose by $16,776 annually, $350/acre or $0.052/lb. The use of six 2.0-acre constructed wetlands in the 48-acre catfish enterprise led to an increase in total costs by $19,225 annually, $401/acre or $0.059/lb.

Building and operating six 2.8-acre constructed wetlands adjacent to the six 8-acre catfish ponds would increase total costs by $25,412 annually, $529/ acre or $0.079/lb.

Catfish production in a multi-enterprise farm in the Mississippi Black Belt is a profitable enterprise. Assuming present technology, the use of constructed wetlands in intensive recirculating catfish pond production, however, is not economically viable. The use of six 1.2, 2.0 and 2.8 acre constructed wetlands in a 48-water-acre catfish farm in a multi-enterprise Mississippi Black Belt farm area would be acceptable to farmers if the annual yield of marketable catfish would increase by 7, 5 and 7 percent, respectively.

Limitations

The annual cost estimates for catfish production are lower than those reported recently for catfish production in the Mississippi Delta. The lower cost of production is attributable to the nature of the catfish production systems in the Mississippi Black Belt area. Some farm-wide assets (management, building, tractor) are jointly used in several enterprises (catfish, crops) thereby reducing fixed cost. There were no pond renovation costs included in the variable cost of producing catfish in the Mississippi Black Belt area. The average costs of pond renovation, management and water supply for a 160-acre catfish farm in the Mississippi Delta were $0.0103, $0.0071, and $0.0300/lb, respectively.

The investment requirements for constructed wetlands were estimated by using one-foot plants in creating the vegetative cover within a short period of time. This method of creating vegetative coverage resulted in a very large cost outlay for the purchase and planting of the desired vegetation. Other cheaper and equally effective methods of creating vegetative coverage have not been explored at this stage of developing this technology. Likewise, other plant species need to be tested for their effectiveness in improving water quality and fish production.

The results of experimental trials conducted at MSU-Coastal Aquaculture Unit showed that at 8,000 fingerlings/water acre stocking density, the expected revenues were not sufficient to justify the costs associated with constructed wetlands. Further testing of this technology needs to be undertaken in order to ascertain the effects on the yields of marketable catfish or other fish species under intensive commercial scale operations.

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Table 1. Mean values (standard deviations) of percentage change of inlet to outlet values of weekly wetland water quality variables in wetlands of variable sizes and fixed retention times by season, Apr. 8-Oct. 30, 1997.

Season	Treatment	Salinity (ppt)	pH	Ammonia (mg/l)	Nitrate (mg/l)	Nitrite (mg/l)	Phosphorus (mg/l)	Suspended Solids (mg/l)
All	15% (n=58)	-1.8 (13.4)	-1.4***a (5.7)	-22.49***a (58.16)	-38.06**a (56.61)	-69.04*a (34.19)	-67.85*a (41.43)	-61.94 (30.53)
	25% (n=87)	0.5 (14.4)	-3.2***a (2.6)	-50.37***b (25.81)	-64.88**b (35.62)	-80.52*a (28.12)	-90.04*b (62.54)	-57.09 (50.79)
	35% (n=58)	-2.5 (19.6)	-9.1***b (8.3)	-41.88***b (27.69)	-53.02**ab (35.29)	-80.54*b (21.57)	-85.81*b (33.46)	-46.02 (168.78)
Spring	15% (n=22)	0.0 (0.0)	2.1***a (6.8)	-40.18 (31.03)	-28.75 (71.41)	-77.56*b (16.65)	-63.04 (29.85)	-52.33 (42.94)
	25% (n=33)	3.0 (21.4)	-2.9***b (3.8)	-49.24 (30.36)	-48.30 (43.68)	-56.97*a (33.45)	-67.47 (32.46)	-54.90 (59.49)
	35% (n=22)	2.2 (10.6)	-10.2***c (6.6)	-41.37 (32.49)	-37.71 (36.00)	-67.67*a,b (24.19)	-76.18 (41.86)	-67.45 (34.24)
Summer	15% (n=24)	-4.5 (21.3)	-3.0***a (3.4)	-18.54**a (81.34)	-46.59***a (38.15)	-66.03***a (35.24)	-74.58 (54.20)	-63.45 (19.02)
	25% (n=36)	-1.4 (8.5)	-3.1***a (1.8)	-63.24**b (13.44)	-80.08***c (14.97)	-93.43***b (8.29)	-107.87 (88.38)	-63.12 (38.09)
	35% (n=24)	-8.3 (28.2)	-10.4***b (10.7)	-51.67**b (21.48)	-67.06***b (26.22)	-86.50***b (16.50)	-91.96 (31.76)	-14.44 (259.78)
Fall	15% (n=12)	0.0 (0.0)	-4.9 (3.1)	2.01**a (23.23)	NA	-59.45**a (51.62)	-63.75***a (31.65)	-76.51 (11.51)
	25% (n=18)	0.0 (0.0)	-3.8 (1.0)	-26.69**b (17.82)	NA	-97.84**b (2.49)	-95.73***b (4.99)	-49.04 (56.98)
	35% (n=12)	0.0 (0.0)	-4.7 (3.1)	-23.22**b (20.07)	NA	-92.23**b (12.91)	-90.37***b (11.14)	-69.89 (23.52)

* = significant at 5%; ** = significant at 1%; *** = significant at 0.01%; means with the same letter are not significantly different; NA=data not available.

Table 2. Mean values (standard deviations) of percentage change of inlet to outlet values of weekly wetland water quality variables in wetlands of variable retention times and fixed size by season, Apr. 8-Oct. 30, 1997

Season	Treatment	Salinity (ppt)	pH	Ammonia (mg/l)	Nitrate (mg/l)	Nitrite (mg/l)	Phosphorus (mg/l)	Suspended Solids (mg/l)
All	3 Days (n=58)	-1.8 (13.6)	-2.0**a (4.3)	-43.47***b (24.41)	-61.65**b (26.95)	-80.84***b (20.70)	-85.81**b (23.75)	-10.42*a (137.06)
	2 Days (n=87)	0.5 (14.4)	3.2**ab (2.6)	-50.37***b (25.81)	-64.88**b (35.62)	-80.52***b (28.12)	-90.0**b (62.54)	-57.09*b (50.79)
	1 Day (n=58)	0.0 (0.0)	-4.0**b (5.7)	-33.29***a (24.00)	-45.69**a (24.89)	-59.51***a (43.13)	-68.48**a (45.88)	-52.01*b (48.05)
	½ Day (n=58)	-1.8 (13.4)	-3.9**b (3.2)	-32.00***a (22.54)	-43.09**a (33.42)	-67.22***a (28.79)	-65.29**a (36.50)	-39.95*a,b (107.41)
Spring	3 Days (n=22)	0.0 (0.0)	-0.5 (5.1)	-55.9 (23.3)	-62.88 (22.72)	-72.15**b (26.85)	-80.94 (22.90)	-2.26 (188.44)
	2 Days (n=33)	3.0 (21.4)	-2.9 (3.8)	-49.24 (30.36)	-48.30 (43.68)	-56.97**b (33.45)	-67.47 (32.46)	-54.90 (59.49)
	1 Day (n=22)	0.0 (0.0)	-2.2 (8.0)	-41.31 (22.02)	-43.16 (21.95)	-29.97**a (57.95)	-75.15 (19.66)	-66.80 (34.03)
	½ Day (n=22)	00.0 (0.0)	-1.9 (2.8)	-40.95 (24.29)	-35.44 (33.90)	-57.73**b (32.97)	-76.87 (16.33)	-60.95 (40.61)
Summer	3 Days (n=24)	-4.3 (20.8)	-2.3**a (4.0)	-41.35***a (23.79)	-60.52***a (30.77)	-88.37***b (11.86)	-89.06***a,b (26.83)	-7.52 (101.75)
	2 Days (n=36)	-1.4 (8.5)	-3.1**a (1.8)	-63.24***b (13.44)	-80.08***b (14.97)	-93.43***b (8.29)	-107.87***b (88.38)	-63.12 (38.09)
	1 Day (n=24)	0.0 (0.0)	-5.1**b (3.6)	-33.02***a (26.27)	-48.01***a (27.58)	-73.81***a (14.42)	-54.11***a (66.23)	-33.04 (55.98)
	½ Day (n=24)	-4.5 (21.3)	-4.5**b (2.7)	-32.69***a (19.13)	-50.10***a (32.06)	-72.06***a (28.36)	-60.97***a (51.51)	-12.19 (159.80)
Fall	3 Days (n=12)	0.0 (0.0)	-4.2*a (2.0)	-24.80 (12.87)	NA	-81.69a***a (16.54)	-88.21***b (18.47)	-31.21 (85.34)
	2 Days (n=18)	0.0 (0.0)	-3.8*a (1.0)	-26.69 (17.82)	NA	-97.84***b (2.49)	-95.73***b (4.99)	-49.04 (56.98)
	1 Day (n=12)	0.0 (0.0)	-5.3*a,b (2.7)	-19.11 (16.34)	NA	-82.61***a (15.25)	-84.97***b (12.81)	-62.84 (43.00)
	½ Day (n=12)	0.0 (0.0)	-6.3*b (3.1)	-14.20 (15.33)	NA	-74.96***a (15.52)	-52.72***a (19.07)	-56.97 (19.01)

* = significant 5%; ** = significant at 1%; *** = significant at 0.01%; means with the same letter are not significantly different; NA=data not available.

Table 3. Mean values (standard deviations) and percentage changes of plant biomass, number of stems and average stem biomass at the inlets and outlets of constructed wetlands of variable sizes and fixed retention times, Dec. 1997.

Sample	Wetland Size	Plant Biomass (g/0.25 m^2)	Number of Stems per 0.25 m^2	Average Stem Biomass (g/stem)
Inlet	15% (n=4)	105.5*b (56.6)	50.0 (31.9)	2.2 (0.5)
	25% (n=6)	169.1*a (48.0)	56.8 (11.7)	2.9 (0.6)
	35% (n=4)	94.2*b (50.7)	35.2 (5.7)	2.5 (1.0)
Outlet	15% (n=4)	68.7*a (28.9)	33.2 (8.0)	2.0*a (0.6)
	25% (n=6)	21.5*b (10.5)	25.6 (6.8)	0.8*b (0.4)
	35% (n=4)	28.7*b (15.6)	30.0 (5.41)	0.9*b (0.4)
% Change	15% (n=4)	-26.5*a (43.4)	-11.6**a (55.1)	-2.4**a (45.9)
	25% (n=7)	-86.6*b (8.84)	-55.9**b (4.24)	-68.9**b (22.1)
	35% (n=4)	-61.6*a, b (24.1)	-11.7**a (26.8)	-59.1**b (20.3)

* = significant at 5%; ** = significant at 1%; means with the same letter are not significantly different.

Table 4. Mean values (standard deviations) and percentage changes of plant biomass, number of stems and average stem biomass at the inlets and outlets of constructed wetlands of variable retention times and fixed size, Dec. 1997.

Sample	Retention Time	Plant Biomass ($g/0.25\ m^2$)	Number of Stems per $0.25\ m^2$	Average Stem Biomass (g/stem)
Inlet	3 Days (n=4)	94.7 (23.7)	34.7*a, b (14.4)	3.05 (1.22)
	2 Days (n=6)	169.1 (48.0)	56.8*a (11.7)	2.98 (0.61)
	1 Day (n=4)	122.2 (147.0)	34.7*a, b (30.6)	2.33 (2.04)
	½ Day (n=2)	53.0 (36.7)	16.5*b (10.6)	3.14 (0.20)
Outlet	3 Days (n=4)	84.5 (42.0)	63.0*a (38.4)	1.44 (0.29)
	2 Days (n=6)	21.5 (10.5)	25.6*b (6.8)	0.86 (0.45)
	1 Day (n=4)	66.0 (47.3)	24.0*b (14.1)	2.73 (1.42)
	½ Day (n=2)	15.5 (7.7)	23.5*b (7.7)	0.64 (0.11)
% Change	3 Days (n=4)	-9.8*b (36.1)	75.6 (47.8)	-49.58**b (10.52)
	2 Days (n=7)	-86.6*b (8.8)	-55.9 (4.2)	-68.89**b (22.10)
	1 Day (n=4)	265.3*a (431.5)	-5.2 (46.4)	188.75**a (304.95)
	½ Day (n=2)	-54.7*b (46.0)	98.6 (174.8)	-79.48**b (4.93)

* = significant at 5%; ** = significant at 1:, means with the same letter are not significantly different.

Table 5. Mean values (standard deviations) of daily pond water quality variables in control ponds and ponds with standard wetlands by season, Mar. 6-Nov. 12, 1997.

Seasons	Treatment	a.m. DO (ppm)	p.m. DO (ppm)	a.m. Temp (ºC)	p.m. Temp (ºC)	Aeration Time (hr)
All	Control (n=751)	6.8 (1.8)	10.4***a (3.4)	24.58 (4.49)	27.39 (4.86)	9.93 (7.93)
	Standard (n=750)	6.7 (1.7)	9.1***b (1.6)	24.59 (4.47)	27.27 (4.85)	9.41 (8.12)
Spring	Control (n=276)	7.7 (1.4)	9.1***a (1.6)	23.22 (3.39)	25.82 (3.62)	6.49 (8.72)
	Standard (n=276)	7.7 (1.4)	9.0***b (1.3)	23.25 (3.38)	25.63 (3.56)	6.27 (8.97)
Summer	Control (n=282)	5.3 (1.1)	10.7***a (4.2)	28.56 (1.45)	31.69 (1.91)	11.81*a (6.47)
	Standard (n=282)	5.2 (1.1)	9.0***b (1.7)	28.54 (1.46)	31.62 (1.90)	10.54*b (6.99)
Fall	Control (n=120)	6.8 (1.6)	11.2***a (4.1)	22.44 (3.95)	24.65 (4.09)	14.74 (2.29)
	Standard (n=120)	7.1 (1.4)	9.6***b (1.7)	22.42 (3.94)	24.44 (4.07)	15.05a (0.51)

* = significant at 5%; *** = significant at 0.01%; means with the same letter are not significantly different.

Table 6. Mean values (standard deviations) of daily pond water quality variables in ponds with wetlands of variable sizes and fixed retention times by season, Mar. 6-Nov. 12, 1997.

Season	Treatment	a.m. DO (ppm)	p.m. DO (ppm)	a.m. Temp (ºC)	p.m. Temp (ºC)	Aeration Time (hr)
All	15% (n=500)	6.7 (1.7)	9.6**a (2.7)	24.83 (4.53)	27.61 (4.94)	8.30*a (8.22)
	25% (n=750)	6.7 (1.7)	9.1**b (1.6)	24.59 (4.47)	27.27 (4.85)	9.41*a (8.12)
	35% (n=500)	6.7 (1.5)	9.5**a (2.7)	24.91 (4.42)	27.75 (5.00)	8.56*a (7.94)
Spring	15% (n=184)	7.3 (1.2)	8.8 (1.3)	23.55 (3.44)	26.05 (3.71)	5.13*a, b (8.56)
	25% (n=276)	7.5 (1.2)	9.0 (1.3)	23.25 (3.38)	25.63 (3.56)	6.27*a (8.97)
	35% (n=184)	7.4 (1.1)	9.1 (1.5)	23.64 (3.36)	26.08 (3.69)	4.11*b (7.55)
Summer	15% (n=188)	5.3 (1.1)	9.8***a (2.8)	28.82 (1.49)	31.97**a, b (1.98)	8.57**b (7.33)
	25% (n=282)	5.2 (1.1)	9.0***b (1.7)	28.54 (1.46)	31.62**b (1.90)	10.54**a (6.99)
	35% (n=188)	5.3 (0.8)	10.0***a (3.9)	28.79 (1.45)	32.26**a (1.98)	10.31**a (6.87)
Fall	15% (n=80)	7.1 (1.4)	10.6**a (1.8)	22.53 (3.95)	24.62 (4.19)	15.36 (1.40)
	25% (n=120)	7.1 (1.4)	9.6**b (1.7)	22.44 (3.94)	24.44 (4.07)	15.36 (1.40)
	35% (n=80)	7.2 (1.3)	9.5**b (1.5)	22.82 (3.87)	24.69 (4.04)	15.25 (1.04)

* = significant at 5%; ** = significant at 0.01%; *** = significant at 0.01%; * = significant at 5%. means with the same letter are not significantly different.

Table 7. Mean values (standard deviations) of daily pond water quality variables in ponds with wetlands of variable retention times and fixed sizes by season, Mar. 6-Nov. 12, 1997.

Season	Treatment	a.m. DO (ppm)	p.m. DO (ppm)	a.m. Temp (°C)	p.m. Temp (°C)	Aeration Time (hr)
All	3 Days (n=499)	6.6 (1.7)	9.8***b (2.9)	24.68 (4.47)	27.26 (4.81)	9.16*b (8.16)
	2 Days (n=750)	6.7 (1.7)	9.1***c (1.6)	24.59 (4.47)	27.27 (4.85)	9.41*b (8.12)
	1 Day (n=499)	6.6 (1.5)	11.2***a (3.8)	24.69 (4.38)	27.37 (4.82)	10.57*a (8.18)
	½ Day (n=500)	6.7 (1.7)	3.8***a (8.1)	24.78 (4.46)	27.52 (4.95)	9.47*b (7.95)
Spring	3 Days (n=184)	7.4 (1.1)	9.0**b (1.3)	23.41 (3.41)	25.59 (3.63)	5.38 (8.45)
	2 Days (n=276)	7.5 (1.2)	9.0**b (1.3)	23.25 (3.38)	25.63 (3.56)	6.27 (8.97)
	1 Day (n=184)	7.7 (1.2)	9.6**a (1.7)	23.41 (3.41)	25.69 (3.64)	7.25 (9.25)
	½ Day (n=184)	7.6 (1.1)	9.3**a,b (1.4)	23.59 (3.45)	25.97 (3.77)	5.46 (8.46)
Summer	3 Days (n=187)	5.1 (1.0)	10.4***b (4.2)	28.62 (1.52)	31.61 (1.82)	10.73**b (7.22)
	2 Days (n=282)	5.2 (1.1)	9.0***c (1.7)	28.54 (1.46)	31.62 (1.90)	10.54**b (6.99)
	1 Day (n=187)	5.1 (1.0)	12.7***a (5.0)	28.52 (1.36)	31.66 (1.97)	12.64**a (6.72)
	½ Day (n=188)	5.3 (1.1)	12.2***a (4.9)	28.65 (1.45)	31.89 (1.97)	11.27**b (6.49)
Fall	3 Days (n=80)	7.0*a,b (1.4)	10.3***b (1.9)	22.45 (3.89)	24.59 (3.90)	15.12 (0.68)
	2 Days (n=120)	7.1*a (1.4)	9.6***b (1.7)	22.42 (3.94)	24.44 (4.07)	15.05 (0.51)
	1 Day (n=80)	6.7*a,b (1.5)	12.2***a (3.4)	22.64 (3.90)	24.76 (4.04)	15.16 (0.82)
	½ Day (n=80)	6.5*b (1.5)	12.2***a (3.7)	22.53 (3.90)	24.56 (4.15)	15.16 (0.82)

* = significant at 5%;** = significant at 1%;*** = significant at 0.01%; means with the same letter are not significantly different.

Table 8. Ranges for daily dissolved oxygen levels (difference between morning and afternoon readings) for control ponds and all pond-wetland treatments by season, Mar. 6-Nov. 12, 1997.

Treatment	Seasons			
	All	Spring	Summer	Fall
Control	3.6	2.0	5.4	4.4
Standard (25%, 2-Days)	2.4	1.5	3.8	2.5
Variable Sizes				
15%	2.9	1.5	4.5	3.5
35%	2.8	1.7	4.7	2.3
Variable Flow				
3-Days	3.2	1.6	5.3	3.3
1-Day	4.6	1.9	7.6	5.5
½ Day	4.2	1.7	6.9	5.7

Table 9. Mean values (standard deviations) of weekly pond water quality variables in control ponds and ponds with standard wetlands by season, Apr. 8-Oct. 30, 1997.

Season	Treatment	Salinity (ppt)	pH	Ammonia (mg/l)	Nitrate (mg/l)	Nitrite (mg/l)	Phosphorus (mg/l)	Suspended Solids (mg/l)	Chlorophyll a (mg/m^3)	Phaeophytin (mg/m^3)
All	Control (n=87)	1.6 (0.7)	7.1**a (0.6)	0.41*b (0.40)	3.77 (6.71)	0.06 (0.07)	0.19 (0.20)	0.01 (0.01)	0.061**a (0.091)	0.019**a (0.028)
	Standard (n=87)	1.5 (0.6)	6.9**b (0.4)	0.56*a (0.54)	4.87 (8.95)	0.08 (0.12)	0.20 (0.38)	0.01 (0.01)	0.031**b (0.036)	0.010**b (0.010)
Spring	Control (n=33)	1.3*b (0.6)	7.1 (0.8)	0.31 (0.47)	2.78 (8.02)	0.02 (0.03)	0.09*a (0.07)	0.01 (0.01)	0.032***a (0.045)	0.014 (0.031)
	Standard (n=33)	1.6*a (0.6)	7.0 (0.5)	0.51 (0.77)	5.50 (12.06)	0.02 (0.03)	0.07*b (0.06)	0.01 (0.01)	0.011***b (0.011)	0.004 (0.003)
Summer	Control (n=36)	1.4 (0.5)	7.0**a (0.4)	0.40*b (0.35)	4.68 (5.19)	0.06*b (0.05)	0.18 (0.22)	0.01 (0.01)	0.040 (0.054)	0.013 (0.011)
	Standard (n=36)	1.2 (0.5)	6.8**b (0.2)	0.63*a (0.40)	4.30 (4.70)	0.11*a (0.13)	0.13 (0.20)	0.01 (0.01)	0.033 (0.027)	0.014 (0.011)
Fall	Control (n=18)	2.5 (0.7)	7.4**a (0.7)	0.62 (0.30)	NA	0.12 (0.10)	0.39**b (0.20)	0.02***a (0.02)	0.158***a (0.142)	0.041***a (0.035)
	Standard (n=18)	2.11 (0.47)	7.0**b (0.30)	0.52 (0.20)	NA	0.15 (0.15)	0.56**a (0.67)	0.01***b (0.01)	0.063***b (0.055)	0.014***b (0.010)

* = significant at 5%; ** = significant at 1%; *** = significant at 0.01%; means with the same letter are not significantly different at 5%; NA=data not available.

Table 10. Mean values (standard deviations) of weekly pond water quality variables in ponds with wetlands of variable sizes and fixed retention times by season, Apr. 8-Oct. 30, 1997.

Season	Treatment	Salinity (ppt)	pH	Ammonia (mg/l)	Nitrate (mg/l)	Nitrite (mg/l)	Phosphorus (mg/l)	Suspended Solids (mg/l)	Chlorophyll a (mg/m^3)	Phaeophytin (mg/m^3)
All	15% (n=58)	1.6 (1.0)	7.0 (0.51	0.62*a (0.52)	3.08 (3.84)	0.06 (0.09)	0.08**b (0.09)	0.02**a (0.01)	0.050*a (0.056)	0.017 (0.017)
	25% (n=87)	1.5 (0.6)	6.9 (0.0)	0.56*b (0.54)	4.87 (8.95)	0.08 (0.12)	0.20**a (0.38)	0.01**b (0.01)	0.031*b (0.036)	0.010 (0.010)
	35% (n=58)	1.8 (0.7)	6.9 (0.5)	0.39*b (0.33)	2.49 (4.23)	0.04 (0.07)	0.10**b (0.08)	0.01**b (0.01)	0.038*a,b (0.054)	0.013 (0.023)
Spring	15% (n=22)	1.5**b (0.5)	7.0 (0.4)	0.49*a (0.40)	2.15*a,b (2.8)	0.02*a (0.03)	0.04*b (0.02)	0.01**a (0.01)	0.012 (0.011)	0.006*a (0.006)
	25% (n=33)	1.6**b (0.6)	7.0 (0.5)	0.51*a (0.77)	5.50*a (12.0)	0.02*a (0.03)	0.07*b (0.06)	0.014**a (0.01)	0.011a (0.011)	0.004*a,b (0.003)
	35% (n=22)	2.0**a (0.2)	7.0 (0.7)	0.22*a (0.21)	0.67*b (0.6)	0.00*b (0.004)	0.11*a (0.12)	0.007**b (0.003)	0.009 (0.010)	0.002*b (0.007)
Summer	15% (n=24)	1.0 (0.4)	6.9*a (0.4)	0.67 (0.58)	3.93 (4.4)	0.09 (0.11)	0.07 (0.07)	0.027 (0.023)	0.049 (0.040)	0.017 (0.009)
	25% (n=36)	1.2 (0.5)	6.8*b (0.2)	0.63 (0.40)	4.30 (4.7)	0.11 (0.13)	0.13 (0.20)	0.019 (0.015)	0.033 (0.027)	0.014 (0.011)
	35% (n=24)	1.1 (0.3)	6.8*b (0.4)	0.56 (0.39)	4.16 (5.3)	0.07 (0.07)	0.09 (0.05)	0.024 (0.021)	0.052 (0.071)	0.021 (0.033)
Fall	15% (n=12)	3.2***a (1.0)	7.3**a (0.6)	0.75*a (0.60)	NA	0.08 (0.07)	0.17**b (0.13)	0.028*a (0.015)	0.125**a (0.059)	0.037**a (0.025)
	25% (n=18)	2.1*** b (0.4)	7.0**b (0.3)	0.52*a,b (0.20)	NA	0.15 (0.15)	0.56**a (0.67)	0.017*b (0.013)	0.063**b (0.055)	0.014**b (0.010)
	35% (n=12)	2.8***a (0.3)	7.1**b (0.4)	0.34*b (0.16)	NA	0.08 (0.09)	0.09**b (0.02)	0.018*b (0.006)	0.065**b (0.036)	0.017**b (0.006)

* = significant at 5%; ** = significant at 1%; *** = significant at 0.01%; means with the same letter are not significantly different; NA=data not available.

Table 11. Mean values (standard deviations) of weekly pond water quality variables in ponds with wetlands of variable retention times and fixed size by season, Apr. 8-Oct. 30, 1997.

Season	Treatment	Salinity (ppt)	Ph	Ammonia (mg/l)	Nitrate (mg/l)	Nitrite (mg/l)	Phosphorus (mg/l)	Suspended Solids (mg/l)	Chlorophyll a (mg/m^3)	Phaeophytin (mg/m^3)
All	3 Days (n=58)	1.2*a (0.6)	7.0***c (0.3)	0.38***b (0.25)	2.36**b (3.2)	0.03***b (0.07)	0.69***a (0.84)	0.01**b (0.01)	0.034**b (0.055)	0.009***b (0.012)
	2 Days (n=87)	1.5*a (0.6)	6.9***c (0.4)	0.56***a (0.54)	4.87**a (8.9)	0.08***a (0.12)	0.20***b (0.38)	0.01**a (0.01)	0.031**b (0.036)	0.010***b (0.010)
	1 Day (n=58)	1.3*a (0.9)	7.4***a (0.3)	0.27***b,c (0.32)	1.20**b (2.4)	0.01***b (0.02)	0.20***b (0.30)	0.01**a,b (0.01)	0.058**a (0.073)	0.022***a (0.032)
	½ Day (n=58)	1.5*a (0.7)	7.2***b (0.4)	0.18***c (0.10)	1.80**b (7.93)	0.02***b (0.34)	0.20***b (0.26)	0.01**a,b (0.01)	0.056**a (0.076)	0.014***b (0.014)
Spring	3 Days (n=22)	0.9***b (0.5)	6.7***c (0.2)	0.34*a,b (0.32)	2.44 (4.3)	0.00 (0.04)	0.07 (0.04)	0.00***b (0.00)	0.009 (0.009)	0.003 (0.003)
	2 Days (n=33)	1.6***a (0.6)	7.0***b (0.5)	0.51*a (0.77)	5.50 (12.0)	0.02 (0.03)	0.07 (0.06)	0.01***a (0.01)	0.011 (0.011)	0.004 (0.003)
	1 Day (n=22)	1.0***b (0.4)	7.4***a (0.3)	0.29*a,b (0.48)	1.56 (3.4)	0.01 (0.02)	0.08 (0.05)	0.00***b (0.00)	0.012 (0.014)	0.003 (0.002)
	½ Day (n=22)	1.5***a (0.6)	7.0***b (0.3)	0.14*b (0.10)	2.84 (11.4)	0.01 (0.03)	0.06 (0.02)	0.00***b (0.00)	0.008 (0.010)	0.003 (0.003)
Summer	3 Days (n=24)	1.0*a,b (0.3)	7.0***b (0.2)	0.35***b (0.18)	2.28***b (1.8)	0.07**a,b (0.10)	0.59***a (0.59)	0.01 (0.01)	0.040 (0.067)	0.013 (0.016)
	2 Days (n=36)	1.2*a (0.5)	6.8***c (0.2)	0.63***a (0.40)	4.30***a (4.7)	0.11**a (0.13)	0.13***b (0.20)	0.01 (0.01)	0.033 (0.027)	0.014 (0.011)
	1 Day (n=24)	0.9*b (0.4)	7.3***a (0.3)	0.23***b (0.19)	0.87***b (0.89)	0.01**b (0.01)	0.08***b (0.04)	0.01 (0.01)	0.068 (0.080)	0.027 (0.037)
	½ Day (n=24)	1.0*a,b (0.4)	7.0***b (0.3)	0.19***b (0.10)	0.85***b (0.88)	0.29**b (0.03)	0.26***b (0.30)	0.01 (0.01)	0.057 (0.072)	0.014 (0.011)

Continued

Table 11. Concluded.

Season	Treatment	Salinity (ppt)	pH	Ammonia (mg/l)	Nitrate (mg/l)	Nitrite (mg/l)	Phosphorus (mg/l)	Suspended Solids (mg/l)	Chlorophyll a (mg/m^3)	Phaeophytin (mg/m^3)
Fall	3 Days (n=12)	2.1**b (0.3)	7.3***b (0.2)	0.52***a (0.16)	NA	0.02***b (0.01)	2.02***a (0.45)	0.01***b (0.01)	0.068***b (0.060)	0.013***c (0.010)
	2 Days (n=18)	2.1**b (0.4)	7.0***b (0.3)	0.52***a (0.20)	NA	0.15***a (0.15)	0.56***b (0.67)	0.01***b (0.01)	0.063***b (0.055)	0.014***c (0.010)
	1 Day (n=12)	2.8**a (1.1)	7.5***a (0.4)	0.31***b (0.13)	NA	0.03***b (0.02)	0.67***b (0.40)	0.02***a (0.01)	0.123***a (0.070)	0.049***a (0.028)
	½ Day (n=12)	2.4**a,b (0.6)	7.7***a (0.4)	0.2***b (0.07)	NA	0.02***b (0.02)	0.34***c (0.30)	0.02***a (0.07)	0.141***a (0.079)	0.033***b (0.012)

*** = significant at 0.01%; ** = significant at 1%; * = significant at 5%; means with the same letter are not significantly different; NA=data not available.

Table 12. Mean values (standard deviations) of fish harvest, harvest weight, production and growth, net and gross feed conversion, fish survival and observed mortality rates and costs of chemicals used in control ponds and ponds with standard wetland sizes and retention times, Mar. 6-Nov. 5, 1997.

Treatment	Fish Harvest (lb/pond)	Fish Weight (lb/fish)	Fish Production (lb/pond)	Fish Growth (lb/fish)	Net Feed Conversion[a]	Gross Feed Conversion[b]	Fish Survival	Observed Fish Mortality	Chemical Costs ($/pond)
Control (n=3)	1673.6 (428.8)	1.50 (0.24)	1457.6 (428.8)	1.39 (0.24)	2.23 (0.57)	1.92 (0.42)	0.58 (0.25)	0.027 (0.042)	62.00 (3.60)
Standard (n=3)	1636.6 (606.3)	1.51 (0.31)	1420.6 (606.3)	1.40 (0.31)	2.62 (1.49)	2.16 (1.02)	0.58 (0.28)	0.004 (0.003)	72.33 (34.38)

a = feed fed ÷ fish production; b = feed fed ÷ fish harvest.

Table 13. Mean values (standard deviations) of fish harvest, harvest weight, production and growth, net and gross feed conversion, fish survival and observed mortality rates and costs of chemicals used in ponds with wetlands of variable sizes and fixed retention times, Mar. 6-Nov. 5, 1997.

Treatment	Fish Harvest (lb/pond)	Fish Weight (lb/fish)	Fish Production (lb/pond)	Fish Growth (lb/fish)	Net Feed Conversion[a]	Gross Feed Conversion[b]	Fish Survival	Observed Fish Mortality	Chemical Costs ($/pond)
15% (n=2)	2091.0 (32.5)	1.2 (0.0)	1875.0 (32.5)	1.16 (0.07)	1.66 (0.02)	1.49 (0.01)	0.82 (0.03)	0.014a (0.000)	54.50 (0.70)
25% (n=3)	1636.6 (606.3)	1.5 (0.3)	1420.6 (606.3)	1.40 (0.31)	2.62 (1.49)	2.16 (1.02)	0.58 (0.28)	0.004*b (0.003)	72.33 (34.38)
35% (n=2)	2003.5 (38.8)	1.4 (0.1)	1787.5 (38.8)	1.32 (0.12)	1.77 (0.02)	1.58 (0.02)	0.70 (0.07)	0.005*b (0.000)	93.50 (101.11)

* = significant at 5%; means with the same letter are not significantly different at 5%; a = feed fed ÷ fish production; b = feed fed ÷ fish harvest.

Table 14. Mean values (standard deviations) of fish harvest, harvest weight, production and growth, net and gross feed conversion, fish survival and observed mortality rates and costs of chemicals used in ponds with wetlands of variable retention times and fixed sizes, Mar. 6-Nov. 5, 1997.

Treatment	Fish Harvest (lb/pond)	Fish Weight (lb/fish)	Fish Production (lb/pond)	Fish Growth (lb/fish)	Net Feed Conversion[a]	Gross Feed Conversion[b]	Fish Survival	Observed Fish Mortality	Chemical Costs ($/pond)
3 Days (n=2)	1237.0 (544.4)	2.0 (0.2)	1021.0 (544.4)	1.91 (0.26)	3.58 (1.88)	2.81 (1.22)	0.31 (0.17)	0.002 (0.001)	114.50 (78.48)
2 Days (n=3)	1636.6 (606.3)	1.5 (0.3)	1420.6 (606.3)	1.40 (0.31)	2.62 (1.49)	0.58 (0.28)	0.58 (0.28)	0.004 (0.003)	72.33 (34.38)
1 Day (n=2)	1537.5 (140.7)	1.8 (0.3)	1321.5 (140.7)	1.75 (0.13)	2.38 (0.20)	2.05 (0.14)	0.41 (0.06)	0.015 (0.015)	183.00 (82.02)
½ Day (n=2)	1652.5 (648.4)	1.9 (0.9)	1436.5 (648.4)	1.79 (0.92)	2.46 (1.15)	2.08 (0.86)	0.54 (0.43)	0.000 (0.000)	154.50 (24.74)

a = feed fed ÷ fish production; b = feed fed ÷ fish harvest.

Table 15. Mean values (standard deviations) of electricity (kwh/pond/week) used by water pumps in ponds with wetlands of variable sizes and fixed retention times by season, Apr. 8-Oct. 29-1997.

Wetland size (%)	Season			
	All***	Spring***	Summer***	Fall***
15%	37.6a (12.9) n=58	36.3a (9.3) n=20	39.3a (15.3) n=26	36.3a (12.9) n=12
25%	20.4c (6.7) n=87	23.0b (8.4) n=30	20.0b (4.9) n=39	17.0c (5.6) n=18
35%	33.3b (8.2) n=58	34.2a (9.4) n=20	34.8a (7.7) n=26	28.5b (5.3) n=12

*** = significant at 0.01%; means with the same letter are not significantly different.

Table 16. Mean values (standard deviations) of electricity (kwh/pond/week) used by water pumps in ponds with wetlands of variable retention times and fixed sizes by season, Apr. 8-Oct. 29-1997.

Retention Time	Season			
	All***	Spring***	Summer***	Fall***
3 Days	15.1d (8.3) n=58	15.1d (7.9) n=20	16.4c (9.1) n=26	12.5c (7.3) n=12
2 Days	20.4c (6.7) n=87	23.0c (8.4) n=30	20.0c (4.9) n=39	17.0c (5.6) n=18
1 Day	45.3b (14.4) n=58	46.9b (13.9) n=20	49.9b (13.6) n=26	32.9b (10.2) n=12
½ Day	72.6a (16.6) n=58	64.0a (12.6) n=20	82.5a (13.4) n=26	65.7a (17.8) n=12

*** = significant at 0.01%; means with the same letter are not significantly different.