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Characterization and Management of Effluents from Aquaculture Ponds in the Southeastern United States

Final Project Report on the
SRAC Regional Research Project

"Characterization of Finfish and Shellfish Aquacultural Effluents"

SRAC No. 600

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Preface

The project summarized in this report was developed and funded through the Southern Regional Aquaculture Center, which is one of five regional aquaculture research and Extension centers established by Congress in 1985 and administered by the United States Department of Agriculture. The five centers are located in the northeastern, north-central, southern, western, and tropical Pacific regions of the country. The Southern Regional Aquaculture Center began organizational activities in 1987, and the first research and Extension projects were initiated in 1988.The thirteen states and two territories included in the Southern Region are Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, Puerto Rico, South Carolina,Tennessee,Texas, U.S.Virgin Islands and Virginia.

The regional aquaculture centers encourage cooperative and collaborative research and Extension educational programs in aquaculture having regional or national applications. Center programs complement and strengthen existing research and Extension educational programs provided by the Department of Agriculture and other public institutions.

The mission of the centers is to support aquaculture research, development, demonstration, and Extension education to enhance viable and profitable domestic aquaculture production for the benefit of consumers, producers, service industries, and the American economy. Projects developed and funded by the centers are based on regional industry needs and are designed to aid commercial aquaculture development in all states and territories. The centers are organized to take advantage of the best aquaculture science, education skills, and facilities in the United States. Center programs ensure effective coordination and a region-wide, team approach to projects jointly conducted by research, Extension, government, and industry personnel. Interagency collaboration and shared funding are strongly encouraged.

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Executive Summary

This document summarizes the findings of the Southern Regional Aquaculture Center project *Characterization of Finfish and Shellfish Aquacultural Effluents.* The primary objectives of the project were to describe the quality of waters discharged from aquaculture ponds in the southeastern United States and to assess the effectiveness and economics of various effluent management practices.

Characterization of Effluents

Multi-year studies of pond effluent quality were conducted in channel catfish ponds in Alabama and Mississippi, crawfish ponds in Louisiana, and hybrid striped bass ponds in South Carolina. Suspended solids, total phosphorus, and, possibly, total nitrogen appeared to be the water quality variables of greatest concern relative to the potential impacts of aquaculture pond effluents on the environment. Catfish pond effluent quality varied seasonally and was generally poorest in the summer months when high fish feeding rates caused the accumulation of organic matter, total nitrogen, and total phosphorus in pond waters. However, highest instantaneous concentrations of potential pollutants were discharged when ponds were drained to facilitate fish harvest, regardless of the time of year. The last 10 to 20% of the effluent that was discharged from ponds during harvest contained relatively high concentrations of solids because fish and seining activities disturbed the bottom soil in the shallow water, and materials associated with the soil were discharged from the pond. In crawfish ponds, concentrations of nutrients and solids in effluents were highest in spring and fall, and certain water quality variables were significantly affected by the type of vegetative forage in the pond. No seasonal variation was seen in the quality of effluents from hybrid striped bass ponds. Most aquaculture in the southeast is conducted in shallow, levee-type ponds; however, deep ponds constructed on watersheds are sometimes used in hilly regions. Water quality in shallow ponds was found to vary little from surface to bottom but waters discharged from the bottoms of deep ponds often contained much higher concentrations of certain substances than commonly found in surface waters.

Management of Effluents

Several pond management practices showed great potential for reducing the impact of effluents on the environment. Reusing channel catfish pond water for multiple crops by harvesting fish without draining the pond greatly reduced the volume of effluent discharged and also made full use of the natural waste assimilation capacity of the pond ecosystem. Effluent volume was also significantly reduced by keeping the pond water level below the level of the pond overflow device so that rainfall was captured rather than allowed to overflow. A model of pond overflow for an average climatological year showed that capturing rainfall, rather than letting it leave the pond as overflow, reduced the discharge of nitrogen by more than 91%, phosphorus by more than 88%, and biochemical oxygen demand by more than 92% compared to ponds managed without water storage potential. A study of marine shrimp ponds showed that water exchange—a common practice in shrimp farming—can be dramatically reduced, or eliminated entirely, without sacrificing growth or survival of shrimp. Reduced or eliminated water exchange decreases the total amounts of nutrients, solids, and organic matter discharged into adjacent water bodies. Water exchange is less often used in the culture of freshwater fish, but another study showed that if water exchange is practiced to improve water quality in freshwater fish ponds, the resulting effluent can be used to irrigate agronomic crops. Although the nutrient content of water from aquaculture ponds may be too low to significantly enhance crop production, use of effluent for crop irrigation reduces the overall volume of effluent discharged. Two studies were conducted to assess the effectiveness of treating effluents before they are discharged into the environment. Passing pond effluents through constructed wetlands was a highly effective technique for reducing the concentrations of nutrients and organic matter in the water ultimately discharged to the environment.

A second study showed that suspended solids from catfish pond effluent can be significantly reduced and concentrations of organic matter and nitrogen lowered by applying the effluent as an overland runoff to well-established strips of either Bahia or Bermudagrass. This filtering technique is relatively easy and inexpensive, although relatively large land areas also may be required to use this technique commercially.

Economics of Effluent Treatment

An economic analysis of effluent treatment options showed that treatment with rice irrigation, constructed wetlands, or a paired-pond system increased costs by $0.00 to $0.11/kg for catfish production. If treatment was required by law, rice irrigation was the preferred treatment from the economic perspective. Constructed wetlands were never selected as a profitable option due to high investment and maintenance costs. Investment tax credits or other incentives would be required for constructed wetlands to become an economically feasible treatment alternative. Effluent standards and tax charges appear to be effective means of internalizing fish pond effluent discharge. However, large farms will do the best job of internalizing the costs of treating effluent. Small farms not only have less access to capital, but also are not efficient enough to adopt new technologies to reduce effluent discharge. Imposing control options will make it harder for new potential catfish farmers to begin operation, particularly with less than 130-ha farms.

Recommendations

The results of this project suggest that the impact of aquaculture pond effluents on the environment can be greatly reduced by following some or all of the following management practices:

- Use high quality feeds and efficient feeding practices;
- Provide adequate aeration and circulation of pond water;
- Minimize water exchange;
- If water must be exchanged in ponds, consider reusing the effluent for some other purpose, such as irrigating terrestrial crops;
- Operate ponds for several years without draining;
- Reuse water that is drained from ponds whenever possible;
- In ponds that are partially drained to facilitate fish harvest, hold the last portion of pond water in the pond for 2 to 3 days to allow solids to settle before draining completely, or do not discharge this last portion of water;
- Maintain some storage volume in ponds to capture rainfall and reduce overflow;
- Optimize watershed areas to reduce excessive discharge; and
- Consider treating effluents by using constructed wetlands.

Project Background

Nearly all of the commercial aquaculture in the southeastern United States is practiced in earthen ponds. In pond aquaculture, rapid growth of finfish or shellfish is encouraged by fertilizing ponds to increase the availability of natural foods or by providing manufactured feeds designed to meet the nutritional requirements of the animal under culture. Although fish generally convert feed into flesh more efficiently than warm-blooded animals, the efficiency of nutrient use by the animal under culture is not high. Regardless of the methods used to enhance production, less than 30% of the feed or fertilizer nitrogen and phosphorus added to aquaculture ponds is recovered in the harvest of the cultured animal. The remainder of the nutrient load is lost to the pond ecosystem. The nutrients entering the water from fertilizer, uneaten feed, fish feces, and fish metabolites stimulate the production of large amounts of organic matter in the form of phytoplankton. Thus, concentrations of potential pollutants accumulate in pond water during the grow-out period, and these substances may be discharged from ponds following rain storms or when ponds are drained between crops. So, aquaculture, as is true of all agriculture, produces waste.

The major constituents of concern in aquaculture effluents are organic matter, nitrogen, phosphorus, and suspended solids. Pesticides and other toxic materials typically are not present in effluents from aquaculture ponds, as they may be in effluents from other industries. Thus, the potential impact of aquaculture on natural waters is eutrophication of the receiving water, rather than a direct toxic effect on animal or plant health downstream from the discharge. The potential environmental effects of water discharged from aquaculture ponds include:

- Organic matter in the effluent may increase the oxygen demand of waters downstream from the discharge.
- Nitrogen and phosphorus in the effluent may stimulate algal blooms in the receiving body of water.
- Solids in the effluent may settle out downstream from the point of discharge.

The effect on receiving waters will depend largely upon the volume and strength of effluents in relation to the volume of the receiving water body, and the aquatic species present in the receiving water body.

From a regulatory standpoint, the issue of aquaculture pond effluents emerged when the National Pollutant Discharge Elimination System (NPDES) was created as part of the Federal Water Pollution Control Act of 1972. That Act, and its subsequent amendments, has become known as the Clean Water Act. Under the Act, the discharge of pollutants from "point sources" is prohibited unless the discharge is authorized by an NPDES permit. The Act also designates the United States Environmental Protection Agency to administer and enforce the NPDES, although states are encouraged to develop and operate their own program in lieu of the Federal program. Most states originally had little interest in regulating discharges from aquaculture facilities because aquaculture was perceived as either a "clean" industry or as too small an industry to have a significant impact on the environment. However, the remarkable growth of the aquaculture industry in the 1980s caused more and more states to develop, or consider developing, regulatory procedures. The development of rational regulations was severely hampered by the lack of information regarding the nature of aquaculture effluents or their possible impacts on natural waters. Prior to 1990, there were many opinions about the quality and quantity of effluents from aquaculture ponds, although most of those opinions were uninformed because almost no data on effluent quality or the environmental impacts of pond aquaculture actually existed.

In 1990, the Board of Directors of the Southern Regional Aquaculture Center addressed the concerns of the aquaculture industry in the southeastern United States by approving the development of a project to investigate the issue of aquaculture effluents. The project was developed through the cooperative efforts of aquaculture industry representatives and scientists from across the region. That group of concerned experts decided that the primary objectives of the project should be to gather definitive information on the quality of effluents from ponds and to assess the effectiveness and economics of various effluent management practices. The 3-year project that was subsequently developed was entitled *Characterization of Finfish and Shellfish Aquacultural Effluents*, and was approved for funding in 1991 by the United States Department of Agriculture, Cooperative State Research, Extension, and Education Service.

The following report summarizes the findings of studies conducted as part of the project and presents recommendations for minimizing the impact of aquacultural effluents on the environment. Readers interested in a more complete account of the findings of the project should consult the individual publications listed at the end of this report.

Project Objectives

Objective 1. Characterize the quality of water discharged from aquaculture ponds in the southeastern United States.

a. Effluents from channel catfish ponds

- Alabama
- Mississippi
- Water discharged during fish harvest

b. Effluents from crawfish ponds

c. Effluents from hybrid striped bass ponds

d. Effluents from hypolimnetic waters of watershed ponds

Objective 2. Evaluate management practices that may reduce the impact of aquaculture effluents on the environment.

a. Reduce the volume of effluents discharged from ponds

- Reusing water for multiple fish crops
- Using conservative water management practices
- Minimizing water exchange in penaeid shrimp ponds
- Using pond effluents for irrigation of soybeans

b. Reduce the concentration of substances in the effluent

- Treating pond effluents using constructed wetlands
- Treating pond effluents using grass filter strips

Objective 3. Evaluate the costs of treating effluents from aquaculture ponds.

Objective 1: Characterization of Effluents from Aquaculture Ponds in the Southeastern United States

Quality of Effluents from Channel Catfish Ponds

Channel catfish farming is the largest aquaculture industry in the United States and almost all commercial production occurs in earthen ponds in the southeastern states. Although there is extensive information regarding water quality in catfish ponds, almost all of this information was collected over short time frames (typically limited to the summer growing season) from small experimental ponds. Such data are of limited usefulness in assessing the impact of pond effluents on the environment because most catfish ponds are operated year around and a large portion of the total effluent volume is discharged in the winter. The following two studies were therefore conducted to describe long-term changes in the quality of effluents from commercial catfish ponds in two of the major catfish-producing states in the region. Matched water samples were collected from all ponds at two depths because waters may be discharged from ponds from either the surface or the bottom of the pond depending on the structure of the drain device.

Methods

Alabama

Water samples were collected four times a year during February, May, August and November of 1991 and 1992 from 25 commercial channel catfish ponds in central and west-central Alabama. Two samples were collected from near the drain of each pond. One sample was dipped approximately 0.3 m from the surface and another sample was collected approximately 0.3 m above the bottom with a manually operated peristaltic pump. Samples were usually collected between 1000 to 1400 hours. After returning to the laboratory, samples were immediately analyzed for 5-day biochemical oxygen demand, total ammonia, total Kjeldahl nitrogen, total phosphorus, suspended solids, and settleable solids (additional measurements were also made and results can be found in M. F. Schwartz and C. E. Boyd, 1994, Channel Catfish Pond Effluents, *Progressive Fish-Culturist* 56:273-281).

Mississippi

Water samples were obtained from 20 ponds in Washington County, northwest Mississippi, over a 2-year period beginning in the summer of 1991. Ponds averaged about 7 ha in area and 1.25 m in depth. All ponds had been in continuous fish production, without draining, for at least 3 years at nominal stocking densities of 18,000 to 24,000 fish/ha. Daily feeding rates averaged between 75 and 100 kg/ha in May through September and between 5 and 20 kg/ha in December through February. Samples were collected between 0800 and 0900 on dates in August (summer), November (autumn), February (winter), and May (spring). On each sampling date, samples were obtained using a 2.2-L Kemmerer bottle from the surface 30 cm and the bottom 30 cm of each pond at a site adjacent to the discharge pipe. Samples were returned to the laboratory and analyses were initiated within 45 minutes of collection for 5-day biochemical oxygen demand, total ammonia, total nitrogen, total phosphorus, suspended solids, and settleable solids (additional measurements were also made and results can be found in C. S. Tucker, S. W. Kingsbury, J. W. Pote, and C. W. Wax, 1996, Effects of Water Management Practices on Discharge of Nutrients and Organic Matter from Channel Catfish Ponds, *Aquaculture* 147:57-69).

Results

Alabama

Concentrations of selected water quality variables in potential pond effluents are summarized in Table 1. All data were highly variable among ponds and it was difficult to distinguish seasonal trends in water quality. Also, there were few differences between the quality of surface and bottom water because the ponds in this study were relatively shallow (less than 1.5 m maximum depth) and rarely stratified. Therefore, analytical results obtained from surface and bottom samples were averaged to obtain one value for each pond and sampling date.

Table 1. Means and ranges of selected water quality variables in potential effluents from 25 commercial channel catfish ponds in central and west-central Alabama from winter 1991 through autumn 1992.

Season	Settleable solids (mL/L)	Suspended solids (mg/L)	Kjeldahl nitrogen (mg N/L)	Total ammonia (mg N/L)	Total phosphorus (mg P/L)	Biochemical oxygen demand (mg O_2/L)
Winter 1991	0.06 (0-0.33)	81 (22-202)	3.7 (0.9-9.2)	0.7 (0.07-2.47)	0.25 (0.04-0.57)	9.0 (1.9-21.9)
Spring	0.05 (0-0.40)	52 (5-134)	4.4 (1.8-10.6)	1.07 (0.02-3.45)	0.21 (0.07-0.37)	6.5 (2.4-21.4)
Summer	0.19 (0-1.80)	96 (14-240)	5.0 (1.7-11.3)	0.85 (0.05-4.71)	0.36 (0.12-0.75)	10.7 (4.3-20.3)
Autumn	0.03 (0-0.54)	103 (18-232)	6.1 (2.2-11.5)	1.86 (0.10-8.07)	0.46 (0.12-1.85)	18.1 (6.1-35.6)
Winter 1992	0.01 (0-0.10)	29 (1-100)	1.9 (0.6-3.7)	0.27 (0.03-1.08)	0.09 (0-0.31)	9.2 (5.5-17.5)
Spring	0.06 (0-0.35)	45 (1-68)	3.8 (1.5-6.8)	0.91 (0.01-4.08)	0.18 (0-0.39)	5.3 (2.1-7.6)
Summer	0.15 (0-0.28)	102 (10-308)	3.9 (1.6-8.4)	1.89 (0.06-3.30)	0.19 (0-0.47)	8.0 (1.4-15.9)
Autumn	0.03 (0-0.25)	73 (14-337)	6.0 (2.2-14.0)	1.91 (0.09-5.26)	0.27 (0.05-0.83)	7.6 (1.2-23.4)

Settleable solid concentrations were highest during the summer, and concentrations were generally greater in the surface waters than in the bottom waters. The major source of settleable solids in the samples was phytoplankton. Suspended solids concentrations peaked during the summer and remained high into the fall. Biochemical oxygen demand concentrations also were lowest in the spring with winter and summer levels being similar and the highest levels occurring during the fall. Total phosphorus concentrations were highest in the summer and fall. Total ammonia-nitrogen concentrations were high throughout most of the year, peaking during the fall and achieving lowest concentrations during winter. Total Kjeldahl nitrogen concentrations were highest during the growing season and peaked in the fall.

Mississippi

Pond water samples collected from near the surface and bottom of each pond on a given date did not differ for any variable measured, indicating well-mixed water columns at the times of sampling. Analytical results for surface and bottom samples were therefore averaged to obtain a single value for each pond and sampling date. Means, standard errors of the mean, and ranges for water quality variables for each sampling period are presented in Table 2.

Settleable solids concentrations were somewhat higher in the summer and spring than at other times, although nearly 80% of all measurements were less than 0.1 mL/L, which is the smallest increment measurable using Imhoff cones. Highest values for settleable solids were obtained from samples with abundant zooplankton, which migrated or settled to the bottom of the Imhoff cone during the analysis. Concentrations of suspended solids, total nitrogen, total phosphorus, and biochemical oxygen demand were highest in the warm seasons.

Conclusions

Catfish pond effluent quality varies considerably from pond to pond and from season to season. Generally, effluent quality is poorest (highest concentrations of solids, organic matter, total phosphorus and total nitrogen) in the summer because seasonal variation in water quality is associated, in large part, with seasonal variation in phytoplankton biomass and metabolism. Phytoplankton biomass in catfish ponds is greatest in the warm months of late spring through early autumn because warm water temperatures, seasonally high values of solar

Table 2. Means and ranges of selected water quality variables in potential effluents from 20 commercial channel catfish ponds in northwest Mississippi from summer 1991 through spring 1992.

Season	Settleable solids (mL/L)	Suspended solids (mg/L)	Total nitrogen (mg N/L)	Total ammonia (mg N/L)	Total phosphorus (mg P/L)	Biochemical oxygen demand (mg O_2/L)
Summer 1991	0.20 (0-0.90)	127 (40-225)	6.1 (2.1-14.1)	1.22 (0.01-3.19)	0.54 (0.23-1.24)	26.1 (14.6-41.2)
Autumn	0.02 (0-0.25)	80 (40-225)	6.1 (2.9-10.8)	2.63 (0.05-6.35)	0.26 (0.14-0.58)	9.7 (1.9-26.4)
Winter 1992	0.06 (0-0.70)	109 (51-194)	5.1 (2.1-8.8)	0.86 (0.04-3.85)	0.34 (0.13-0.62)	13.7 (5.7-29.7)
Spring	0.11 (0-1.35)	123 (72-204)	4.5 (1.8-6.7)	1.06 (0.04-3.04)	0.31 (0.15-0.56)	14.8 (8.2-27.1)
Summer	0.09 (0-0.58)	117 (47-197)	7.0 (2.6-10.9)	0.71 (0.03-2.02)	0.51 (0.26-0.87)	21.2 (10.5-36.4)
Autumn	0.02 (0-0.15)	93 (41-175)	6.9 (3.8-10.4)	2.76 (0.07-8.10)	0.35 (0.15-1.03)	12.3 (5.4-34.0)
Winter 1993	0.01 (0-0.03)	93 (39-165)	5.5 (0.6-8.8)	1.48 (0.02-5.14)	0.34 (0.14-0.62)	11.9 (4.8-22.9)
Spring	0.12 (0-0.70)	135 (46-289)	5.2 (1.5-7.9)	2.21 (0.03-4.44)	0.37 (0.24-0.58)	14.9 (8.5-25.5)

radiation, and large inputs of plant nutrients (derived from feed via fish metabolic waste) support rapid rates of phytoplankton growth. Most of the organic matter in channel catfish pond water consists of living phytoplankton cells and phytoplankton-derived detritus. Accordingly, biochemical oxygen demand, which is a surrogate measure of the organic matter content of water, varies with changes in phytoplankton biomass and is generally highest in the summer. Concentrations of suspended solids also tend to correspond to phytoplankton biomass because phytoplankton and phytoplankton-derived detritus constitute most of the particulate material in catfish pond waters, except in ponds with high levels of suspended clay particles. Similarly, most of the combined nitrogen and phosphorus in catfish pond waters are present in particulate organic matter, primarily within phytoplankton cells, so total nitrogen and total phosphorus concentrations also vary with phytoplankton biomass and are highest in the warmer seasons.

In general, concentrations of settleable solids and suspended solids were similar in Alabama and Mississippi catfish ponds. Concentrations of Kjeldahl nitrogen (in Alabama ponds) and total nitrogen (in Mississippi ponds) are not directly comparable because of the different analytical methods that were used. However, if nitrogen compounds not measured in the Kjeldahl analysis (oxidized forms of inorganic nitrogen and refractory cyclic organic nitrogen compounds) are accounted for, then values for total nitrogen are probably similar in effluents from ponds in both states. However, concentrations of total phosphorus and biochemical oxygen demand are noticeably higher in potential effluents from ponds in Mississippi than in Alabama, particularly in the warmer seasons. This is likely the result of higher fish stocking and feeding rates commonly used in Mississippi, which would lead to higher standing crops of phytoplankton in ponds during the summer growing season.

Comparison of data from this study to other studies shows that concentrations of nutrients and organic matter are generally higher in catfish pond effluent than in natural stream waters, but much lower than in municipal and industrial wastewaters. Similarly, comparison of data gathered in this study to national and regional effluent water quality standards indicates catfish pond effluents are most likely to exceed concentration limits for suspended solids and total phosphorus. Other measured water quality variables in pond effluents seldom or never exceeded recommended standards. Treatment of aquaculture effluents will present a unique problem because traditional wastewater treatment systems are designed for waters that are much more concentrated in pollutants than aquaculture effluents. Most of the materials in pond effluents are discharged in the form of solids. This includes phosphorus because most of the total phosphorus in pond waters is present as organic phosphorus compounds in live phytoplankton cells or particulate detritus. Therefore, the impact of suspended solids and total phosphorus concentrations—the variables that most often exceeded recommended effluent concentration limits—could be greatly reduced by sedimentation or other processes that remove particulate material.

Quality of Effluents from Channel Catfish Ponds During Harvest

There are two basic types of channel catfish ponds: levee ponds and watershed ponds. Levee ponds discharge little water following rains, because they have small watershed areas. Watershed ponds normally discharge considerable water following heavy rains because they have large watershed areas. However, the most significant release of effluents from channel catfish ponds occurs when ponds are drained. Some catfish farmers drain ponds annually for fish harvest. Others drain ponds only every 3 to 8 years as dictated by the need to repair pond levees or to adjust the fish inventory. Surface water that flows from ponds following rains is similar in composition to pond water and is not highly polluted. Draining a pond for harvest results in the fish being concentrated into a smaller volume of water, which causes sediments to be stirred up by the activity of fish and the seining operation. Thus, the quality of effluents deteriorates during pond draining. Therefore, this study was conducted to obtain additional information on quality of effluents released from channel catfish ponds during pond draining and fish harvest.

Methods

Three watershed ponds on the Auburn University Fisheries Research Unit of the Alabama Agricultural Experiment Station near Auburn, Alabama were used in this study. Pond surface areas ranged from 0.92 to 1.32 ha and average depths were 1.37 to 1.73 m. The ponds were stocked with fingerling channel catfish at a rate of 10,000/ha in April 1991 and were fed daily at approximately 3% of body weight per day with a pelleted commercial ration of 32% crude protein during the growing season and intermittently during the winter. Ponds were drained during the period 7 January through 28 January 1992. Drains were opened early in the morning and closed in the evening. This procedure was repeated daily until the water levels were low enough to permit seining. Drains were then closed and ponds seined. After the first seining, drains were re-opened to allow ponds to drain further and concentrate remaining fish for easy capture. All fish were removed from one of the ponds in one day; it was necessary to seine the other two ponds on more than one day. After as many fish as possible had been removed by seining, ponds were allowed to drain completely so fish that escaped seining could be removed from the bottoms by hand. Water samples were collected twice daily, 1 to 2 hours after drains were opened in the morning, and 6 hours after morning samples were collected. One sample was collected 0.3 m below the water surface and one from the flow of the drain pipe. Water levels were recorded from staff gages in each pond in order to calculate the volume of water discharged per day. Samples were immediately analyzed for 5-day biochemical oxygen demand, nitrite, nitrate, total ammonia, Kjeldahl nitrogen, total phosphorus, soluble reactive phosphorus, and settleable solids.

Results

Total masses of substances released from ponds in effluents were calculated by summing products of daily mean concentration of a variable (g/m^3) and daily effluent volume (m^3) for each day. There was considerable variation among ponds in amounts of each water quality variable released. This difference was thought to be related to the fact that fish were seined from one pond in a single day, whereas the other two ponds were seined on more than one day. Each time ponds were seined, sediments were stirred into the water and concentrations of various substances increased. Most of the nitrogen and phosphorus in the effluent were contained in dissolved organic matter or particulate matter, for there was little total ammonia nitrogen, nitrite-nitrogen, and nitrate-nitrogen in relation to total Kjeldahl-nitrogen, and only a small proportion of the total phosphorus could be accounted for in soluble reactive phosphorus. Ponds did not contain heavy phytoplankton blooms at harvest because of low winter temperatures. The biochemical oxygen demand was expressed by soluble organic matter and particulate organic matter stirred into the water from the bottom sediments during seining. The major component of total settleable solids was suspended soil particles.

Changes in concentrations of water quality variables in effluents during draining and harvest followed similar trends in all three ponds. Data from one pond are summarized for illustration. Seining commenced after approximately 96 hours of draining. Concentrations of total ammonia-nitrogen remained below 0.1 mg/L during the first 48 hours of draining and did not exceed 0.5 mg/L until the drain had been open for more than 120 hours. Concentrations in the surface and effluent samples were roughly equivalent throughout the draining event. Concentrations of total Kjeldahl nitrogen remained below 5.0 mg/L for the first 72 hours of draining in both the surface and effluent samples. After that time, the surface concentration increased slightly to peak at 10 mg/L while the effluent concentration increased sharply to a peak of 137 mg/L. Concentrations of nitrite-nitrogen fluctuated with no apparent trend during the first 120 hours of draining. After this time, the surface concentration increased from 0.002 mg/L to 0.006 mg/L while the effluent concentration increased from 0.002 mg/L to a peak of 0.007 mg/L at 144 hours. Concentrations of nitrate-nitrogen fluctuated greatly throughout the draining event with surface concentrations showing almost no increase over time. Effluent concentrations increased from 0.36 mg/L at the beginning of draining to 0.64 mg/L at the end. Concentrations of soluble reactive phosphorus remained stable at 0.001 mg/L for the first 48 hours of draining, increased gradually to 0.02 mg/L after 96 hours and then increased sharply to peak at 0.12 mg/L at the surface and 0.16 mg/L in the effluent. Total phosphorus concentrations were about 0.15 mg/L in the surface water and effluent for the first 72 hours of draining. They then increased markedly to 1.0 mg/L at the surface and 1.3 mg/L in the effluent. Biochemical oxygen demand was around 10 mg/l in surface water for the first 48 hours and then increased gradually to peak at 18 mg/L. Effluent values for biochemical oxygen demand remained about the same as surface values for the first 120 hours and then increased sharply to peak at 296 mg/L. Concentrations of total settleable solids remained negligible in the surface water throughout the draining event. Effluent concentrations of total settleable solids paralleled those at the surface for the first 120 hours of draining, after which they increased sharply to peak at 60 ml/L. Values of pH fluctuated throughout draining while decreasing steadily.

The cumulative percentages of total nitrogen, total phosphorous, biochemical oxygen demand, and settleable matter discharged relative to the cumulative percentages of effluent discharged were calculated for the pond described above. Approximately 50% of the nitrogen, phosphorus, and biochemical oxygen demand was discharged in the last 15 to 20% of the effluent discharged from a pond. For settleable solids, 50% of the total was discharged in the last 5% of the effluent discharged.

Conclusions

Concentrations of total Kjeldahl nitrogen, biochemical oxygen demand, and settleable solids were fairly constant throughout the draining phase. It was not until the seining phase that these variables increased in concentration. On the other hand, total ammonia nitrogen, soluble reactive phosphorous, and total phosphorus steadily increased during the draining phase and sharply increased during the seining phase. Increases in phosphorus were most likely a result of sediments being stirred up, while the elevated total ammonia nitrogen concentrations were probably a result of metabolic wastes becoming more concentrated in a decreasing volume of water. Values of pH steadily decreased throughout pond draining. As the fish in a pond become more concentrated in a decreasing volume of water, carbon dioxide from their respiration was a major factor causing pH to decline. Both nitrite-nitrogen and nitrate-nitrogen concentrations fluctuated widely in all three ponds during draining and seining. These findings suggest that the best way to minimize the pollution potential of aquaculture pond effluents is to harvest ponds as quickly as possible, and either not discharge water during the seining phase or to discharge this highly contaminated water into a settling basin or retention pond. It also may be feasible to allow effluents to flow untreated into the environment during the pre-seining phase of draining, because concentrations of potential pollutants are low during this phase of draining.

Quality of Effluents from Crawfish Ponds

Freshwater crawfishes are exploited for food worldwide and most of the United States crawfish production is derived from ponds, nearly all of which are located in Louisiana. As with many types of pond aquaculture, crawfish producers occasionally discharge water from ponds to maintain good water quality and increase production. Water is also discharged from ponds when precipitation exceeds pond storage capacity. This study was conducted to characterize the quality of effluents from commercial crawfish ponds and to describe the relationship between pond management (specifically the type of vegetative forage) and effluent quality.

Methods

Seventeen commercial crawfish ponds (2.2 to 23.6 ha in surface area) in south-central and southwest Louisiana were used in this study. Three types of crawfish culture systems were selected: rice-field, permanent, and wooded. Rice-field ponds had rice foliage as the forage detrital base for crawfish. Rice-field ponds included rice-crawfish double-cropping systems in which rice was planted in April and the grain harvested in July or August. Rice "set-aside" ponds (rice planted August 1 or later) were also included as study sites. Permanent crawfish ponds selected were either planted with rice or sorghum-sudan grass in early to late summer, or they were not planted with cultivated forages and had native aquatic and terrestrial plants. Wooded ponds were characterized as having native terrestrial and aquatic flora and leaf litter. Commercial ponds were managed according to the owners' discretion with regards to flooding date, pumping hours, effluent discharge, and draining dates. Two crawfish ponds at the Louisiana Agricultural Experiment Station's Ben Hur Aquaculture Research Farm, Baton Rouge, were included in the effluent study. The ponds, which ranged in surface area from 1.5 to 2.0 ha, were planted with rice in late July 1991.

Effluent samples were collected from within each pond on 4 days in November 1991, February 1992, and April 1992 (corresponding to fall, winter, and spring seasons, respectively). During the draining of the ponds, which began in May and ended in July 1992 (summer season), at least three samples were collected at the drain inside each pond on different dates over 1 to 2 weeks. In each pond, a sample of water representing a composite of surface to bottom was collected at a drain when not flowing, and before the outfall when flowing, and transported on ice to the laboratory for analysis. Samples were stored and preserved following standard procedures.

Samples of effluent were collected between 0700 and 1000 hours. Laboratory analyses generally began by 1300 hours. Dissolved oxygen and water temperature were measured in situ at the drain with a polarographic oxygen meter. In addition, the following water quality analyses were conducted in the laboratory: total ammonia, nitrite, nitrate, Kjeldahl nitrogen, total phosphorus, soluble reactive phosphorus, chemical oxygen demand, settleable solids, total solids, total volatile solids, and 5-day biochemical oxygen demand (other analyses were also made and results can be found in F. X. Orellana, 1992, Characterization of Effluents from Commercial Crawfish Ponds in South Louisiana, M. S. Thesis, Louisiana State University).

Results

Dissolved oxygen concentrations in crawfish pond effluents ranged from 0.4 to 12.6 mg/L. Concentration in effluent during fall (mean = 6.5 mg/L) was higher than the concentration in winter (mean = 4.7 mg/L), spring (mean = 4.9 mg/L), and summer (mean = 4.3 mg/L) because low water temperature increased oxygen solubility and decreased metabolism by aquatic biota. Ponds with rice and native vegetation generally had higher concentrations of dissolved oxygen than ponds with sorghum-sudan grass. Because of their low vegetative biomass, ponds with native vegetation had the highest dissolved oxygen concentrations in the fall (mean =

7.8 mg/L). Ponds with sorghum-sudan grass had the lowest fall dissolved oxygen concentrations (mean = 5.0 mg/L) because of high vegetative standing crops. In contrast, by spring and summer, ponds with native vegetation had the lowest concentration of dissolved oxygen in effluents (mean less than 3.5 mg/L) because a relatively high quantity of vegetative biomass depleted ponds of the oxygen. Ponds with rice and sorghum-sudan grass had the highest dissolved oxygen concentrations (mean values greater than 4.5 mg/L) in spring and summer because vegetation had completely dissipated, and this reduced oxygen consumption.

Chemical oxygen demand concentrations ranged from 3.9 to 163.8 mg/L (overall mean = 38.7 mg/L), and biochemical oxygen demand values ranged from 0.6 to 26.6 mg/L (overall mean = 5.3 mg/L. The chemical oxygen demand in spring (mean = 46.5 mg/L) and summer (mean = 61.3) was 75 to 130% higher, respectively, than chemical oxygen demand concentrations in fall (mean = 27.4 mg/L) and winter (mean = 26.2 mg/L).The concentrations of biochemical oxygen demand followed a similar trend to chemical oxygen demand, with biochemical oxygen demand values in spring (mean = 5.1 mg/L) and summer (mean = 11.6 mg/L) being 63 to 270% higher, respectively, than biochemical oxygen demand in fall (mean = 2.7 mg/L) and winter (mean = 3.6 mg/L). Several ponds had effluents with biochemical oxygen demand concentrations that exceeded 20 mg/L during summer drainage. The high concentrations of chemical oxygen demand and biochemical oxygen demand in crawfish pond effluent in spring and summer probably resulted from an increase in phytoplankton and zooplankton production which was favored by warmer temperatures and longer photoperiod. Decomposition of macrophytes and an increase in suspended bottom sediments from crawfish foraging and harvesting activities were also responsible for higher chemical oxygen demand and biochemical oxygen demand in spring and summer. The chemical oxygen demand concentration of effluents in ponds with rice (mean = 41.3 mg/L) and sorghum-sudan grass (mean = 40.7 mg/L) was higher than in ponds with native terrestrial and aquatic flora (mean = 33.4 mg/L), but there was no difference in biochemical oxygen demand of effluents among the three forage types. The high chemical oxygen demand in rice and sorghum-sudan grass pond effluents resulted from an increase in particulate organic matter from decomposition of the high standing crop of planted forages compared with native vegetation.

Total solids concentration in spring and summer ranged from 143 mg/L to 2,431 mg/L (mean = 522 mg/L), and total volatile solids ranged from 0 mg/L to 432 mg/L (mean = 96 mg/L). Total solids and total volatile solids concentrations in summer (mean = 607 mg/L and 109 mg/L, respectively) increased significantly from concentrations in spring (mean = 460 mg/L and 87 mg/L), and the increase was attributed to crawfish harvesting, a decrease in vegetation, and bottom foraging by crawfish which suspended sediment. Bottom sediments were also evident in summer effluents as water was discharged during summer drainage. Effluents from ponds with native vegetation had significantly lower concentrations of total solids and total volatile solids in spring and summer (mean = 286 mg/L and 69 mg/L, respectively) than in rice ponds (mean = 646 mg/L and 113 mg/L) and sorghum-sudan grass ponds (mean = 578 mg/L and 92 mg/L. Ponds with native vegetation had high standing crops of aquatic macrophytes in spring and summer which helped to settle sediments that were suspended from harvesting activities. Macrophytes also reduced the effect of wind on ponds which contributes significantly to suspension of bottom sediments, particularly in shallow ponds. Settleable solids concentration in summer (mean = 0.312 mL/L) increased 429% from fall, winter, and spring concentrations (mean = 0.059 mL/L). Bottom foraging activity by crawfish and harvesting contributed to the high levels of settleable solids in spring and summer by suspending bottom sediments. Also, bottom sediments were higher in effluent water during drainage. No difference in the concentration of settleable solids was observed among the three forage regimes.

Soluble reactive phosphorus concentrations ranged from 0.002 to 0.653 mg/L (mean = 0.116 mg/L), and total phosphorus concentrations ranged from 0.039 mg/L to 1.126 mg/L (mean = 0.329 mg/L). The concentrations of soluble reactive phosphorus and total phosphorus in crawfish pond effluents increased from fall (mean soluble reactive phosphorus = 0.081 mg/L and mean TP = 0.141 mg/L) to winter (mean soluble reactive phosphorus = 0.132 mg/L and mean total phosphorus = 0.314 mg/L). The concentration of soluble reactive phosphorus in the fall (mean = 0.081 mg/L) differed significantly from that in winter (mean = 0.132 mg/L), spring (mean = 0.118 mg/L), and summer (mean = 0.139 mg/L). The soluble reactive phosphorus concentrations in effluents from ponds with native vegetation (mean = 0.093 mg/L) and rice (mean = 0.114 mg/L) were less than in ponds with sorghum-sudan grass (mean = 0.164 mg/L).The concentration of total phosphorus did not differ between winter (mean = 0.314 mg/L) and spring (mean = 0.324 mg/L). Total phosphorus concentration in summer (mean = 0.614 mg/L) differed significantly from concentrations in fall, winter, and spring. Total phosphorus concentrations were lower in ponds with native vegetation (mean = 0.268 mg/L) than in ponds with rice (mean = 0.327 mg/L) and sorghum-sudan grass (mean = 0.425 mg/L). The decomposition of macrophytes after ponds were flooded in the fall was reflected in higher concentrations of soluble reactive phosphorus and total phosphorus in effluents in winter and spring. Relatively high soluble reactive phosphorus and total phosphorus concentrations were present in summer effluents, particularly in rice and sorghum-sudan grass ponds, from the release of phosphorus in suspended bottom sediments. High concentrations of soluble reactive phosphorus in rice and sorghum-sudan grass ponds in winter, spring, and summer was also indicative of a low phytoplankton density. The summer concentration of soluble reactive phosphorus was relatively low in ponds with native vegetation because inorganic phosphates were utilized by aquatic macrophytes.

Concentrations of total ammonia-nitrogen in winter (mean = 0.232 mg/L) and spring (mean = 0.302 mg/L) was 160 and 240% higher, respectively, than in fall (mean = 0.089 mg/L), and the increase was largely attributed to decomposition of macrophytes and an increase in suspended bottom sediments. The mean total ammonia-nitrogen concentration in summer (mean = 0.353 mg/L) did not differ from the spring concentration. Total ammonia-nitrogen was higher in ponds with sorghum-sudan grass (mean = 0.304 mg/L) than in ponds with rice (mean = 0.215 mg/L) or native vegetation (mean = 0.236 mg/L). The mean concentration of Kjeldahl nitrogen in spring (mean = 3.063 mg/L) and summer (mean = 3.007 mg/L) was higher than the concentration in fall (mean = 1.039 mg/L) and winter (mean = 1.688 mg/L), and the increase was caused by an increase in organic matter from decomposition of macrophytes, and an increase in suspended bottom sediments. The concentration of Kjeldahl nitrogen was higher in ponds with rice (mean = 2.615 mg/L) and sorghum-sudan grass (mean = 2.546 mg/L) than in ponds with native vegetation (mean = 2.005 mg/L). Nitrite-nitrogen and nitrate-nitrogen concentration increased 167% and 114% from fall (mean nitrite = 0.006 mg/L and mean nitrate = 0.035 mg/L) through spring (mean nitrite = 0.016 mg/L and mean nitrate = 0.075 mg/L), but declined 44% and 47% by summer (mean nitrite = 0.009 mg/L and mean nitrate = 0.040 mg/L). Nitrite and nitrate concentration in ponds with sorghum-sudan grass (mean nitrite = 0.018 mg/L and mean nitrate = 0.087 mg/L) were about 100% and 102% higher, respectively, than concentrations in ponds with rice (mean nitrite = 0.009 mg/L and mean nitrate = 0.043 mg/L) or with native vegetation (mean nitrite = 0.007 mg/L and mean nitrate = 0.043 mg/L). Nitrite-nitrogen concentrations are highest in cold months because of lower assimilation rates of nitrogen by phytoplankton, nitrification of ammonia and denitrification of nitrate, and disturbance of anaerobic sediments by mechanical aeration. Concentrations of nitrate are correlated with nitrite because of nitrification of nitrite to nitrate, and high concentrations of nitrate are favored by low phytoplankton abundance.

Conclusions

The concentrations of nutrients and solids in effluents in crawfish ponds are generally much higher in spring and summer than fall and winter. Effluent quality is poorest during the summer drainage period. The type and quantity of summer vegetative foliage have a significant influence on the quality of the water discharged from crawfish ponds. Ponds with native vegetation generally have lower concentrations of nutrients and solids than ponds with rice or sorghum-sudan grass, and thus are most likely to comply with effluent standards. Ponds with volunteer vegetation generally have lower vegetative biomass in fall than ponds with planted forages, and the presence of aquatic macrophytes in spring and summer in ponds with native vegetation increases nutrient uptake and reduces the level of suspended sediments. Ponds planted with rice or sorghum-sudan grass could require some pretreatment of effluents prior to discharge to reduce the concentration of nutrients and solids. Also, planting aquatic macrophytes near the pond drain may act as a natural filtration system to reduce the amount of suspended solids and nutrients discharged in effluents of crawfish ponds.

Quality of Effluents from Hybrid Striped Bass Ponds

Commercial production of hybrid striped bass is a rapidly growing segment of aquaculture in the southeastern United States. Most of the production occurs in the south Atlantic coastal states, although some production can be found in all states of the region. Water is periodically discharged from ponds used to raise hybrid striped bass and concern over the impact of those discharges has been voiced by some regulatory agencies. Much of this concern is based on the lack of any information regarding the nature and volume of effluents released from commercial culture ponds. Therefore, this study was conducted to provide a representative database from commercial hybrid striped bass ponds.

Methods

Twenty commercial hybrid striped bass ponds in South Carolina were sampled in this study. An attempt was made to include ponds on both large and small operations, as well as ponds from both the coastal plain and piedmont areas of the state. Most striped bass hybrids are farmed using freshwater, although there is some interest in including striped bass hybrids in the diversification of coastal aquaculture farms which raise shrimp and estuarine fish. Most of the commercial ponds sampled were freshwater but there was some representation of saltwater ponds as well. The striped bass farming industry in the state is vertically integrated with production of broodstock, sac fry, fingerlings and several categories of market fish. While the sampling tended to concentrate on growout ponds, fingerling production ponds and one broodstock pond were also included. Where possible, individual ponds were followed through a production cycle from one quarter to the next. The same pond and group of fish were tracked for up to four consecutive annual quarters.

Water samples were collected from the surface and bottom of each pond using a Kemmerer water sampler. Samples were also collected from the water source (either well or surface water) for each farm on the day ponds were sampled. From each sample, a subsample was acid-preserved for nutrient analysis and a corresponding subsample was placed on ice for analysis of other variables. Water samples were returned to the laboratory as quickly as possible and analyses were initiated immediately upon receipt at the laboratory.

Results

Overall means, ranges, and standard deviations for water quality data are presented in Table 3. The 5-day biochemical oxygen demand of samples was highly variable and ranged from less than 2 mg/L to more than 60 mg/L. Three different measures of particulate matter were made for each water sample: total suspended solids, volatile suspended solids, and settleable solids. None of the 350 settleable solids samples had enough settleable material to reach the 0.4 mL/L minimal detection line on Imhoff cones. Suspended solids and volatile suspended solids were typically high but extremely variable. Concentrations of total ammonia-nitrogen, nitrite-nitrogen, nitrate-nitrogen, Kjeldahl nitrogen, soluble reactive orthophosphate, and total phosphorus were also highly variable among ponds.

Table 3. Means and ranges for selected water quality variables from hybrid striped bass ponds in South Carolina.

Variable	Mean	Range
Suspended solids (mg/L)	49	0 - 370
Volatile suspended solids (mg/L)	29	0 - 135
Biochemical oxygen demand (mg/L)	11.5	1.4 - 64.4
Kjeldahl nitrogen (mg N/L)	7.1	0 - 97.0
Total ammonia (mg N/L)	0.95	0.02 - 7.29
Nitrite (mg N/L)	0.07	0 - 2.94
Nitrate (mg N/L)	0.36	0 - 4.61
Total phosphorus (mg P/L)	0.31	0 - 1.9
Soluble reactive phosphorus	0.02	0 - 0.18

Generally, concentrations were considerably higher in pond samples than in samples from the water source (Table 4).

Sampling of commercial hybrid striped bass farms included fingerling ponds and growout ponds. To assess the overall effect of the complete production cycle, water quality of ponds containing fingerlings (size arbitrarily set at less than 50 grams) was compared to ponds growing fish to market size. As expected, fingerlings are often produced in smaller ponds. While average aeration rates were similar for fingerling and growout ponds, water exchange was less in fingerling production. Biomass and feeding rates were considerably lower for fingerling ponds as were all parameters associated with particulate matter and nutrients (Table 5). However, the average biochemical oxygen demand was slightly higher in fingerling ponds.

When the data were sorted by season (early spring, early summer, early autumn and early winter), surprisingly few trends were found. For example, no seasonal trends were noted in concentrations of parameters such as fish biomass, feeding rate, total ammonia, nitrite, suspended solids, or organic matter using seasonal averages for all ponds. There did appear to be some trend towards increased concentrations of reactive orthophosphate and total phosphorus as seasons progressed from spring to winter. Other studies have noted distinct seasonal trends in water quality in hybrid striped bass ponds and it may be that large pond-to-pond differences in water quality, the limited number of ponds that were sampled, and the coarse sampling schedule compromised the ability to detect seasonal changes in water quality in this study.

Hybrid striped bass may be produced at either freshwater of saltwater aquaculture farms. There are indications that freshwaters with low hardness may not promote optimal growth. Inland, freshwater sites are typically less costly to purchase and develop into fish farms. Some coastal mariculture farms have diversified their product line to include striped bass hybrids as well as estuarine species. The commercial hybrid striped bass farm sampling protocol was not designed to be a direct comparison of freshwater and saltwater ponds. However, a few saltwater ponds were included in order to cover the spectrum of commercial hybrid striped bass farming activity. While differences were influenced by a variety of factors in addition to water salinity, the saltwater ponds had higher average concentrations of suspended solids, suspended organic matter, total Kjeldahl nitrogen, and total phosphorus. The freshwater ponds had higher average concentrations of total ammonia, nitrite, nitrate, reactive orthophosphate, and biochemical oxygen demand.

Table 4. Average values for selected water quality variables in water supplies and in potential effluents from hybrid striped bass ponds in South Carolina. The percent increase is the increase in the concentration in potential effluents from ponds relative to that in the water supply.

Variable	Concentration in water supply	Concentration in potential effluents	Percent increase
Nitrite (mg/L as N)	0.01	0.07	652
Suspended solids (mg/L)	7.6	49.2	550
Total ammonia (mg/L as N)	0.15	0.95	544
Volatile suspended solids (mg/L)	5.1	28.7	462
Biochemical oxygen demand (mg O_2/L)	2.9	11.6	301
Kjeldahl nitrogen (mg/L as N)	2.52	7.06	180
Soluble reactive phosphorus (mg/L as P)	0.011	0.025	132
Total phosphorus (mg/L as P)	0.196	0.304	55
Nitrate (mg/L as N)	0.32	0.36	15
Dissolved oxygen (mg/L)	6.85	7.61	5
Settleable solids (mL/L)	<0.4	<0.4	0

Table 5. Production characteristics and average concentrations of selected water quality variables in potential effluents from fingerling hybrid striped bass ponds and in hybrid striped bass foodfish growout ponds in South Carolina.

Variable	Fingerling ponds	Foodfish ponds
Pond size (ha)	0.4	0.7
Aeration rate (kW/ha)	0.37	0.37
Average water exchange rate (%/day)	0.4	1.3
Fish biomass (kg/ha)	160	3,780
Feeding rate (kg feed/ha per day)	11	42
Total ammonia (mg/L as N)	0.62	1.04
Nitrite (mg/L as N)	0.03	0.08
Nitrate (mg/L as N)	0.28	0.38
Kjeldahl nitrogen (mg/L as N)	4.14	7.85
Soluble reactive phosphorus (mg/L as P)	0.013	0.028
Total phosphorus (mg/L as P)	0.15	0.34
Suspended solids (mg/L)	33	53
Volatile suspended solids (mg/L)	20	31
Settleable solids (mL/L)	<0.4	<0.4
Biochemical oxygen demand (mg O_2/L)	15	11

Conclusions

The quality of effluents from hybrid striped bass ponds varied greatly from pond to pond. There was little indication of significant seasonal variation in quality, although the sampling protocol used in this study may have obscured any true seasonal effect. Concentrations of suspended solids, total nitrogen (including total ammonia), and biochemical oxygen demand were the significant water quality variables most elevated in pond effluents relative to the source water, and may therefore have greatest impact on the environment of receiving bodies of water.

Quality of Effluents from the Hypolimnia of Watershed Ponds

Most aquaculture ponds are levee ponds with average depths of 0.8 to 1.2 m and maximum depths of 1.5 to 2 m. Although shallow ponds temporarily stratify during the day, convective heat loss at night causes destratification and mixing of the water. Water mixing caused by aeration also counteracts thermal stratification. Thus the quality of water in shallow levee-type ponds is relatively homogeneous with depth, and effluent quality will not differ significantly if waters are discharged from either the surface or bottom of the pond. However, in some regions, channel catfish are grown in deeper, watershed ponds which exhibit relatively stable thermal stratification. Those ponds may have anaerobic bottom waters (hypolimnia) for prolonged periods during warm months. In the southern United States, sportfish are cultured in fertilized, watershed ponds which thermally stratify in summer. Watershed ponds usually are drained from a drain pipe extending through the dam from the deepest part of the pond. Many watershed ponds also are fitted with trickle tube overflow pipes for deep water release, and discharges following heavy summer rains originate from hypolimnia. Under such circumstances, consideration should be given to the concentration of dissolved oxygen and reduced substances in effluents originating from hypolimnia of watershed ponds. This study provides data on selected water quality variables in bottom waters of watershed ponds stocked with channel catfish or combinations of sunfish and largemouth bass.

Methods

Three catfish ponds and three sportfish ponds on the Auburn University Fisheries Research Unit were used in this study. Ponds were filled and their water levels maintained by runoff from wooded watersheds. All ponds had maximum depths greater than 3 m; average depths ranged from 1.4 to 2.5 m. Channel catfish ponds were stocked at 5,000 fish/ha and fed at 3% body weight 6 days per week with a pelleted, 32% protein feed. Dissolved oxygen concentrations were monitored at night, and aeration was applied with tractor-powered or floating electric paddlewheel aerators on nights when low dissolved oxygen concentrations were anticipated. Sportfish ponds were stocked with sunfish and largemouth bass. Ponds were fertilized monthly with 8 L/ha of 10-34-0 liquid fertilizer. Aeration was not applied to sportfish ponds.

Depth profiles of dissolved oxygen concentrations and water temperatures were made on six dates between 7 July and 16 September 1992 with a polarographic oxygen meter and thermistor at the deepest areas (near the drain pipe inlets) of ponds. Water samples were collected about 30 cm above the pond bottoms in the deepest parts of the ponds with a van Dorn water sampler. Samples were transferred without air contamination through a latex tube to BOD bottles. Temperature and dissolved oxygen measurements and water sample collections were made on clear days between 0930 and 1230 hours. Samples were maintained on ice in insulated chests and transported to the laboratory for analysis on the same day. The following water analyses were conducted: biochemical oxygen demand, total ammonia, nitrite, ferrous iron, total manganese, and total sulfide.

Results

Thermal stratification was much more pronounced in sportfish ponds than in catfish ponds. Lack of strong thermal stratification in catfish ponds was probably the result of frequent nighttime aeration in the catfish ponds. Cooler weather in September resulted in thermal destratification of all ponds by the last sampling date. Dissolved oxygen concentrations in catfish ponds often fell to 5 mg/L or less within the surface 1 m. Sportfish ponds were oxygenated to a greater depth than catfish ponds, and surface strata containing more than 5 mg/L dissolved oxygen were usually 1.5 m thick or more. Secchi disk visibilities usually were 15 to 25 cm in catfish ponds, but sportfish ponds had Secchi disk visibilities of 30 to 40 cm. The greater abundance of phytoplankton was responsible for shallower dissolved oxygen stratification in catfish ponds than in sportfish ponds. Based upon calculations made from bathometric maps of the ponds, roughly one-half of pond volumes were above 1-m contours, and about three-fourths of pond volumes were above the 1.7-m contour. Oxygen-depleted water did not, therefore, constitute a large percentage of pond volumes; averages were 3.6% and 11.4% for catfish ponds and sportfish ponds, respectively. A considerably larger volume of water contained less than 3 and 5 mg/L dissolved oxygen. Of course, dissolved oxygen concentrations within the epilimnion fluctuated during the day in response to changes in insolation. Measurements of dissolved oxygen were made between 0930 and 1230 hours and percentages of the pond volume containing 3 and 5 mg/L dissolved oxygen were no doubt smaller in the mid afternoon and greater at night and early morning than those reported above. After the ponds destratified in mid-September, water in the bottom 30-cm stratum of catfish ponds was still depleted of dissolved oxygen. This probably resulted from inadequate light penetration for photosynthesis and high rates of microbial respiration at the soil-water interface.

Ferrous iron concentrations in hypolimnetic waters ranged from 2.4 to 26 mg/L in catfish ponds and from 1.0 to 43.2 mg/L in sportfish ponds. The source of ferrous iron in anaerobic water is the microbial reduction of insoluble ferric iron in the bottom soil to soluble ferrous iron. Catfish ponds had lower concentrations of ferrous iron than sportfish ponds on most sampling dates. Aeration of catfish ponds probably mixed oxygenated water from the hypolimnion into the epilimnion, causing oxidation of a part of the ferrous iron to ferric hydroxide. There was a drastic decrease in ferrous iron concentration when the sportfish ponds thermally destratified in the autumn, but no such decline was observed in the catfish ponds. This is in agreement with the observation that the bottom 0.3-m layer of water in catfish ponds was still anaerobic even after thermal destratification occurred.

Concentrations of total manganese as high as 0.25 mg/L were found in the oxygen-depleted water. Previous studies have shown that concentrations of total manganese in surface waters of

Alabama ponds seldom exceed 0.05 mg/L. Concentrations of total sulfide in bottom waters were 0 to 1.29 mg/L. Much higher concentrations of total sulfide have been measured in anaerobic waters in other locations. However, waters on the Auburn University Fisheries Research Unit contain 1 to 2 mg/L of sulfate-S, so little sulfate is available for reduction to sulfide. High concentrations of ferrous iron also would result in precipitation of sulfide as insoluble iron pyrite. Concentrations of nitrite-N in bottom waters were 0 to 0.15 mg/L. It is not unusual to find even higher concentrations of nitrite-N in surface water of fish ponds. Concentrations of total ammonia-nitrogen were higher in the hypolimnetic waters of catfish ponds than in sportfish ponds. This observation reflects the high inputs of nitrogen in feed. Surface waters of catfish ponds stocked at the rates used in the present study normally contain 0.5-1.5 mg/L total ammonia-nitrogen, while sportfish ponds fertilized at rates used in this study seldom contain more than 0.25 mg/L of total ammonia-nitrogen. Higher concentrations of total ammonia-nitrogen in bottom water than surface water likely resulted from microbial mineralization of ammonia from organic matter which settled to pond bottoms from epilimnia. Values of biochemical oxygen demand ranged from 9.6 to 19.8 mg/L. Because the raw water samples were diluted directly in the BOD bottles, biochemical oxygen demand values represent oxygen consumption by both oxidation of organic matter and reduced inorganic substances (primarily ferrous iron). The biochemical oxygen demand was similar in catfish and sportfish ponds on all but two dates (18 August and 2 September). These differences cannot be explained from existing data. Surface waters of fish ponds usually have biochemical oxygen demand values of 10 to 25 mg/L (Boyd 1990), so the bottom waters were not exceptionally high in biochemical oxygen demand.

Conclusions

Hypolimnetic water from deep watershed ponds fertilized to promote sunfish production or fed to enhance channel catfish yields may be of lower quality than corresponding surface waters. Specifically, hypolimnetic waters may contain lower dissolved oxygen concentrations and higher concentrations of ferrous iron, total manganese, total sulfide, and total ammonia than commonly found in surface waters. Discharge of hypolimnetic water from ponds into natural waterways could have toxic effects on fish and other aquatic organisms. Logical steps can be implemented to minimize problems with hypolimnetic discharges from watershed ponds as follows:

1) fill deep water areas of watershed ponds with soil during construction;
2) do not install deep water intake overflow pipes;
3) use water circulation devices or sufficient aeration to prevent thermal stratification;
4) harvest fish without draining water from ponds;
5) if ponds must be drained, drain after natural thermal destratification occurs in the fall;
6) if water must be drained from the bottom of thermally destratified ponds, detain the effluent in holding ponds or let it flow over a series of cascades for reaeration before discharging into natural waterways.

Objective 2: Evaluation of Management Practices That May Reduce the Impact of Aquaculture Effluents on the Environment

Reusing Water for Multiple Fish Crops

The mass of nutrients or organic matter discharged from ponds is a function of the concentration of the substance in the effluent and the volume of water discharged. Although it may be difficult to reduce the concentration of potential pollutants in pond effluents, it is relatively easy to control discharge volume. The most obvious procedure for reducing the volume of effluents from channel catfish ponds is to harvest the fish without draining the ponds. However, this practice is usable only if year-to-year reuse of water does not cause reduced fish yields due to deterioration of water quality over time. This study was conducted to compare water quality and fish production between annually drained ponds and undrained ponds over a 3-year period.

Methods

Six levee ponds (400 to 660 m^2 with average depths of 0.9 to 1.0 m and maximum depths of 1.3 to 1.5 m) on the Auburn University Fisheries Research Unit were used in this research. In 1990, 1991 and 1992, ponds were stocked with small channel catfish at 15,000 fish/ha in March and harvested in late September or October. A 32% crude protein, pelleted feed was offered 6 days per week at 3% of body weight per day. Feeding rates were increased weekly assuming a feed conversion ratio of 1.6. When dead fish were observed in ponds, they were removed and weighed so that feeding rates could be adjusted. Daily feeding rate did not exceed 67 kg/ha per day. When this rate was reached, it was continued until fish harvest. All ponds had a 0.37-kW vertical pump aerator connected to a timer. Aerators were operated from midnight until 0700 hours daily from 15 June until harvest each year. Water levels in ponds were maintained 10 to 12 cm below the tops of standing drain pipes to prevent overflow after rains. Water was added from a pipeline when necessary to replace evaporation and seepage losses.

Three ponds were designated to be harvested by draining each year. To harvest fish, water levels were lowered to about 10% of pond area and fish removed with a seine. A wire mesh cap was placed around the drain pipe and the remainder of the water was discharged so that fish which escaped seining could be harvested by hand. After a 3-week drying period, ponds were refilled. In the other three ponds, a large seine was passed through the ponds several times to capture the fish. Afterwards, rotenone was applied at 2.5 mg/L to kill any remaining fish. Ponds were checked every few hours for several days to make sure that all dead fish were removed. The total number of fish in each pond was counted and weighed. A 10% subsample was taken for estimating average weight of individual fish.

Near the middle of each month, a 1-m water column sampler was used to collect a water sample from the deep end of each pond. Samples were taken between 0700 and 0800 hours and immediately carried to the laboratory for analyses. The following water quality variables were determined: settleable solids, total suspended solids, 5-day biochemical oxygen demand, Kjeldahl nitrogen, total ammonia, total phosphorus, and chlorophyll *a* (results of additional analyses can be found in K. S. Seok, C. E. Boyd, and M. F. Schwartz, 1995, Water Quality in Annually Drained and Undrained Channel Catfish Ponds over a Three-Year Period, *Progressive Fish-Culturist* 57:52- 58).

Results

Ponds for this study were selected for similarity of treatment history and inputs of organic matter, nitrogen and phosphorus to the ponds over the 19-year period of pond use were roughly equal. The water supply for all six ponds was a reservoir filled by surface runoff from a forested watershed.

This water has a total alkalinity of 10 to 12 mg/L and low concentrations of nitrogen and phosphorus.

Fish production data are summarized in Table 6. Each year, fish stock were of different weights, and growing seasons were of different lengths. These differences could not be avoided because of limits on availability of small fish and labor for harvesting the fish. Net fish production, average weight of fish at harvest, and feed conversion ratio did not differ significantly between treatments in any of the three years. However, net fish production was greater in both treatments in 1990 than in other years and was lower in 1992 than in 1990 and 1991, but feed conversion did not differ significantly among years in either treatment.

Phytoplankton blooms, as estimated from chlorophyll *a* concentrations, increased as the grow-out period progressed in response to greater nutrient inputs from fish feed. Average chlorophyll *a* concentrations (Table 7) did not differ between treatments in 1990 and 1992, but in 1991, undrained ponds contained more chlorophyll *a* than drained ponds. Because of aeration, dissolved oxygen concentrations were usually above 3 mg/L at dawn in both treatments. During July, August and September of all years, there were mornings when average dissolved oxygen concentrations fell below 3 mg/L, and in individual ponds, dissolved oxygen concentrations as low as 1.5 mg/L were observed. However, there was no significant mortality of fish as a result of oxygen depletion. There were no differences in dissolved oxygen concentration between treatments or among years.

Total ammonia-nitrogen concentrations were almost identical between treatments in 1990. In 1991 and 1992, much higher peaks in total ammonia-nitrogen were observed in the undrained treatment than in the drained treatment, and average total ammonia-nitrogen concentrations were greater in the undrained ponds than in the drained ponds in 1992. This suggests that higher total ammonia-nitrogen concentrations may be expected in undrained ponds. However, on the last sampling dates in October of 1991 and 1992, total ammonia-nitrogen concentrations were similar in both treatments. Concentrations of suspended solids, biochemical oxygen demand, Kjeldahl nitrogen, and total phosphorus increased as the growing seasons progressed each year. The highest concentrations of individual variables observed in late summer and early fall when feeding rates were high were: biochemical oxygen demand, 25 to 30 mg/L; total phosphorus, 0.3 to 0.5 mg/L; Kjeldahl nitrogen, 3 to 6 mg/L; and suspended solids, 80 to 100 mg/L. As noted above, differences between treatments were found for chlorophyll *a* and total ammonia-nitrogen, but no other differences in water quality variables were noted. The tendency for Kjeldahl nitrogen concentrations to increase over time in both drained and undrained ponds is interesting, but it cannot be explained from existing data.

Table 6. Average channel catfish production data for three annually drained and three undrained ponds. Fish were stocked at 15,000 fish/ha. Feed conversion is the weight of feed offered divided by net fish production.

Year and treatment	Net fish production (kg/ha)	Average harvest size (g/fish)	Feed conversion (kg feed/kg fish)
1990			
Drained	6,580	452	1.47
Undrained	6,683	465	1.51
1991			
Drained	5,750	430	1.31
Undrained	5,860	480	1.31
1992			
Drained	5,230	360	1.28
Undrained	4,990	390	1.33

Table 7. Average concentrations (± 95% confidence intervals) for selected water quality variables in three annually drained and three undrained channel catfish ponds.

Variable	1990 Drained	1990 Undrained	1991 Drained	1991 Undrained	1992 Drained	1992 Undrained
Suspended solids (mg/L)	35.2±9.8	40.0±12.2	28.1±11.9	46.3±21.5	70.6±16.5	74.3±11.5
BOD_5 (mg O_2/L)	12.8±3.6	11.7±4.1	12.0±5.3	13.3±2.5	11.6±2.6	10.4±3.4
Kjeldahl nitrogen (mg N/L)	0.66±0.35	1.12±0.39	2.53±0.41	3.34±0.52	4.12±0.60	4.79±0.71
Total ammonia (mg N/L)	0.47±0.12	0.38±0.09	0.97±0.13	0.91±0.07	0.59±0.10	1.11±0.15
Total phosphorus (mg P/L)	0.29±0.09	0.23±0.05	0.35±0.10	0.24±0.08	0.42±0.15	0.27±0.17
Chorophyll *a* (µg/L)	98±15	115±25	116±27	188±20	65±12	72±10

Conclusions

Few differences in water quality and no differences in fish production were observed between annually drained and undrained catfish ponds over a 3-year period. Findings also suggested that effluents from catfish ponds which had not been drained for 3 years were similar in quality to those from catfish ponds drained each year. Natural processes, such as nutrient uptake by bottom soils, microbial decomposition of organic matter, denitrification, and sedimentation, continually remove potential pollutants from pond water. Operation of ponds without draining makes use of the waste assimilation capacity of the pond ecosystem; it is not merely a way to delay discharge of wastes. As such, ponds may be operated for multiple years without draining with no decrease in fish production attributable to deterioration in environmental conditions within the pond. Reuse of water for multiple crops will result in significant savings in water use and will also reduce overall effluent volume.

Using Conservative Water Management Practices

When fish are grown in ponds, wastes are held within the culture system for some time before they are released. During that time, natural processes remove potential pollutants from the water and the amounts of nutrients and organic matter ultimately discharged from ponds are, therefore, substantially less than the overall waste loading to the pond. Also, the volume of water discharged from ponds can be controlled to some extent by manipulating pond water storage capacity and reusing water for multiple fish crops before draining the pond. Therefore, it may be possible to significantly reduce discharge of nutrients and organic matter from ponds and, by extension, diminish the impact of discharge on receiving waters by using relatively simple water management practices that reduce effluent volume or delay water discharge from ponds. The following study was undertaken to characterize effluents from channel catfish culture ponds in northwest Mississippi and to model the reduction in waste discharge that could result from the use of two water management practices: maintaining surplus water storage capacity and not draining ponds between fish crops.

Methods

A water quality data set was generated by sampling commercial channel catfish ponds in northwest Mississippi for 2 years (summarized in Table 2, above). That information was then used in a hydrologic model of pond overflow volume to describe the reduction in waste discharge that could result from the use of two water management practices: maintaining surplus water storage capacity and not draining ponds between fish crops.

Water discharged from catfish ponds, as a result of overflow only, was calculated using a hydrological equation, with appropriate climatological data for the period 1961-1990 obtained from the National Weather Service Cooperative Observation System for Stoneville, Mississippi. Pond evaporation was obtained by multiplying pan evaporation data by 0.8 and a value of 0.04 cm/day was assumed for infiltration losses.

Quarterly overflow losses were determined for two pond water management scenarios. One scenario assumed that ground water was pumped into the pond at the end of each day to replace evaporation plus infiltration. In other words, no storage capacity was maintained in the pond and any rainfall in excess of losses was lost as overflow through the drain. This scenario estimated the maximum pond overflow that could occur under a given set of climatic conditions. The other scenario is a management option designed to reduce the need for pumped water and reduce overflow volume by allowing for storage of much of the annual rainfall. In that scenario, pond water level was allowed to fluctuate with climatic conditions until pond water levels dropped to 15 cm below the overflow structure due to evaporation and infiltration losses in excess of rainfall. At that point, ground water was added to raise the water level to 7.5 cm below the top of the drain leaving 7.5 cm of storage potential to capture rainfall that subsequently occurred. Overflow losses were estimated using weather data for the 30-year (1961-1990) average, the year of record with the most precipitation (1979), the year of record with the least precipitation (1986), quarters of record with the most precipitation, and quarters of record with the least precipitation.

Pond overflow volumes estimated for the two water management scenarios were then used to calculate amounts of nitrogen, phosphorus, and organic matter discharged from ponds as a result of overflow only. Mass discharges (in kg/ha of pond surface) were computed as the product of pond overflow volume and overall mean concentrations of total nitrogen, total phosphorus, chemical oxygen demand, and biochemical oxygen demand for each season.

Annual nutrient and organic matter mass discharges were then calculated for ponds managed under the two different water management scenarios (with and without storage potential) and operated with three intervals (1, 3 and 5 years) between total pond drainings. For ponds drained annually it was assumed that fingerling channel catfish were stocked in early spring, fish were grown through spring, summer and autumn, and ponds were drained in winter. Pond discharge thus consisted of overflow in spring, summer and autumn plus 125 cm of water discharged during pond draining in winter. Nutrient and organic matter mass discharges were calculated as the product of the modeled total water volume released from ponds (overflow plus pond draining) and the overall average concentration of total nitrogen, total phosphorus, and chemical oxygen demand measured in ponds in the corresponding seasons. Mass discharges were similarly calculated for ponds used for culture with 3 and 5 years between pond drainings, again assuming ponds were stocked in early spring and drained in winter of the appropriate year. Total mass discharges over the 3- or 5-year period were then divided by the 3 or 5, respectively, to obtain average annual discharges of nitrogen, phosphorus and organic matter.

Results

Seasonal variation in pond overflow volume was related in a direct and obvious manner to annual changes in climatic conditions because precipitation and evaporation are major components of the hydrologic equation. Modeled pond overflow volumes for the average year were predictably highest in the winter and spring when rainfall was highest and pond evaporation rates were lowest (Table 8), except during the driest year on record (1986) when rainfall was evenly distributed among seasons.

Combining the modeled overflow volumes and measured concentrations of pond water quality variables revealed that seasonal changes in overflow volume were more important than seasonal changes in the composition of the pond effluent in determining the mass of nutrients and organic matter discharged from Mississippi catfish ponds. Specifically, predicted mass discharge was greatest in the winter when overflow volume was maximum and not in the summer when concentrations of nutrients and organic matter in the pond were highest.

The model showed that managing ponds to maintain water storage potential resulted in large reductions in nutrient and organic matter discharge (Table 9). In an average year, modeled annual discharge of nitrogen, phosphorus, and organic matter from ponds managed to maintain water storage potential was only about 30% of that from ponds not managed to maintain surplus storage capacity. Even in wet years, modeled discharge of nutrients and organic matter was considerably lower from

Table 8. Predicted pond overflows (cm) from levee-type channel catfish ponds under two water-management scenarios (No *S* = pond water level managed with no water storage potential; *S* = pond water level managed to maintain a minimum 7.5-cm water storage potential). Overflows were based on a 30-year (1961-1990) climatological record for Stoneville, Mississippi, and were calculated for the 30-year average, the wettest year (1979), the driest year (1986), the wettest individual quarters, and the driest individual quarters.

	Average year		Wet year		Dry year		Wet quarter		Dry quarter	
Season	No *S*	*S*	No *S*	*S*	No *S*	*S*	No *S*	*S*	No *S*	*S*
Spring	30.5	8.7	50.8	23.4	19.0	0.0	57.8	32.4	10.5	0.0
Summer	17.4	1.4	23.8	0.0	12.1	0.0	28.0	9.5	7.3	0.0
Autumn	23.2	3.1	35.5	2.9	19.8	0.0	43.3	20.0	9.9	0.0
Winter	33.2	19.4	43.8	34.8	13.0	0.0	65.3	47.6	11.9	0.0
Total	104.3	32.6	153.9	61.1	63.9	0.0	194.4	109.5	39.6	0.0

Table 9. Predicted discharge (kg/ha of pond surface) of total nitrogen, total phosphorus, and biochemical oxygen demand from levee-type channel catfish ponds under two water-management scenarios (No *S* = pond water level managed with no water storage potential; *S* = pond water level managed to maintain a minimum 7.5-cm water storage potential). Values were calculated as the product of average measured concentrations of each variable (Table 2) and pond overflow volumes modeled in Table 8.

	Average year		Wet year		Dry year		Wet quarter		Dry quarter	
Season	No *S*	*S*	No *S*	*S*	No *S*	*S*	No *S*	*S*	No *S*	*S*
Total Nitrogen (as N)										
Spring	14.7	4.2	24.6	11.3	9.7	0.0	28.0	15.7	5.1	0.0
Summer	12.4	1.0	16.9	0.0	8.6	0.0	19.9	6.8	5.2	0.0
Autumn	15.2	2.0	23.2	1.9	12.9	0.0	28.2	13.1	6.5	0.0
Winter	17.2	10.1	22.8	18.1	6.8	0.0	33.9	24.7	6.2	0.0
Total	59.5	17.3	87.5	31.3	38.8	0.0	109.0	60.6	23.0	0.0
Total Phosphorus (as P)										
Spring	1.0	0.3	1.7	0.8	0.6	0.0	2.0	1.1	0.4	0.0
Summer	0.9	0.1	1.2	0.0	0.6	0.0	1.5	0.6	0.4	0.0
Autumn	0.7	0.2	1.1	0.1	0.6	0.0	1.3	0.6	0.3	0.0
Winter	1.1	0.7	1.5	1.2	0.4	0.0	2.2	1.6	0.4	0.0
Total	3.7	1.3	5.5	2.1	2.2	0.0	7.0	3.9	1.5	0.0
Biochemical oxygen demand (as O_2)										
Spring	45	13	75	35	28	0	86	48	16	0
Summer	41	3	56	0	28	0	66	22	17	0
Autumn	25	3	39	3	22	0	48	22	11	0
Winter	42	25	56	45	17	0	84	61	15	0
Total	153	44	226	83	95	0	284	153	59	0

ponds managed to reduce overflow volume, and annual discharge from managed ponds was nil in exceptionally dry years. The greatest relative reduction in predicted mass discharge of nutrients and organic matter occurred in the summer quarter. In an average summer, managing pond water levels to maintain water storage potential reduced the predicted discharge of nitrogen by more than 91%, phosphorus by more than 88%, chemical oxygen demand by more than 91%, and biochemical oxygen demand by more than 92% compared to summertime discharge from ponds managed without storage potential. Based on the model, no nitrogen, phosphorus or organic matter would have been discharged as a result of overflow from ponds managed to maintain storage potential during the summer of the wettest and driest year of record and in the driest individual summer quarter. Although the model demonstrated that greatest amounts of nutrients and organic matter are discharged from ponds in northwest Mississippi in the winter and spring, reducing waste discharge in summer may be relatively more important than at other times of the year because the quality of potential pond effluents is poorest and stream flows are at their annual minimum, resulting in low rates of dilution of any water discharged from ponds.

Harvesting fish without draining ponds between crops substantially reduced the average volume of water discharged each year, and the reduction was greatest when ponds were also managed to maintain water storage potential. For ponds not managed to maintain surplus water storage, the model showed that using ponds for 3 years before draining reduced annual average waste discharge by approximately 30% compared to annually drained ponds and by about 45% when ponds were not drained for 5 years (Table 10). When pond water levels were managed for water storage potential, discharge of nutrients and organic matter was reduced relative to annually drained ponds by more than 50% when ponds were used for 3 years between drainings, and by more than 60% and when ponds were used for 5 years between drainings. The use of ponds for several years without draining and refilling is possible, in large part, because natural microbial and physicochemical processes continually remove nutrients and organic matter from pond water. The rate at which these processes act is such that channel catfish ponds in the southeastern United States can be used for many years without significant long-term accumulation of nutrients and organic matter in the water column, despite large inputs of metabolic waste resulting from fish feeding practices. When ponds are drained, the quantities of nutrients and organic matter in the water that is discharged are, therefore, much less than the total waste loading to the pond. Increasing the interval between pond drainings simply makes fuller use of the "waste treatment" capability of the pond ecosystem by allowing natural processes to remove more wastes from the water before discharging the water.

Table 10. Predicted quantities (kg/ha per year) of nitrogen, phosphorus and organic matter (expressed as chemical oxygen demand) discharged annually from levee-type channel catfish ponds under two water-management scenarios and three different intervals between pond drainings. Pond effluent volumes used to calculate mass discharges were for the average weather year based on a 30-year (1961-1990) climatological record for Stoneville, Mississippi. No *S* = pond water level managed with no water storage potential; *S* = pond water level managed to maintain a minimum 7.5-cm water storage potential.

	Mass discharge (kg/ha per year)	
Pond draining schedule	**No *S***	***S***
Total Nitrogen (as N)		
Drained annually	109	74
Drained every 3 years	76	36
Drained every 5 years	69	29
Total Phosphorus (as N)		
Drained annually	7	5
Drained every 3 years	5	3
Drained every 5 years	4	2
Chemical oxygen demand (as O_2)		
Drained annually	1,480	1,020
Drained every 3 years	1,030	500
Drained every 5 years	940	400

Conclusions

Reducing overflow volume by maintaining water storage potential in ponds appears to be a simple, inexpensive, and highly effective technique for reducing nutrient and organic matter discharge. In addition to the environmental benefits accruing from reduced waste discharge, maintenance of storage potential in ponds helps conserve ground water resources by dramatically reducing the need for pumped water to maintain pond water levels during fish culture. If surplus water storage capacity is available, rainfall is captured in the pond rather than lost as overflow, and the stored water helps offset evaporative and infiltration losses. Further reduction in nutrient and organic matter discharge can be achieved by not draining ponds annually for harvest.

Minimizing Water Exchange in Penaeid Shrimp Ponds

Culture of marine shrimp is the largest aquaculture industry in the world. Although culture technologies for marine shrimp vary widely, most pond management practices involve some amount of water exchange in the belief that exchange is needed to maintain adequate environmental conditions for good shrimp growth. Obviously, water exchange can greatly increase the volume of effluent discharged from ponds. This study was conducted to determine the effects of water exchange on marine shrimp production and to determine the impact of water exchange on pond effluent characteristics.

Methods

This study was conducted during 1991 at the Waddell Mariculture Center (WMC), a field station of the Marine Resources Division of the South Carolina Wildlife and Marine Resources Department. Five 0.1-ha, 1,300-m^3 ponds were used. Three ponds were stocked with postlarval *Penaeus setiferus* at a density of 44 postlarvae/m^2; one pond was stocked at 22/m^2 and a fifth pond at 66/m^2. Ponds were fed a 3-mm diamenter, 40% protein pellet formulated specifically for shrimp twice daily. Feeding actually began 10 days prior to stocking to induce a bloom of forage prey for postlarvae. Total amounts of feed applied before stocking as "fertilizer" was proportionately 137.5, 275.0 and 412.5 kg/ha for the three stocking densities of 22, 44 and 66/m^2 respectively. Feeding rates were identical for the three ponds stocked at 44/m^2 and proportional for the two ponds stocked at 22 and 66/m^2 (50% and 150% of the rate used for the 44/m^2 ponds, respectively).

The following water quality variables were measured routinely in all ponds: 5-day biochemical oxygen demand, nitrite, nitrate, total ammonia, Kjeldahl nitrogen, soluble reactive phosphorus, suspended solids, volatile suspended solids, and in vivo chlorophyll flourescence (other variables were also measured and data can be found in J. S. Hopkins, R. D. Hamilton, P. A. Sandifer, C. L. Browdy, and A. D. Stokes, 1993, Effect of Water Exchange Rate on Production, Water Quality, Effluent Characteristics and Nitrogen Budgets of Intensive Shrimp Ponds, *Journal of the World Aquaculture Society* 24:304-320). Except for those paramenters measured in situ (such as dissolved oxygen), all samples were collected in polypropylene bottles and returned immediately to the lab for analysis. Samples were drawn from just below the surface as water in these heavily aerated ponds has been found to be very homogenous.

One 44/m^2 pond and the ponds stocked at 22 and 66/m^2 received no water exchange (except as noted below), while water in the other two 44/m^2 ponds was exchanged continuously beginning on day 37 at target rates of 25.0 and 2.5%/day, respectively. The ponds are hereafter referred to as 0%-22/m^2, 0%-44/m^2, 0%-66/m^2, 2.5%-44/m^2 and 25%-44/m^2. The combined effects of precipitation, exchange efficiency, and no pumping until day 37 resulted in overall average water exchange rates of 0.36%, 2.21%, and 18.44% per day for the three treatments. Drain harvesting increases overall volume of effluent to an average of 1.03%, 2.89% and 19.10% of the pond volume per day for 0%, 2.5% and 25% exchange treatments, respectively. Cumulative water exchange over the course of this study totaled 1.5, 4.3 and 28.3 pond volumes for 0%, 2.5%t and 25% exchange treatments, respectively.

Results

Water exchange and density treatments clearly affected shrimp survival. The pond stocked at 66/m^2 (0%-66/m^2) was experiencing heavy mortalities by day 89. The 0%-44/m^2 treatment also experienced mass mortalities. However, noticeable mortality did not occur until day 125 and was sporadic over the remaining 4 weeks of the study. Survival in the other three ponds was excellent, ranging from 81.3 to 83.8 percent from direct stocking of postlarvae. Water exchange did not appear to affect growth rate. Fastest growth was seen in the 2.5%-44/m^2 pond, followed by 0%-22/m^2, 25%-44/m^2, 0%-44/m^2 and 0%-66/m^2. Growth rates were 0.8, 0.9 and 0.9g/wk for 25%-44/m^2, 2.5%-44/m^2 and 0%-22/m^2 ponds, respectively. Analysis of variance indicated that shrimp from 2.5%-44/m^2 and 0%-22/m^2 ponds were not significantly different in size at harvest yet both were different from shrimp in the 25%-44/m^2 pond. Production was highest in the 2.5%-44/m^2 pond with 6,375 kg/ha/crop, followed by 25%-44/m^2 and 0%-22/m^2 with 5,655 and 3,169 kg/ha/crop, respectively. These growth rates and production levels are considered good for this species in intensive culture. Shrimp production levels as high as 3,169 kg/ha/crop without water exchange have not been reported elsewhere. The level of production achieved without water exchange is in excess of average production levels of commercial shrimp farms in South Carolina and the United States. Production of 6,375 kg/ha with only 2.5%/d exchange is also noteworthy.

Water quality differed dramatically among shrimp density and water exchange treatments for many paramenters. Since the 0%-66/m^2 pond was terminated and water flushed on day 89 due to massive mortalities, data for this pond was omitted from most analyses. Average concentrations and standard deviations for selected water variables in three water exchange treatments stocked at 44 postlarvae/m^2 and the no-exchange treatment stocked at 22 postlarvae/m^2 are summarized in Table 11. Total ammonia-nitrogen concentrations fluctuated widely, often as an inverse response to changes in phytoplankton density. Total ammonia concentrations were low initially but the magnitude of fluctuations and, thus, average concentration tended to increase as the season progressed. Total ammonia levels in the 25%-44/m^2 pond was not significantly different from that of inlet water. However, total ammonia concentrations increased significantly with decreasing water exchange or increasing density. Maximum recorded concentrations of total ammonia-nitrogen were 2.7 mg/L for the 25%-44/m^2 treatment, 5.6 mg/L for the 2.5%-44/m^2 treatment, 9.1 mg/L for the 0%-44/m^2 treatment, and 11.0 mg/L for the 0%-22/m^2 treatment. Prior to termination, the 0%-66/m^2 pond had a maximum recorded value of 9.0 mg/L.

No significant difference in either nitrite-N or nitrate-N was observed between inlet water and any pond except the 0%-44/m^2 treatment. In inlet as well as pond water, both nitrite-N and nitrate-N tended to increase substantially about day 70-75 and were declining abruptly just prior to harvest. Maximum recorded values of nitrite-N were

Table 11. Average values (± standard deviation) for selected water quality variables in the water supply and in ponds used to raise shrimp, Penaeus setiferus, at three different daily water exchange rates (25%, 2.5%, and 0%) and two different shrimp densities (44 shrimp/m^2 and 22 shrimp/m^2).

		Treatment (water exchange rate:shrimp density)			
Variable	Water supply	25:44	2.5:44	0:44	0:22
Total ammonia (mgN/L)	0.3±0.4	0.5±0.4	1.0±0.9	3.0±2.2	1.5±1.5
Nitrite (mg N/L)	0.4±0.6	0.5±0.8	0.8±0.9	1.3±1.5	0.8±0.9
Nitrate (mg N/L)	4.1±4.9	3.9±5.0	7.2±7.2	9.8±11.0	6.4±6.8
Kjeldahl nitrogen (mg N/L)	4.2±4.7	6.5±3.7	9.2±2.8	15.4±5.2	11.8±6.8
BOD_5 (mg O_2/L)	1.5±1.4	8.5±4.3	14.7±6.6	18.8±8.1	12.1±5.4

3.8 mg/L for 25%-44/m^2 treatment, 3.5 mg/L for the 2.5%-44/m^2 treatment, 6.3 mg/L for the 0%-44/m^2 treatment, and 3.1 mg/L for the 0%-22/m^2 treatment. Prior to termination, the 0%-66/m^2 pond had a maximum recorded value of 15.0 mg/L. Kjeldahl nitrogen was significantly higher in the 25% exchange pond than inlet water but increased with higher stocking densities and lower water exchange. Total nitrogen tended to decrease during periods when phytoplankton concentration was low.

Soluble reactive phosphorus in the 25% exchange pond was not significantly different from inlet water. However, significant differences were noted as water exchange decreased or density increased. Soluble reactive phosphorus tended to be low when phytoplankton was high. Total suspended solids and the volatile suspended solids tended to increase over the course of the season, but there were no significant differences between inlet water and any of the ponds. Inlet water had the highest average concentration of organic solids. Like organic nitrogen, solids tended to decrease during periods when phytoplankton abundance was low. The 5-day biochemical oxygen demand of pond water was higher than that of inlet water and tended to increase as water exchange was reduced and density increased. Differences between the inlet water and all ponds were significant. There were also significant differences between several groups of ponds. The average biochemical oxygen demand in low exchange and 0% exchange ponds was an order of magnitude higher than that of inlet water.

The amount of water discharged to produce a crop in ponds with normal survival was 6, 9 and 64 metric tons of water per kg of whole shrimp for the 0%-20/m^2, 2.5%-44/m^2 and 25%-44/m^2 treatments, respectively. Thus, the 0% exchange and reduced exchange treatments result in water usage which is considerably below the estimated world-wide range of 39-199 mt water/kg shrimp. The "normal" 25% exchange treatment used in the present study had a water consumption rate (64 mt/kg) which fell within the range of values reported for commercial farms.

The water quality parameters of primary importance in discharge regulation are biochemical oxygen demand, suspended solids, total ammonia, and soluble reactive phosphorus. Therefore, these four parameters were further analyzed by determining total mass of each discharged over the production season. Water exiting ponds due to precipitation was included in the analysis. Daily concentrations were multiplied by daily flows to determine total mass of each paramenter in discharge water. The mass of each paramenter which entered ponds from the adjacent estuary through water exchange (via the inlet water sampling data) was subtracted from the daily discharge. Finally, daily discharge values for each paramenter were summed for the season and extrapolated to kg/ha per crop.

The total weight of nutrients, solids and oxygen demand being added to receiving water tended to decrease with decreasing water exchange and/or decreasing stocking density (Table 12). Thus, shrimp farmers may have a cost effective means of immediately reducing impacts of their effluent on receiving waters simply by reducing rates of water exchange.

Mass transfer of these nutrients, solids and oxygen demand was then calculated after inclusion of appropriate values for pond drainage at the end of the study and subtracting nutrients, solids and

Table 12. Mass discharge (kg/ha per crop) of substances from ponds prior to pond draining, less the quantities pumped into ponds for routine water exchange. Ponds were used to raise shrimp, Penaeus setiferus, at three different daily water exchange rates (25%, 2.5%, and 0%) and two different shrimp densities (44 shrimp/m^2 and 22 shrimp/m^2).

Treatment	Total ammonia	Reactive phosphorus	Suspended solids	Biochemical oxygen demand
25% exchange:44 shrimp/m^2	79.1	30.4	6,699	2,197
2.5% exchange:44 shrimp/m^2	41.4	37.2	1,317	551
0% exchange:44 shrimp/m^2	21.1	15.7	1,143	125
0% exchange:22 shrimp/m^2	9.2	11.3	1,190	92

oxygen demand of water used to fill ponds initially. These values (Table 13) represent total transfer of nutrients, solids, and biochemical oxygen demand from ponds to receiving streams for the entire production process. For ponds with very little routine water exchange, draining dramatically increases total nutrients, solids and oxygen demand in discharged water. On the other hand, total discharge of nutrients, solids and oxygen demand from ponds with routine water exchange and continual dilution is affected relatively little by incorporating pond drainage in the model. When ponds stocked at $44/m^2$ are compared after incorporating pond drainage into total effluent loading, the 0% exchange treatment actually released more ammonia and orthophosphate than the 2.5% exchange treatment (Table 13). It must be noted that concentrations of these dissolved inorganic nutrients are extremely dynamic and fluctuate widely from one week to the next. Therefore, it may be possible to minimize effects of pond drainage on total nutrient discharge by timing harvest to coincide with periods of minimal concentrations of certain dissolved nutrients. For example, if the hypothetical drainage day for the $0\%-44/m^2$ pond had been three days earlier, the total amount of total ammonia released for the season would have been 20% lower.

Conclusions

Without resorting to water exchange or some type of filtration, maximum stocking rates for shrimp farms are somewhere between $22-44/m^2$ which corresponds to a peak feeding rate of about 70-140 kg/ha per day. This agrees with estimates of the assimilative capacity of static freshwater catfish ponds in the southeastern United States, which is thought to be about 112 kg/ha per day of 32% protein feed. The much higher inorganic nitrogen concentrations for shrimp ponds with no water exchange compared to freshwater catfish ponds fed at similar rates suggests that the assimilative capacity of marine ponds is lower than that of freshwater ponds. In addition, the percentage of nitrogen lost from the system through volatilization and/or denitrification, as determined by nitrogen budgets, may be lower for marine ponds.

This study has important implications for the intensive shrimp farming industry. First, water exchange in intensive pond culture can be dramatically reduced without sacrificing growth or survival. At lower limits of intensive production, or upper limits of semi-intensive production, water exchange may be eliminated entirely. Second, reduced or eliminated water exchange reduces total amounts of nutrients, solids and BOD discharged into adjacent water bodies.

Using Pond Effluents for Irrigation of Soybeans

Water discharged from aquaculture ponds is often viewed simply as a waste product of the culture process. However, that water still has value and its reuse may have multiple benefits. For instance, if ponds are located near terrestrial crops that require irrigation, it may be possible to use pond discharge for irrigation water. That use will reduce actual pond discharge volume (and associated effects on receiving bodies of water) and will benefit the crop. The objectives of this research were to characterize the various water quality parameters in the pond effluent which can be used as irrigation water for crops and to estimate their impact on integrated crop and fish production system.

Table 13. Mass discharge (kg/ha per crop) of substances from ponds including water discharged during pond draining, less the quantities pumped into ponds for initial filling and routine water exchange. Ponds were used to raise shrimp, *Penaeus setiferus*, at three different daily water exchange rates (25%, 2.5%, and 0%) and two different shrimp densities (44 shrimp/m2 and 22 shrimp/m2).

Treatment	Total ammonia	Reactive phosphorus	Suspended solids	Biochemical oxygen demand
25% exchange:44 $shrimp/m^2$	92.6	38.6	11,289	2,147
2.5% exchange:44 $shrimp/m^2$	42.0	40.9	6,662	603
0% exchange:44 $shrimp/m^2$	87.4	84.7	5,554	302
0% exchange:22 $shrimp/m^2$	21.2	24.1	6,693	183

Methods

Nine, 0. l-ha earthen ponds were filled to a depth of 1.2 m with well water and stocked, in triplicate, with 10- to 15-cm channel catfish fingerlings at 22,000, 44,000 and 66,000 fish/ha. Fish were fed daily at 3% of body weight. Ponds were continuously aerated and oxygen levels were above 4 mg/L at all times. Beginning in July, fish weighing more than about 0.25 kg were selectively harvested during the first week of each month. The last harvest was during the first week of November. Ponds were partially drained (25% of pond volume or about 30 cm of water) several times and the effluent applied to a soybean crop planted in a nearby field. Partially drained ponds were immediately filled with well water. The number of partial draining and refilling events were in proportion to the stocking densities; the high-density ponds were partially drained and refilled eleven times, the medium-density five times, and the low-density two times. The high-density ponds were thus drained approximately at 2-week intervals.

Soybeans were planted in the first week of June and harvested in the first week of November. The crop was planted with a conservation tillage planter and no fertilizer was used. Twenty-four (six replicates of four treatments in a randomized complete block design) 13 m x 13 m field plots were irrigated with the drained effluent. Control plots were irrigated with well water on the same days when the high-density effluent was applied. Plots were sprinkler irrigated for about 3 hours which amounted to about 3 cm of water during each application.

Pond effluent samples were analyzed for chemical oxygen demand, total ammonia, total phosphorus, Kjeldahl nitrogen, and total solids.

Results

Water quality in pond effluents were not affected by the fish density. Mean values of Kjeldahl nitrogen were from 9 to 12 mg N/L and mean total phosphorus concentrations ranged from 0.2 to 0.6 mg P/L. Chemical oxygen demand concentrations varied from 56 to 108 mg/L. The average total ammonia nitrogen values in the effluent were from 0.4 to 1.24 mg/L and total solids contents were 139 to 206 mg/L.

Since pond effluents contain nitrogen, phosphorus and other plant nutrients, crops can benefit if it is used as irrigation water. Based on the Kjeldahl nitrogen concentrations, it appears that the total amount of nitrogen available for crops varied from 0.9 to 1.2 kg N/ha from each centimeter of water applied. If the average irrigation amount is assumed to be 30 cm, then the available nitrogen would be from 27 to 36 kg/ha. This represents a significant portion of nitrogen requirements of many agronomic crops. However, soybean yield was not affected by the effluent treatment, although the average soybean yield for all treatments was 3.6 metric tons/ha, which was double the average yield in Georgia. The higher-than-average yield in this study was due to irrigation alone.

Conclusions

If water exchange is practiced to improve water quality in fish ponds, the resulting effluent can be used to irrigate agronomic crops, although the nutrient content of the water may be too low to affect crop production. The main advantage of using water from fish ponds for irrigation is that the overall discharge volume from the pond is reduced.

Treating Pond Effluents Using Constructed Wetlands

Wetlands act as biological filters to remove pollutants from water, and natural and constructed wetlands sometimes are used for treatment of agricultural, municipal and industrial wastewaters. There are several advantages to wetland wastewater treatment. Wetlands are inexpensive to build and operate, chemical treatment of wastewater is eliminated, wetlands contribute stability to local hydrologic processes, and plant communities in wetlands are excellent wildlife habitats. There is concern over the feasibility of wetlands for treating aquaculture effluents, because large areas of land may be necessary. In the following study, a free water surface wetland was constructed adjacent to a commercial channel catfish pond, and its efficiency in removing potential pollutants from pond water was evaluated.

Methods

The constructed wetland used in this study was adjacent to a 6.9-ha channel catfish production pond near Greensboro in Hale County, Alabama. Two cells, each 84 m long x 14 m wide, were built in series. Perimeter levees were 3 m wide at tops with 2:1 (horizontal:vertical) side slopes. Vertical distance from cell bottoms to levee tops was 0.61 m at the middle of the long axes. Cell bottoms and levees were constructed of heavy clay soil.

The 5-cm-diameter intake pipe of an electric pump was extended 10 m horizontally from the pond bank and then from the pump to the head of Cell I where it discharged into a manifold that was perpendicular to the long axis of the cell. Three 10-cm-diameter drain pipes were installed between the end of Cell I and the head of Cell II. Two 10-cm-diameter drain pipes with elbows for attaching stand pipes were installed through the levee at the end of Cell II and then connected to another 10-cm-diameter drain pipe so that outflow from Cell II returned to the pond.

Rootstocks of California bulrush (*Scirpus californicus*), giant cutgrass (*Zizaniopsis miliacea*), and Halifax maidencane (*Panicum hemitomon*) were provided by the Alabama State Office of the USDA Soil Conservation Service. Cells were planted during the last week of May 1992. Holes were made in the dry pond bottom with a tool for transplanting pine tree seedlings. Rootstocks were placed in holes and holes were closed around rootstocks by tamping. The upper half of Cell I was planted with bulrush on 90-cm centers, and the lower half of the cell was planted with giant cutgrass on 180-cm centers. Cell II was planted with maidencane on 90-cm centers. A single application of 10 g/m^2 of fertilizer (8% N, 8% P_2O_5, 8% K_2O) was applied over Cell II two months after planting because the maidencane was not growing very well. The pump was operated continuously, and water depth was maintained at 5 cm while plants became established.

Four mean hydraulic residence time regimes (1, 2, 3 and 4 days) were used in the study. The efficiency of the wetland in reducing concentrations of selected water quality variables at each mean hydraulic residence time was determined over 6-week periods. A 3-day mean hydraulic residence time was conducted from 13 October to 24 November 1992 during the non-growing season. The 2-day mean hydraulic residence time was tested between 11 May and 15 June 1993; the 1-day mean hydraulic residence time was tested from 6 July to 10 August 1993; the 4-day mean hydraulic residence time was tested from 24 August to 29 September 1993. Water flow through the wetland was maintained between trials by operating the pump continuously.

During a trial, water samples were collected weekly from the inflow pipe, the drain of Cell I, and the drain of Cell II. Samples were analyzed for 5-day biochemical oxygen demand, total Kjeldahl nitrogen, total phosphorus, suspended solids, volatile suspended solids, and settleable solids.

Results

Plants grew slowly, and by the end of September 1992 only the bulrush had grown enough to provide full canopy over the area in which it was planted. By summer 1993, after a growing period of 280 days, the cutgrass had formed a full canopy over the area where it was planted. The maidencane continued to spread, but even at the end of the study it had not produced a full canopy. Sampling to estimate the quantity of vegetation and composition of soil in the cells was not conducted during the study to avoid destruction and disturbance of the plants. Standing crops of plant biomass in Cell I at the end of the study averaged about 3,400 g dry weight/m^2 for bulrush, and about 6,500 g dry weight/m^2 for cutgrass. In Cell II, standing crop of maidencane averaged about 3,000 g dry weight/m^2. Vegetation consisted primarily of the species planted, but there was some invasion of cattail (*Typha latifolia*) along the shallow edges of the cells and mats of filamentous algae were present. Standing crops of bulrush in Cell I were slightly higher near the inlet at the head of the cell than 25 m away. Standing crops of bulrush and maidencane tended to decrease with distance from the point of inflow. This suggests that nutrient concentrations declined as water flowed through the two cells.

Air temperatures averaged 15°C during the 3-day mean hydraulic residence time trial conducted from 13 October to 24 November 1992. Plants were not growing and shoots had been killed by frost. Bulrush had grown enough during the summer to form a dense canopy, but other plants provided less than 25 percent cover. Nevertheless, the wetland removed large amounts of potential nutrients from the water even when vegetation was dormant and temperature was low. Removal rates of potential pollutants by the wetland during the cool-weather trial were 37% for biochemical oxygen demand, 45% for Kjeldahl nitrogen, 69% for total phosphorus, 75% for suspended solids, and 69% for volatile suspended solids. Much of the observed removal during both dormant seasons probably occurred through non-biological processes of sedimentation, filtration and soil adsorption.

It is difficult to assess the effectiveness of the wetland in removing potential pollutants from influent by considering only changes in concentrations of water quality variables over time in influent and effluent samples because of the continually changing conditions within the pond and the wetland. Therefore, concentrations of water quality variables were averaged for influent and cell effluent samples over each mean hydraulic residence time trial, and the percentage removal of each variable was computed (Table 14). Cell I removed a greater proportion of pollutants from the water than Cell II, and concentrations of water quality variables were reduced 50% or more by the wetland. Removal of suspended solids and volatile suspended solids exceeded 78%, and increasing the mean hydraulic residence time beyond 1 day did not appear to enhance the removal of these variables. The greatest removal of total phosphorus (84%) was obtained in the 4-day mean hydraulic residence time. Removal of biochemical oxygen demand ranged from 54 to 67%, but lengthening mean hydraulic residence time did not improve BOD removal. Both the 2-day and 4-day mean hydraulic residence time trials gave 100% removal of suspended solids (additional data for other water quality variables can be found in M. F. Schwartz and C. E. Boyd, 1995, Constructed Wetlands for Treatment of Channel Catfish Pond Effluents, *Progressive Fish-Culturist* 57:255-266).

The disadvantage of wetlands for treating aquaculture pond wastes is the large amount of space necessary to provide an adequate hydraulic residence time. Assuming a 1-ha pond of 1.5 m average depth, a draining time of 7 days, and mean hydraulic loading rate to the wetland of 80 L/m^2 per day, 26,786 m^2 of wetland would be required. Even a 1-day mean hydraulic residence time would

Table 14. Percent reductions in concentrations of selected potential pollutants in effluent from a channel catfish pond after treatment by flow through a constructed wetland at three different mean hydraulic residence times. The wetland had two cells of equal size. Percent removal was calculated for each cell and the overall removal after flow through both cells.

Component	Kjeldahl nitrogen	Total phosphorus	BOD_5	Suspended solids	Settleable solids
1-day hydraulic residence time					
Cell I	46	43	59	78	21
Cell II	9	23	7	10	36
Overall	55	66	66	88	57
2-day hydraulic residence time					
Cell I	48	39	47	68	89
Cell II	13	20	7	19	11
Overall	61	59	54	87	100
4-day hydraulic residence time					
Cell I	37	62	64	81	91
Cell II	18	22	3	7	9
Overall	55	84	67	88	100

require 6,696 m^2 of wetland. Wetland areas of 0.7 to 2.7 times pond area are not feasible for commercial catfish farms. Thus, it will probably be necessary to integrate wetland treatment of effluents with other pond management procedures to reduce the area of wetland necessary for treating effluents. For example, when a pond must be drained, about 80% of the water could be pumped into adjacent ponds for reuse, and the remaining 20% of water could be discharged through a wetland. Draining time would not be a critical factor after fish have been removed by seining. If a 15-day draining time is used, a 1-ha by 1.5-m-deep pond would require a 2,500 m^2 wetland (25% of pond area) to provide a 4-day hydraulic residence time at a mean hydraulic loading rate of 80 L/m^2 per day. On a large catfish farm, all ponds would not need to be drained each year and draining could be extended over several weeks or months to further reduce the area of wetland required. Wetlands also could be used for treated overflow from ponds after rains. Most channel catfish farming is conducted in levee ponds where watersheds consist only of inside slopes and tops of levees. Ponds receive little runoff, and overflow normally does not occur except in winter and early spring following heavy rains. Most overflow from levee ponds in the southeastern United States occurs during January, February and March and average daily overflow rates of 1 to 5 L/m^2 pond surface per day can be expected. The wetland area necessary to provide an average hydraulic residence time of 4 days at a mean hydraulic loading rate of 80 L/m^2 per day for average winter time overflow of 5 L/m^2 per day from a 1-ha catfish pond is 625 m^2 or 6.25% of pond area.

Conclusions

Passing pond effluents through constructed wetlands can be a highly effective technique for reducing the concentrations of nutrients and organic matter in the water ultimately discharged to the environment. Concentrations of water quality variables in the outflow from the wetland were always much reduced relative to untreated waters regardless of the hydraulic residence time. However, a 4-day hydraulic residence time is recommended, because it provided the greatest reduction in total phosphorus and biochemical oxygen demand$_5$, which are important variables in considerations of environmental impacts of effluents. The disadvantage of wetlands for treating aquaculture pond wastes is the large amount of space necessary to provide an adequate hydraulic residence time. Thus, it will probably be necessary to integrate wetland treatment of effluents with other pond effluent management procedures to reduce the area of wetland necessary for treating catfish farm effluents. For example, pond water levels could be lowered for fish harvest by pumping 80 to 90% of the water to adjacent ponds for storage, and the remaining water, which is highly concentrated with wastes, could be discharged through a constructed wetland. A wetland centrally located on a farm, or connected to an integrated drainage system, would save on construction costs and use land efficiently. Such a system would also allow a wetland to be used to treat the overflow coming from ponds after rainfall. Pond drainings could be staged so that only one pond is being drained at a time; this will allow the use of only one wetland to treat the effluents from numerous ponds and will also allow water from a draining pond to be transferred to another drained pond so that only the effluents from one pond might need to be released into the environment and the rest could be conserved. Effluent from a constructed wetland could even be pumped back into ponds and reused if needed.

Treating Pond Effluents Using Grass Filter Strips

Overland flow has been recommended as a possible cost-effective land treatment process for treating municipal wastewater. The system is highly effective in reducing the concentrations of suspended solids, biochemical oxygen demand, and ammonia, but not efficient in removing algae. Recommended terrace slopes have been between 2 to 8%, lengths from 30 to 60 m, and annual application rates from 3 to 20 m^3 of water/m^2. The recommended grasses for the vegetative cover included common and coastal Bermuda, Dallis, and Bahia for warm climates and fescue, reed canary, and rye grass for cool climates. Preapplication treatment of the wastewater has been recommended, based on the type of wastewater, before applying as an overland flow in a thin sheet over the vegetative surface. In some agricultural systems, grass buffer strips have been used for filtering solids from animal waste and the use of such strips or other filtering methods might be viable for filtering catfish pond effluent. The objective of this study was to investigate the effectiveness of grass strips for filtering catfish pond effluent to remove solids and nutrients.

Methods

Nine ponds at the Coastal Plain Experiment Station, Tifton, Georgia, were filled to a depth of 1.2 m with well water and stocked with channel catfish fingerlings at the rate 44,000 fish/ha in 1993 and 55,000 fish/ha in 1994. The daily feeding rate was kept at 3 percent of fish body mass. All ponds were aerated using air-lift aerators to keep the oxygen level above 4 mg/L at all times. In addition, surface aerators were used as an emergency aeration method.

Grass strips were established in a field adjacent to the catfish pond research facility. The facility consisted of twelve 0.1-ha catfish ponds, tanks to collect effluent from the pond drainage system, a pumping station, and an irrigation pipe network to deliver pond effluent to the field. Twelve grass strip plots were established for the filtration experiment; they consisted of two different slopes, two different grasses, and three replications. Each grass strip was 24 m long x 4.5 m wide. Six strips had a uniform land slope of 1.5% and six had a slope of 3%. Three strips on each slope were planted with Bermudagrass sod (*Cynodon dactylon*) and three were planted with Bahiagrass (*Paspalum notatum*) seed. The six 1.5% slope strips were separated from the six 3% slope strips by a 3-m-wide buffer plot. The filtered sample (output) collection locations were at 8 m, 16 m, and 24 m away from the input location.

Filtration experiments were conducted in the morning hours so that most of the analyses could be completed on the same day. The grass plots were irrigated with well water for about 3 hours the previous afternoon in order to minimize water infiltration during the experiment. Water was pumped from the pond bottoms and the effluent was applied uniformly over a narrow strip of gravel to minimize any soil erosion due to application intensity. There were two rates of effluent application (26 and 18 L/min) in 1994 and one rate (26 L/min) in 1993. Input samples (500 mL) were collected in three replicates. Each complete test lasted for 3 hours, $1^1/_2$ hours for each six-plot area having the same slope. Thus, any plot received effluent for $1^1/_2$ hours during a test; a total amount of 2,340 L at the higher rate and 1,620 L at the lower rate.

A device similar to a dust pan (30 cm wide) was constructed from sheet metal and held manually at the desired locations to collect the water travelling through the grass for analysis. While collecting the output samples, care was taken to minimize soil disturbance due to the sample collector. In 1993, all samples were analyzed for total ammonia and suspended solids. One sample collected in each test at the 24 m location from each plot was analyzed for Kjeldahl nitrogen, total phosphorus, and chemical oxygen demand. In 1994, all samples were analyzed for suspended solids and nine samples (three input, six filtered) from either grass on a 1.5% slope were analyzed on alternate test dates for total Kjeldahl nitrogen, total phosphorus, and chemical oxygen demand.

Results

The 1993 experiments were conducted from September through November and the 1994 experiments from May through November. The temperature range during those months was from 10 to 37°C. The temperature generally stayed over 15°C. Grasses appeared to be better established in 1994 compared to 1993, especially in Bahia plots. The 1993 results indicated that the filtration technique removed 18 to 62% of the suspended solids from the pond effluent. Filter strip slope and type of grass had no effect on filtration efficiency. Samples collected at the bottom of the plots (24 m travel distance) had significantly less solids than the samples collected at intermediate travel distances of 8 m or 16 m. In 1994 (Table 15), again, it was found that the type of grass, effluent application rate, and the land slope did not significantly alter the amounts of suspended solids removed by the grass strips.

When the suspended solids concentration was low (less than 30 mg/L), the filter strips were not effective in filtering the solids (Table 15). The strips

Table 15. Percent removal of suspended solids in channel catfish pond effluents after flowing through grass filter strips of different slopes and at different effluent application rates. Values within a column followed by common letters do not differ at the 5 percent level of probability.

Suspended solids (mg/L) in effluent	1.5% slope		3% slope	
	High rate	Low rate	High rate	Low rate
> 200 mg/L	73a	84a	90a	83a
100 - 200 mg/L	55ab	48b	50b	51b
30 - 100 mg/L	45b	40bc	42b	45b
<30 mg/L	—	27c	18c	14c

were most effective in solids removal when the solids concentration in the pond effluent was greater than 200 mg/L. For situations where the concentration of solids in the effluent was between 30 to 200 mg/L, the strips removed the solids by as much as 50%. The results from both years were similar. The 1994 results were better than 1993 probably because of better established grass plots. The rate of solids removal is substantial considering that the filtering process was simple.

In 1993, there was no difference in the concentrations of total ammonia-nitrogen, total Kjeldahl nitrogen, total phosphorus , or chemical oxygen demand in the input and filtered water samples. However, in 1994 the filtered samples had significantly lower concentrations of chemical oxygen demand and total Kjeldahl nitrogen than those of the input samples (Table 16). Simultaneous reduction in solids, chemical oxygen demand, and Kjeldahl nitrogen was expected because the three variables are highly correlated in aquaculture pond waters. Since suspended solids concentrations in the filtered effluent were reduced by filtration in 1994, chemical oxygen demand and Kjeldahl nitrogen were also significantly lower in 1994. In 1994 there was no signficant effect of type of grass and the effluent application rate on removal of chemical oxygen demand, Kjeldahl nitrogen, and total phosphorus.

Table 16. Average concentrations of selected water quality variables in effluents from channel catfish ponds before and after flowing through grass filter strips. * = values after treatment differ from values before treatment at the 5% level of probability.

Variable	Before treatment	After treatment
Kjeldahl nitrogen (mg N/L)	17.9	11.8*
Chemical oxygen demand (mg O_2/L)	77.9	60.8*
Total phosphorus (mg P/L)	0.59	0.53

Conclusions

Suspended solids from catfish pond effluent can be significantly reduced and concentrations of organic matter and total nitrogen can be lowered by applying the effluent as an overland runoff to well-established strips of either Bahia or Bermudagrass. This filtering technique is relatively easy and inexpensive. This technique may have application if the filtered effluent is to be reused for fish production to conserve groundwater. It could also be used as an effluent treatment before discharging to receiving waters. The filtered effluent will have lower suspended solids and lower concentrations of organic matter and nitrogen than before application to the grass strips, and, therefore, be potentially less objectionable to regulators. Further research is needed to find the efficacy of filters over longer periods of operation such as over several hours of continuous usage. Effects of grass filtered effluent on fish production also need to be evaluated. These findings will then be useful in establishing the design parameters of a grass filter system for a commercial size pond.

Objective 3: An Economic Analysis of Treating Effluents from Channel Catfish Ponds

The potential for environmental impact of effluent discharge from fishpond water is a growing concern among policy makers. The argument is that components of the effluent from aquaculture production facilities may contribute nutrients and suspended matter that may impact the ecosystem of receiving bodies of water. Pollution control regulations may include either direct or indirect measures. Direct control usually aims at prohibiting the use of a specific pollutant. Due to the difficulties that may arise in completely banning the use of a certain pollutant, environmental agencies tend to set absolute standards as a direct control measure. Indirect controls, such as placing a tax on polluting activities, provide an economic incentive to not pollute or to reduce the amount of pollution. The greater the amount of pollution, the higher the tax. While taxes provide some economic incentive not to pollute, it is difficult to determine its net welfare to society.

While water quality and effluent discharge have raised much concern among farmers, scientists, and policy makers, few studies have focused on the economic feasibility of management practices that might be adopted by farmers to deal with possible regulations on effluent discharge. Therefore, this study was conducted to provide an economic analysis of the farm-level economic impact of establishing certain effluent treatment technologies. Specifically, the methodology used would result in selection of the profit-maximizing effluent management strategies for various levels of allowable effluent discharge for catfish in the event that regulations would enforce fixed levels of allowable effluent discharge or in the case of policies enacted to tax effluent discharge. The effect on net farm income was compared to that of no treatment. In addition, the economic tradeoff between policies and alternative management implications of different enforcement practices was assessed.

Methods

Four alternative management practices to reduce potential environmental impacts from effluent discharges from aquaculture production facilities were considered: (1) no treatment with possibility of an imposed tax on effluent discharged; (2) irrigation of rice with effluents from fishponds; (3) recycling water through constructed wetlands; and (4) circulating water from a catfish pond through a pond stocked with filter-feeding fish (bighead carp).

Three hypothetical catfish farms of various sizes (65, 130 and 260 water hectares) were considered. In each farm, individual ponds were assumed to be 8 water hectares. Based on previous studies, budgets were developed for the hypothesized farm sizes. Catfish were assumed to be stocked at 4,942, 9,884 or 14,826 fish/ha with feed conversion rates of 2:1 and a mortality of 8% during a 200-day production period. The representative farm stocked 10- to 15-cm and 18- to 20-cm fingerlings with a harvest weight of 0.68 and 0.91 kg, respectively. Marketing constraints were assumed to be due solely to fish off-flavor and represented a charge of $0.02/kg produced and sold.

Table 17 presents catfish production costs and returns for the assumed base scenario of no effluent treatment. Net returns per hectare were $2,345, $2,614 and $2,740 for the 65-, 130- and 260-hectare farms, respectively. The average costs for producing catfish were $1.41/kg, $1.39/kg and $1.34/kg for the 65-, 130- and 260-ha farms, respectively. Additional costs encountered in implementing alternative effluent treatments were derived from published experimental data. The studies from which the data were obtained measured impacts on pond water quality but did not specifically measure effluent removal efficiencies. Engineering methods were used to estimate costs for each technology. The major cost items include

Table 17. Channel catfish production costs and returns with a pond stocking rate of 9,884 fish/ha and no treatment of pond effluent.

Item	Farm size		
	65 hectares	130 hectares	260 hectares
Investment ($, without land)	8,597	7,317	6,897
Gross receipts ($, at $1.54/kg)	12,731	12,731	12,731
Operating cost ($)	9,699	9,526	9,440
Fixed cost ($)	687	591	551
Total cost ($)	10,386	10,117	9,991
Returns ($)	2,345	2,614	2,740
Breakeven price ($/kg)	1.41	1.39	1.34
Breakeven yield (kg/ha)	6,730	6,556	6,475

the cost of piping and plumbing and an additional pumping cost. In some areas, it may be possible to construct ponds in such a way as to use gravity for irrigation, but in areas with level terrain, this additional pumping cost will be required. Experimental data have demonstrated no change in yield of catfish when water was removed for irrigation.

The wetland area needed is estimated by specifying that it treats 5% of the pond volume and equals 0.08 and 0.04 ha of wetland for each pond ha for surface and subsurface flow wetland systems, respectively. To establish the wetland system with the current land base, some land would have to be taken out of production to create the wetland areas. These estimates of constructed wetlands costs do not include any potential value from the wetland vegetation itself, but they take into account the opportunity cost of the land, represented by a lost income of $858/ha for rice production, the most likely alternative crop.

Using a paired-ponds treatment method requires removing one pond from catfish production for every pond remaining in production. The lost profits that would have resulted from such a system constitute a major cost for this alternative. However, this cost is partially offset by revenues from bighead carp production and the higher catfish stocking density of 17,637 fish/ha in the remaining catfish production ponds. The revenues from bighead carp may range from $919 to $1,226/ha (yield ranging from 1,323 to 1,764 kg/ha sold at a price of $1.37/kg). Studies have shown that there was no significant difference in catfish yield when bighead carp were stocked in catfish ponds at 1,174 bighead/ha. However, catfish consumed about 12% more feed in the filter-fed ponds paired with bighead ponds than in regular catfish ponds.

The fixed costs of construction and revenues generated from either the rice or bighead carp crops exceed other economic factors such as a change in the price of catfish. This implies that the results of this study are not likely to change even if the technologies have widely varying degrees of effluent removal efficiencies.

A linear programming model was developed to evaluate the economics of alternative effluent treatment methods. The linear program was modeled for the representative farm using the General Algebraic Modeling System (GAMS). Farm-level data were used to formulate the level of activities and constraints. Because of the number of activities defined in the model, the linear programming tableau is not presented. The objective function was assumed to maximize profits subject to technical as well as environmental constraints. Technical constraints included constraints on (a) labor availability, (b) feed requirements, (c) chemical requirements, (d) fingerlings purchased, (e) water usage, (f) fuel, oil, and lubrication requirements, (g) repair and maintenance, (h) marketing constraints attributed solely to off-flavor, and (i) constraints due to other production requirements. Environmental constraints were defined by levels of biochemical oxygen demand and ammonia used as indicators of water pollution. Different effluent discharge

Table 18. **Additional costs (dollars per kilogram of fish produced) under alternative treatments and additional production (kg/ha) required to break even.**

Item	Baseline	Constructed wetlands	Paired ponds	Rice irrigation
Cost ($/kg)	0	0.11	0.07	0
Yield (kg/ha)	0	646	371	0

standards, ranging from "no discharge" to "maximum allowable discharge," were simulated. Simulations were analyzed with standards of 0, 15, and 30 mg/L biochemical oxygen demand and 0, 1.5 and 3 mg/L total ammonia. The nominal tax to be paid was assumed to be $5.00/ppm. A sensitivity analysis was also conducted to account for variation in standards and tax rates.

The model incorporated two methods of internalization or externalization of an effluent discharge: (1) direct controls represented by set absolute standards and (2) indirect controls represented by taxes on effluent discharges. The costs associated with the use of crop irrigation, constructed wetlands, and filter-feeding treatments were included as factors influencing the decision to treat effluents or not and which method to use. Choice variables were included in alternative treatment methods to determine the most economically feasible and least expensive alternatives. Changes in activity levels in the linear programming solution between the unregulated farm and the regulated farm under effluents absolute standard and taxes provided a measure of policy effectiveness.

Results

The additional cost per kilogram of fish produced under the various alternatives studied are presented in Table 18. Under the assumption that no significant change occurred in production and yield of catfish, cost of production would increase by $0.07/kg in the paired-ponds treatment and $0.11/kg in the constructed wetlands treatment. Profit margins in catfish production (based on a 10-year average price) average $0.02 to $0.20/kg, depending on farm size; hence this additional production cost that would be incurred by utilizing these management options to treat effluents would make catfish production unprofitable at small farm sizes. Larger farms could better incur these costs and still remain profitable. No change in cost per kilogram of catfish was observed when pond water was used to irrigate rice because the additional revenue and reduced cost obtained from irrigating rice from catfish ponds offset the additional piping and pumping costs.

Results of the linear programming model are summarized in Table 19. The profit-maximizing combination for a catfish farm would be obtained with a

Table 19. Results of the linear programming model. The allowable discharge standard was set at 30 ppm BOD_5 and 3 mg/L total ammonia, and the tax rate was set at $5.00 per mg/L. Net returns do not include revenue from rice or carp, if any. Additional revenue does include revenue from rice and carp; additional rice revenues were estimated at $133/pond ha and carp revenues were estimated at $1072/ha.

Type of parameter selected by model	Unit	Effluent control measure: None	Allowable discharge standard	Tax
Effluent treatment option		None	Rice irrigation	Rice irrigation
Farm size	ha	260	130	130
Fingerling size	cm	18 - 20	18 - 20	18 - 20
Stocking rate	fish/ha	9,884	9,884	4,942
Harvest weight	kg	0.91	0.91	0.91
Net returns	$/ha	2,740	2,600	1,243
Additional revenue	$/ha	0	133	133

260-ha farm stocking 18-20 centimeter fingerlings at 9,884 fish/ha, with no effluent control or treatment measures. Estimated costs and returns for the selected farm situation producing 0.91-kilogram fish during a 200-day production period generated net returns to land, labor and management of $2,740/ha for a total of $712,400 (sales price of $1.54/kg).

Under the premise that environmental legislation would require a formal effluent treatment system, rice irrigation was the best (in economic terms) method for effluent treatment under both regulatory options of an allowable discharge standard and a tax on effluents. This can be attributed to the fact that the additional revenue from increased rice yield in the vicinity of the point of discharge offset the additional piping and pumping costs, resulting in no additional cost to the farm. The other effluent treatment options increased the cost of producing catfish.

Under a regulatory policy of setting an allowable discharge standard of 0 to 30 mg/L for biochemical oxygen demand and 0 to 3 mg/L for total ammonia-nitrogen, the most profitable farm size selected was the 130-ha farm. The 65-ha farm was never selected. For the selected 130-ha farm, catfish were stocked at 9,884 fish/ha. Net revenues averaged $2,600/ha for a total of $355,280, which includes $17,280 in additional income from increased rice production and sales. The selection of the 130-ha farm rather than the 260-ha farm may be attributable to total investment costs, even though the 260-ha unit should lower production cost per hectare.

When taxation was considered as a means of effluent control, at a basic tax rate of $5.00/ppm of effluent discharged, a 130-ha farm was selected. However, stocking rate was reduced to 4,942 18- to 20-cm catfish/ha, and net returns/ha decreased by 52%. The low stocking density is explained by the inverse relationship between stocking density and nutrient levels in effluent discharge. Farmers assumed to be risk neutral will stock fish at a lower rate to avoid the imposed tax by discharging a low amount of effluent.

Overall, the results suggested that a combination of tax and standard would provide the least punitive alternative to farmers. However, at a basic tax rate of $5.00 mg/L and a set standard of 30 mg/L of biochemical oxygen demand and 3 mg/L of total ammonia-nitrogen, linear programming results indicated no change in the selected representative farm than that of the case of a tax alone.

Imposition of allowable discharge standards and taxes to control effluent discharge decreased net revenues. While rice irrigation (the least-cost control option) did not increase production cost for a given farm size, the whole-farm linear programming analysis showed that both regulatory options resulted in selection of a smaller farm for the least-cost compliance. A byproduct of imposing discharge standards or taxes is to introduce factors encouraging smaller farm sizes, thereby increasing production cost. Taxes further provide an incentive to reduce stocking densities, which would add an additional barrier to entry for new farmers. New farmers have heavy debt burdens from high levels of capital investment and need to stock fish at high rates to meet debt servicing requirements. Taxes that induce economic forces that reduce fish stocking rates favor established farmers who have little or no debt service. Reduced farm size and stocking rates reduce the quantity of fish produced, thereby exacerbating the short supplies of catfish, and may result in increased prices to consumers.

Conclusions

This study showed that effluent treatment with rice irrigation, constructed wetlands, or a paired-ponds system increased costs by $0.00 to $0.11/kg for catfish production. Rice irrigation was the treatment technology that most often was selected. Rice revenues and benefits to the rice from pond water offset the additional cost and was the profit-maximizing alternative under most scenarios. Constructed wetlands were never selected as a profitable option due to high investment and maintenance costs. Investment tax credits or other incentives would be required for constructed wetlands to become an economically feasible treatment alternative. Effluent standards and tax charges appear to be effective means of internalizing fish pond effluent discharge. However, some concerns must be raised. Large farms will do the best job at internalizing the costs of treating effluent. Small farms not only have restricted access to capital, but also are not efficient enough to adopt new technologies to reduce effluent discharge.

However, small farms may not produce levels of effluent discharge harmful to the environment. All policies to control effluent discharge reduced net farm revenues. Even rice irrigation, that showed no increase in cost of production for a given farm size, resulted in selecting a smaller farm size that increased production cost per kilogram of fish due to economies of scale. Imposing control options will create additional barriers to entry for new potential catfish farmers, particularly small-scale (less than 130-ha) farms. Imposing effluent controls has an impact on farm size and stocking density. Because effluent standards or tax charges affect farmers, policy makers would be well advised to account for the impact of proposed effluent reduction policy on the welfare of fish farmers. While this study was limited to analyzing a few technologies currently available for effluent management in aquaculture, a wide range of options should be studied and the impact assessed. Furthermore, it would be advisable to consider farm-level decision-making for farmers who are risk averse. To minimize unintended adverse impacts, policy makers should ensure that adequate research data, both biological and economic, are available to represent the breadth of aquaculture production systems and receiving streams before enacting regulations.

Recommendations for Managing Aquaculture Pond Effluents

The results of this project suggest that the impact of aquaculture pond effluents on the environment can be reduced by using relatively simple management practices. Some of these practices require labor and expense to implement, and may not be applicable to all culture situations. However, some of the practices examined in this project and discussed below are logical extensions of good overall farm management or are simple solutions that do not require extra expense or labor. All aquaculturists should strive to reduce the impact of their activities on the environment to the greatest extent possible. The following recommendations should help achieve that goal.

- **Use high quality feeds and efficient feeding practices.** Feeds are the origin of all pollutants in catfish pond effluents. The use of a high quality feed improves feed conversion efficiency and reduces amounts of metabolic waste and uneaten feed. Efficient feeding practices that reduce waste will reduce feed inputs and improve feed conversion ratios. Inefficient feed conversion results in poorer quality effluents because the feed not converted into fish flesh enters the pond as waste.
- **Provide adequate aeration and circulation of pond water.** Maintenance of dissolved oxygen concentrations above 4 or 5 mg/L enhances the appetite of fish and encourages good feed conversion ratios. Circulation prevents stratification and enhances degradation of organic matter in pond bottoms. An evenly oxygenated pond will oxidize organic matter rapidly. Oxidation of organic matter within the pond diminishes the amount of organic matter in effluents.
- **Minimize water exchange.** Water exchange can be used to reduce high concentrations of ammonia or other toxic substances if large volumes of pond water are exchanged at once. However, the displaced pond water represents a pollution load in receiving waters, and heavy water exchange should not be used unless absolutely necessary. Furthermore, the effectiveness of water exchange as a water quality management procedure in large commercial aquaculture ponds is questionable. Because incoming water is greatly diluted when added to large ponds, it is unlikely that sufficient water can be exchanged in a short enough period of time to have a beneficial effect during acute water quality crises. Also, research has shown that routine water exchange at low rates (several pond water exchanges over the growing season) has little or no effect on pond water quality and should not be used.
- **Operate ponds for several years without draining.** This is a common practice of catfish farmers in the southeastern United States, and research conducted as part of this project showed that it was possible to maintain adequate water quality for good fish production for at least 3 years in undrained ponds harvested each year by seining. Reuse of water for multiple crops also reduces the need for pumped water to refill ponds. After several years, catfish ponds must be drained to repair levees and for fish inventory adjustment. When it is necessary to drain ponds, the last 10 to 20% of water in the pond can be held for 2 or 3 days before final release to significantly reduce amounts of pollutants through sedimentation.
- **Capture rainfall to reduce pond overflow.** Maintaining storage volume by keeping the pond water level 7 to 9 cm (2 to 3 inches) below the level of the drain greatly reduces the volume of water discharged from ponds during rainfall events. Capturing rainfall in this manner also reduces the need for pumped water to maintain pond water levels.
- **Allow solids to settle before discharging water.** In ponds that are partially drained to facilitate fish harvest, minimize seining activity during harvest to avoid resuspension of sediments. After seining, hold the water in the pond for 2 to 3 days to allow solids to settle before draining completely. An even better method is to not discharge this last portion of water. Holding water for 2 days after seining can greatly reduce the discharge of nutrients, solids and organic matter.

- **Reuse water that is drained from ponds.** Instead of draining ponds for fish harvest, water can be pumped to adjacent ponds and then reused in the same or other ponds. Production ponds can be built with higher levees or water levels maintained with more free board to provide storage volume. Water from one pond can be transferred to another with a low-lift pump and then transferred back by siphon.

- **Optimize watershed areas.** Watershed ponds should not have watershed areas larger than necessary to keep ponds full, because excessively large watersheds increase runoff into ponds and result in high discharge. Runoff from watersheds may be partially diverted from ponds by terracing or other means.

- **Treat effluents by using constructed wetlands.** Constructed wetlands are very efficient in removing potential pollutants from pond water providing that at least a 2-day hydraulic retention time is used. Because wetlands function best with emergent, reed swamp plants such as bulrushes and cattails, the maximum depth for a wetland should be about 50 cm (20 inches), and can be created by constructing a dike 60 cm (2 feet) high around the area in which the water will be impounded. Common cattails and bulrushes can be gathered from the wild and planted in wetlands. The wetland should be large enough to provide a 2- to 4-day retention time for influent water. Wetlands should be downslope from ponds, so water can flow by gravity from ponds into the wetland. The USDA Soil Conservation Service can provide advice on designing and constructing wetlands. Because of the large land requirement for constructed wetlands, treating only the most concentrated effluents in the final stages of draining would minimize the amount of land needed for constructed wetlands and significantly improve the quality of those effluents.

- **Use effluents to irrigate terrestrial crops.** Under certain conditions, the water discharged from ponds may have value as irrigation water for agronomic crops. Routine overflow from ponds cannot be relied upon for irrigation water because crop water requirements will be highest when pond overflow volumes are lowest. Also, pumping water through a pond solely to provide irrigation water should not be practiced because water is lost to evaporation while the water is in the pond and the nutrient content of water from aquaculture ponds is probably too low to significantly reduce the crop's fertilizer requirements. However, if water must be pumped through a pond for some purpose, such as to improve water quality conditions within the pond, then further use of the effluent as irrigation water will provide multiple benefits to the farm and will reduce the overall volume of water discharged to the environment.

Publications and Presentations

The following publications and presentations were developed as part of this Southern Regional Aquaculture Center project:

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