JOURNAL OF THE
WORLD AQUACULTURE SOCIETY

Vol. 43, No. 4
August, 2012

Approximate Water and Chemical Budgets for an Experimental, In-pond Raceway System

Travis W. Brown[2], Claude E. Boyd[1], and Jesse A. Chappell

Department of Fisheries and Allied Aquacultures, Auburn University, Alabama 36849, USA

Abstract

There is increasing interest in intensive production of Ictalurid catfish in the United States and a better understanding of water quality dynamics in intensive culture is needed. Budgets for water, nitrogen, and phosphorus were estimated over a production season (March–November) for an In-pond Raceway System for channel catfish, *Ictalurus punctatus*, and hybrid catfish, *I. punctatus* × *I. furcatus*, with co-culture of paddlefish, *Polyodon spathula*, and Nile tilapia, *Oreochromis niloticus*. In addition to the rainfall and runoff, 70 cm of water was applied from a well to offset evaporation and seepage. Production of each kilogram of live catfish required 1.50 kg of feed and released 51.7 g nitrogen and 9.7 g phosphorus. Harvest of catfish accounted for 34.0% of nitrogen and 37.1% of phosphorus applied in feed. Seepage and overflow removed only small portions of nitrogen and phosphorus, while denitrification and ammonia volatilization removed large amounts of nitrogen. Some nitrogen accumulated in sediment. Phosphorus was harvested in fish and absorbed by pond sediment. Mechanical aeration aided in maintaining appropriate dissolved oxygen levels for fish production.

The future development of aquaculture may be limited by resources, such as land, water, and fish meal (Naylor et al. 2000; Westers 2000). Environmental pollution – mainly eutrophication from nitrogen and phosphorus in effluents from aquaculture facilities – also can limit the growth of aquaculture and negatively impact natural ecosystems (Hakanson et al. 1998; Lemarie et al. 1998). Integrated pond systems, similar to recirculating aquaculture systems, utilize management practices that allow natural processes to partially recycle or assimilate nutrients that would normally be lost in effluent. These practices focus on nutrient reduction through immobilization in bacterial biomass, volatilization to the atmosphere, and conversion into harvestable products (Schneider et al. 2005). The use of these practices reduces waste discharge to the environment which can be an issue in public waters. It also fosters more efficient use of resources as compared with open raceways, cage culture, and ponds that are drained on a regular basis.

Catfish farming is the leading form of aquaculture in the USA with over 231,215 m.t. of food-sized channel catfish produced in 2008 (USDA/NASS 2009). Most catfish are cultured in levee-type ponds filled mainly from wells or watershed ponds supplied primarily by runoff. A traditional pond has production of 4500–5500 kg/ha/yr (Brune 1991; USDA 2006), but maximum annual production rates may exceed 10,000 kg/ha/yr on some farms.

Development of more efficient production methods for catfish has been of interest in the USA since the 1960s (Schmittou 1969). Cages, raceways, and tanks were originally utilized to intensify culture practices (Schmittou 1969; Andrews et al. 1971; Hill et al. 1974). Masser (2004) reported that the concept of floating raceways can be traced back to the early 1920s, while most of the research was performed during the 1970s (Brown et al. 1971; Fremont 1972; Hill et al. 1974, USEPA 1974; Fast 1977) and 1990s (Long 1990, Fast 1991; Hawcroft 1994; Masser and Duarte 1994; Bernardez 1995; Masser 1995; Wilcox 1998).

Recent studies have demonstrated new production methodologies that utilize high rate

[1] Corresponding author.

[2] Present address: United States Department of Agriculture, Agriculture Research Service, Thad Cochran National Warmwater Aquaculture Center, Post Office Box 38, Stoneville, Mississippi 38776, USA

photosynthetic systems such as the partitioned aquaculture system (Brune et al. 2004a; 2004b), split-pond system (Tucker and Kingsburg 2010), and In-pond Raceway System (IPRS) (Brown et al. 2011). These systems are believed to be more controllable and efficient at producing catfish than traditional pond methods, because they combine a number of biological, chemical, and physical intensification practices into a single, integrated system.

Chemical and nutrient budgets can accurately account for sources and fates of nutrients entering ecosystems and improve understanding of nutrient use. Green (1993) reported fertilizers and feeds are generally the largest source of nitrogen and phosphorus inputs into fish ponds, albeit ponds also receive nutrients from rainfall, surface runoff, and regulated water inflow.

Nutrient budgets for traditional channel catfish ponds have been calculated (Boyd 1985a; Gross et al. 2000); however, minimal knowledge is available for integrated pond production systems (Krom and Neori 1989; Drapcho and Brune 1999; Yi et al. 2003; Brune et al. 2003; Schneider et al. 2005; Nhan et al. 2006). This study reports concentrations of various water quality variables and provides a water budget and nutrient budgets of an IPRS for the production of catfish over an 8-mo period.

Materials and Methods

An intensive, IPRS was constructed in a traditional 2.43-ha earthen pond of 1.67 m average depth supplied by well water and watershed runoff in west Alabama (Fig. 1). The IPRS consisted of six, individual raceways that shared common walls and were attached to a permanent concrete foundation (overall length, width, and height: 30.48 × 13.72 × 1.42 m). Fish were confined in culture units by end partition barriers that spanned the width (4.88 m) of each raceway unit. Water flow into raceways was aided by a paddle wheel which rotated at 1.2 rpm; water was exchanged in each raceway unit once every 4.9 min. Water flowed from raceway units into the north side of the pond, moved counterclockwise to the south side of the pond, and returned to the inflow side of the raceways.

A 1.12-kW, regenerative blower with diffuser grid (airlift type aerator) was operated when dissolved oxygen (DO) concentration fell below 3.0 mg/L in raceway units. In addition, a 7.46-kW, paddle-wheel aerator was installed near the water inflow channel, and it was operated when the blower system could not maintain appropriate DO concentrations for fish production. Standard oxygen transfer rates were determined as described by Boyd and Tucker

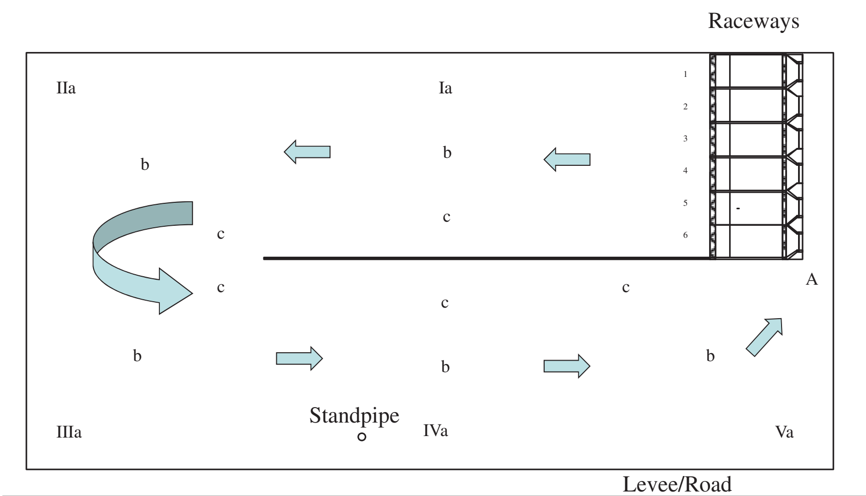

FIGURE 1. *Aerial view of the In-pond Raceway System displaying various water quality and pond mud samples sites with arrows indicating direction of water flow (all sample sites are associated with Table 1).*

(1998) for the paddle-wheel aerator and airlift type aerator.

Fingerling channel catfish, *Ictalurus punctatus*, and hybrid catfish, *I. punctatus* × *I. furcatus*, were obtained from commercial suppliers (Eagle Aquaculture, Indianola, MS and Need More Fisheries, Glen Allan, MS, USA). Once inventory and acclimation of fingerlings were complete, fish (59.1–418.2 g each) were stocked separately into raceways on March 13 and 18, 2008, at densities of 12,000–30,000 fish per raceway. The grow-out phase was conducted for 96–250 d depending on size of fish initially stocked. Fish were hand fed a commercial, floating feed (32% protein and 3.53% lipid; Alabama Feed Mill, Uniontown, AL, USA) 2–4 times per day based on biomass, water temperature, and fish size. Catfish were harvested throughout the study as they reached marketable size. Feed conversion ratios (FCRs) for each cohort of fish were calculated by dividing the amount of feed consumed by amount of weight gained.

The open pond part of the system was stocked with paddlefish, *Polyodon spathula*, having an average individual weight of 328 g at a rate of 288/ha, while Nile tilapia, *Oreochromis niloticus*, brood fish with an average weight of 232 g were sexed and stocked in the pond at a rate of 12 breeding pairs/ha.

A Class A evaporation pan and standard rain gauge were placed on a foundation 50-m from the IPRS. The evaporation pan was filled with well water, and water levels in the pan were measured with a hook gauge. Pond evaporation was estimated as 0.81 times pan evaporation (Boyd 1985b). Measurements of rainfall, evaporation, and pond water level were measured daily between 0600 and 0700 h. Storm runoff (overland flow) into the pond was estimated by the curve number technique of the U.S. Soil Conservation Service (1972).

A staff gauge installed in the IPRS allowed water level measurements to the nearest 0.3 cm. Pond water levels were maintained approximately 10 cm below the standpipe. This practice allowed storage capacity to avoid overflow after most rain events, and pond overflow occurred only once for a 3-d period during tropical storm Fay (August 25–27, 2008). The total amount of overflow was estimated according to Boyd (1982).

A water budget for the IPRS was made by aid of the hydrologic equation:

$$\text{Inflow} = \text{Outflow} \pm \Delta S \qquad (1)$$

where Inflow = rainfall, runoff, and well water; Outflow = evaporation, seepage, and overflow; and ΔS = change in storage during the period of measurement (Yoo and Boyd 1994). Seepage was determined by adding the difference of all inflows and outflows to the change in storage. All regulated water inflow was timed and calculated utilizing the coordinate method for a horizontal pipe (Yoo and Boyd 1994).

The water quality monitoring program is described in Figure 1 and Table 1. Samples for laboratory analyses were collected with a 90-cm water column sampler (Boyd and Tucker 1992). Most water quality variables followed protocol described in Standard Methods for Analysis of Water and Wastewater (Eaton et al. 2005): total alkalinity (acidimetry); chloride (mercuric sulfate method); total hardness (ethylenediaminetetraacetic acid titration); chlorophyll *a* (membrane filtration, acetone–methanol extraction, and spectroscopy); soluble reactive phosphorus (SRP; ascorbic acid procedure); total ammonia nitrogen (TAN; Nesslerization); nitrite nitrogen (diazotization). Total nitrogen (TN) and total phosphorus (TP) were determined by spectroscopy following digestion in potassium persulfate solution (Gross and Boyd 1998); chemical oxygen demand (COD) – through sulfuric acid–potassium dichromate digestion (Boyd 2000). Total suspended solids (TSS) through filtration and measure weight (Boyd and Tucker 1992). Water samples were also collected when well water was applied as makeup water and when overflow occurred.

Dark bottles prepared from 300-mL biochemical oxygen demand (BOD) bottles were filled with pond water and incubated weekly for 4–8 h between 0600 and 1400 h at 50-cm water depth (Table 1). Concentrations of DO in bottles were measured with a polarographic

TABLE 1. *Water quality variables, sample location(s), frequencies, and methods of analysis for an In-pond Raceway System in Browns, Alabama (all sample locations are associated with Figure 1).*

Variable	Sample location(s)	Frequency	Method of analysis
Dissolved oxygen	A, 1-6	2×/d	Polarographic DO/conductivity meter
Temperature	A, 1-6	2×/d	Polarographic DO/conductivity meter
pH	A, 1-6	2×/d	Digital pH meter
Total alkalinity	A	Weekly	Sulfuric acid titration
Total hardness	A	Start & finish	EDTA titration
Chloride	A	Weekly	Mercuric sulfate titration
Secchi disk visibility	A	3×/week	Measurement of Secchi disk depth
Chlorophyll *a*	A	Weekly	Acetone–methanol extraction
Soluble reactive phosphorus	A	Weekly	Filterable orthophosphate (ascorbic acid procedure)
Total ammonia nitrogen	A, 1-6, I-V	Weekly	Nesslerization
Nitrite nitrogen	A, 1-6, I-V	Weekly	Diazotization
Total nitrogen	A, standpipe, well	4×	Persulfate digestion
Total phosphorus	A, standpipe, well	4×	Persulfate digestion
Chemical oxygen demand	A, standpipe, well	4×	Sulfuric acid–potassium dichromate digestion
Total suspended solids	A, standpipe, well	4×	Filtration and measured weight
Respiration	I-V	Weekly	Dark bottle technique (DO difference from time 1 and time 2)

DO = dissolved oxygen; EDTA = ethylenediaminetetraacetic acid.

DO meter (Yellow Springs Instrument Company Model 57, Yellow Springs, OH, USA) and BOD bottle probe before and after incubation. Water samples were reaerated with a small, diaphragm air pump and aquarium air stone if DO dropped below 5.0 mg/L. Community respiration was estimated from the decreases in DO in dark bottles and was converted to a daily basis by multiplying measured values by the factor 24 h of incubation (Boyd 2000).

Sediment samples were collected with a 5-cm diameter, polycarbonate tube from the upper 15-cm stratum of the pond bottom at 15 locations (Fig. 1; Locations Ia-Vc) throughout the pond on March 13, 2008, and on November 18, 2008. The flocculent layer was measured to the nearest mm (Munsiri et al. 1995). Cores were oven dried at 70 C and pulverized to pass a 0.25-mm screen. The samples were shipped to Brookside Laboratories, Inc., New Knoxville, OH, USA, where they were analyzed for TN (combustion) and TP (persulfate digestion).

Nine samples of feed were retained for chemical analysis. Each feed sample was oven dried at 70 C and pulverized to pass a 0.85-mm screen. A sample of four whole fish (small and large) was taken from each cohort of fish at stocking and harvest. Catfish samples were placed in an autoclave at 120 C at a pressure of 1.4 kg/cm^2 for 1 h. The fish was then homogenized using a hand mixer, and a 40–60 g sample was removed and oven dried at 70 C until a constant mass was achieved for two consecutive days (Glover et al. 2010). Samples were shipped to the New Jersey Feed Laboratory, Inc. (Trenton, NJ, USA), where they were analyzed for TN and TP by combustion and persulfate digestion, respectively (AOAC Methods 990.03 and 985.01). Ash content was analyzed by combustion (600 C) and organic matter was estimated by difference. Paddlefish and tilapia were considered to contain approximately 25% dry matter, and the dry matter to be 9.7% nitrogen and 3.3% phosphorus (Davis and Boyd 1978; Boyd and Green 1998).

The mass balance approach was used to allow inputs and outputs of nitrogen and phosphorus:

$$F_{in} + R + Q_{in} = S_f + Q_{out} + A + F_{out} \pm \Delta S \quad (2)$$

where F_{in} = fish stocked; R = feed; Q_{in} = inflow; S_f = final amount in pond water;

Q_{out} = outflow; A = sediment absorption and accumulation; F_{out} = fish harvested; and ΔS = change in the amount in pond water between starting and ending date. Quantities of fish, feed, and water were multiplied by their respective concentrations of chemical substances to calculate amounts of substances added to or removed from the IPRS. Rainfall was considered to be saturated with DO, and the concentrations of other substances in rainwater were taken from (NADP 2008). Seepage could not be collected and was considered to be devoid of DO but identical to pond water in concentrations of other substances. Runoff was assumed to have the same composition as rainfall, because it had minimal contact time with the surrounding grass cover, soil, and levees before entering the pond.

Statistical analyses were performed using SAS (version 9.3, SAS Institute, Cary, NC, USA). Data from pond mud samples were analyzed using a paired t-test to determine if significant differences existed ($P \leq 0.05$).

Results and Discussion

Aeration was applied an average of 4 h/d throughout the study with an airlift pump and a paddle-wheel aerator and standard oxygen transfer rates were determined to be 2.87 kg O_2/h and 12.96 kg O_2/h, respectively. The majority of the aeration was applied when feed rates were elevated. The survival of fish at night when DO concentration was lowest depended heavily on DO provided by mechanical aeration. Maintaining optimal DO levels for fish production reduces the chances of stress or mortality and improves production efficiency (Tucker and Robinson 1990).

Catfish and paddlefish survival was 83.7 and 85.9%, respectively. Tilapia survival was not calculated as males and females continued to spawn throughout the production season (i.e., a greater number of fish at harvest as compared with the start of the study). Channel catfish grown under single-batch conditions in traditional ponds at different densities had mean survival rates ranging from 67 to 83% (Southworth et al. 2006a). Southworth et al. (2006b) showed that channel catfish grown under multiple-batch conditions in traditional ponds had mean survival rates ranging from 24 to 36% and 77 to 94% for fingerlings and carryover fish, respectively. Survival rates of 54.4–83.6% (Hawcroft 1994), 67.5–81.4% (Bernardez 1995), 58.9% (Martin 1997), and 85.6% (Wilcox 1998) have been observed for catfish in, in-pond floating raceways. Masser and Lazur (1997) have observed catfish survival as high as 98% for in-pond raceways under research conditions.

Rainfall during the 250-d period totaled 66.1 cm (Fig. 2). August received the greatest

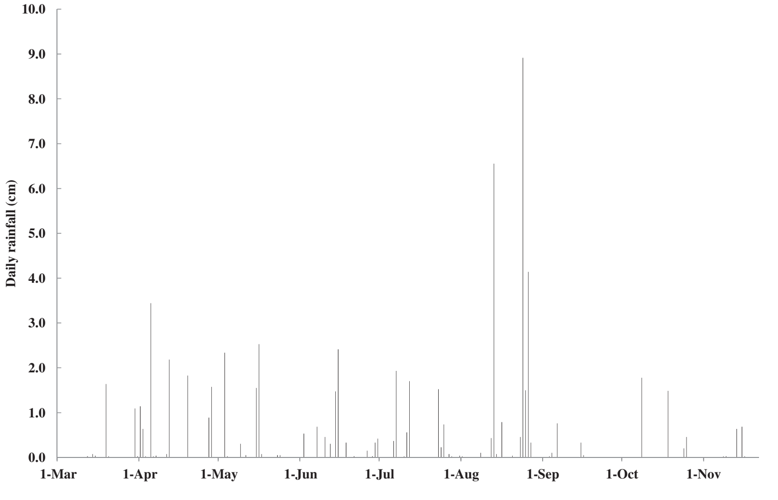

FIGURE 2. *Distribution of rainfall during the production season of an In-pond Raceway System in Browns, Alabama.*

TABLE 2. *Average water budget for an In-pond Raceway System on a catfish farm in Browns, Alabama, from March 13 to November 18, 2008. All quantities are in centimeters of depth.*

Variable	March	April	May	June	July	August	September	October	November	Total
Rainfall	2.9	11.9	7.0	7.2	7.2	23.4	1.3	3.9	1.4	66.1
Runoff	0.5	3.5	1.8	1.0	0.9	25.4	0.0	0.5	0.0	33.7
Well water	2.0	8.4	12.8	14.8	9.4	9.3	6.7	6.8	0.0	70.1
Evaporation	8.0	11.4	15.3	18.2	18.3	17.2	13.6	10.1	4.5	116.7
Seepage out	1.1	4.1	5.0	9.6	0.6	3.5	5.1	3.2	1.1	33.4
Overflow	0.0	0.0	0.0	0.0	0.0	26.1	0.0	0.0	0.0	26.1
ΔS	−3.7	8.2	1.2	−4.9	−1.4	11.3	−10.7	−2.2	−4.3	−6.3

rainfall, accounting for over 35.4% of total precipitation. Mean rainfall per event was 0.87 cm. Daily pond evaporation was 0.46 cm, while total pond evaporation during this study was 116.7 cm (Table 2).

Estimated storm runoff from the watershed for the production season was 21.4 cm (Table 2), but it accounted for merely 33.7 cm of pond depth, because watershed area was only 1.58 times greater than pond surface area. Estimates of pond seepage varied widely: 0.02–0.32 cm/d (0.55–9.65 cm/mo). Nevertheless, estimated seepage for the entire study period, 33.4 cm, is thought to be fairly reliable. In comparison with ponds in general (Boyd 2009), the seepage rate is very low, because the heavy clay soils in the Blackland Prairie region allow construction of ponds that resist seepage (Yoo and Boyd 1994).

The average water budget for the pond of the IPRS is reliable, because total gains were 169.9 cm and total losses were 176.2 cm (Table 2), and only 6.3 cm of water loss were unaccounted. Rain and regulated inflow accounted for 38.9 and 41.3% of gains, respectively, with the majority of the water coming from the well. Evaporation resulted in 66.2% of the total water loss; seepage, and overflow accounted for the remaining water loss. In contrast to this study, evaporation and seepage from small ponds in the Piedmont Plateau region near Auburn, Alabama, accounted for 31 and 61% of water losses, while rain and regulated inflow accounted for 24 and 75% of respective gains (Boyd 1982). Ponds at Auburn in the Piedmont Plateau region seep much more than ponds in the Blackland Prairie (Yoo and Boyd 1994).

DO (6.38 ± 3.62 mg/L), water temperature (25.15 ± 5.12 C), pH (7.74 ± 0.48), total alkalinity (164.6 ±16.4 mg/L), total hardness (140.1 ± 8.6 mg/L), and chloride (705.3 ± 75.6 mg/L) remained within acceptable ranges for catfish production throughout the study. The relatively high alkalinity provided buffering capacity to minimize daily changes in pH in response to photosynthesis and respiration, and the high chloride concentration protected fish against toxicity from a sudden spike in nitrite concentration (Boyd and Tucker 1998).

Secchi disk visibility averaged 23.7 ± 5.1 cm with minimum and maximum values of 13.5 and 42.0 cm, respectively (Fig. 3), while chlorophyll *a* concentration averaged 274 ± 179 µg/L with a peak value of 949 µg/L in May, and a minimal value of 49.07 µg/L in March (Fig. 3). Yi et al. (2003) observed mean chlorophyll *a* concentrations of 44, 72, and 132 µg/L in a nonintegrated system and in integrated pen-cum-pond systems with either natural or artificial water circulation, respectively. Southworth et al. (2006a) found that with increased stocking density and feeding rates, concentrations of chlorophyll *a* increased to about 181 ± 147 µg/L at densities of 34,600 catfish/ha. SRP averaged 0.086 ± 0.071 mg/L with minimum and maximum concentrations of 0.007 and 0.257 mg/L, respectively (Fig. 3). This is within the range of 0.0–0.93 mg/L that Yi et al. (2003) observed for the culture of catfish and tilapia.

TAN concentration averaged 1.45 ± 1.16 mg/L and reached a maximum concentration of 4.69 mg/L in September. The minimum level was 0.089 mg/L in May (Fig. 3). Nitrite nitrogen (nitrite-N) averaged 0.17 ±

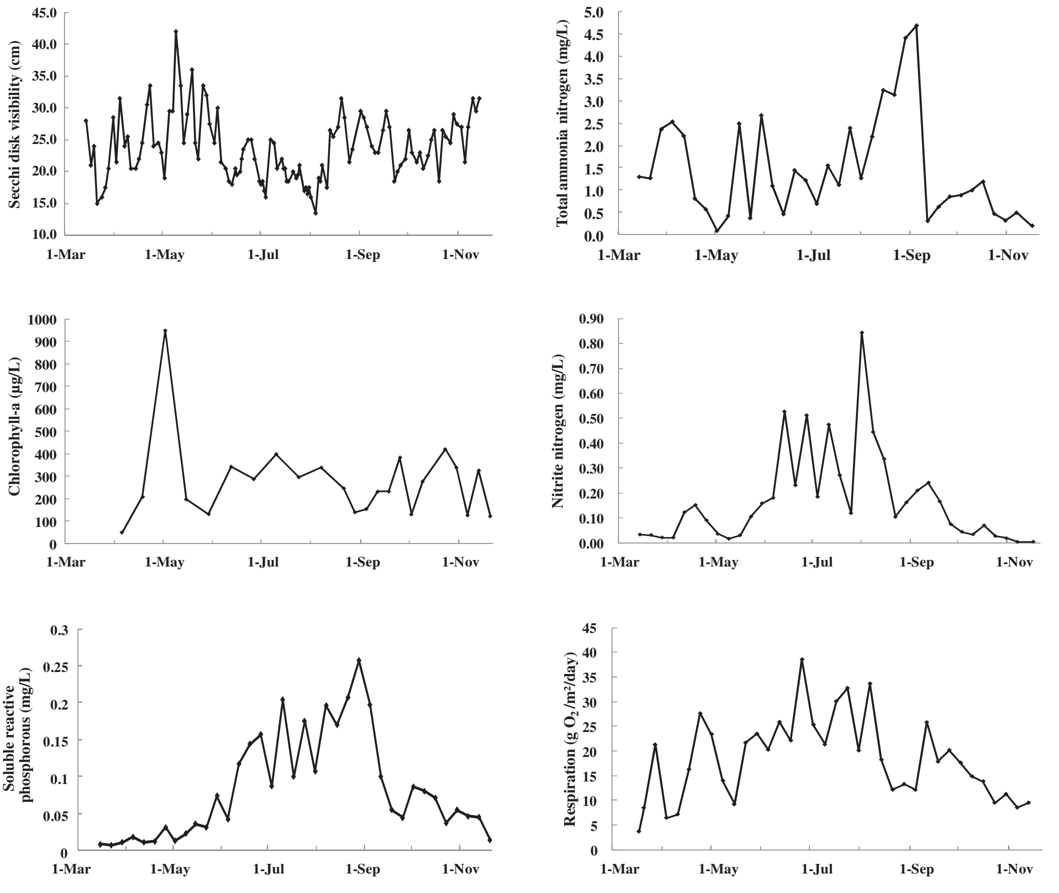

FIGURE 3. *Observed Secchi disk visibility, chlorophyll a concentrations, soluble reactive phosphorus concentrations, total ammonia nitrogen concentrations, nitrite nitrogen concentrations, and respiration (as oxygen) within the pond of an In-pond Raceway System in Browns, Alabama.*

0.19 mg/L with a minimal concentration of 0.004 mg/L in November and a maximum concentration of 0.84 mg/L in August (Fig. 3). Concentrations of TAN and nitrite-N remained within acceptable levels for catfish production. Yi et al. (2003) observed levels of 3.09–4.13 mg/L TAN and 0.01–0.02 mg/L nitrite-N with catfish and tilapia, while Southworth et al. (2006a) recorded values of 0.211 ± 0.165 to 0.750 ± 0.922 mg/L and 0.005 ± 0.001 to 0.144 ± 0.162 mg/L for TAN and nitrite-N, respectively, for channel catfish culture.

Respiration by planktonic communities and associated bacteria in the pond water was high averaging 18.3 g O_2/m^2/d and ranging from 3.7 g O_2/m^2/d in March to 38.6 g O_2/m^2/d in June (Fig. 3). Phytoplankton typically comprise the majority of the suspended, microscopic biomass in catfish ponds (Boyd 1985a) and thereby are responsible for most of the water column respiration. Dead plankton and other organic matter that settle to the bottom also is the organic carbon source for benthic respiration.

Concentrations of TN, TP, COD, and TSS in water applied from the well were low compared with pond water (Table 3). The concentrations of TN, TP, COD, and TSS in pond water were usually at moderate concentrations. This agrees with the assessment by Boyd (1985a) that concentrations of pollution in aquaculture ponds are not as high as expected from feed input, because nitrogen is rapidly lost through denitrification and ammonia volatilization and

TABLE 3. *Mean concentrations of total nitrogen, total phosphorus, chemical oxygen demand (COD – an estimate of organic matter), and total suspended solids collected from the initial pond water, added well water, stand pipe overflow, and final pond water from an In-pond Raceway System in Browns, Alabama.*

Water quality variable	Initial (pond)	Well	Overflow	Final (pond)
Total nitrogen (mg/L)	3.19	0.53	7.38	2.18
Total phosphorus (mg/L)	0.18	0.10	0.75	0.18
COD (mg/L)	45.12	0.00	58.08	37.75
Total suspended solids (mg/L)	70.15	0.00	64.90	43.25

phosphorus is absorbed by the pond mud. Concentrations of TN, COD, and TSS in the pond decreased over time, but TP concentrations remained relatively unchanged during the study. Considerable amounts of nutrients and organic matter were flushed from the pond during tropical storm Fay. Boyd (1985a) observed an increase in concentrations of TN, TP, and COD over time in small earthen ponds at Auburn, Alabama, while Daniels and Boyd (1989) observed that concentrations of these variables remained relatively low over the production season in polyethylene-lined, brackish water ponds for the production of striped bass, *Morone saxatilis*. Green and Boyd (1995) reported a steady increase in TN, TP, and COD over time in organically fertilized fish ponds in Honduras. In natural and artificial, water-circulated environments, significantly lower levels of TN and TP were observed in pond effluents as compared with a nonintegrated treatment (Yi et al. 2003). This supports the hypothesis that tilapia can efficiently recover nutrients contained in the wastewater of an intensive catfish culture system and suggests that continuous water circulation can reduce nutrient concentrations in pond effluents.

There were significant increases ($P < 0.05$) in concentrations of TN and TP in sediment between March and November 2008 (Table 4). The increase in sediment nitrogen during the study was 310.2 kg. Phosphorus concentrations increased in pond sediment during the study by 251.5 kg. Other studies have shown that pond sediment and water-logged agricultural soils have a strong affinity for phosphorus (Rigler 1964; Sanyal and De Datta 1991; Masuda and Boyd 1994), and Boyd (1985a) found that phosphorus loss from pond waters resulted mainly from adsorption by pond mud.

TABLE 4. *Average composition and standard deviations for sediment samples collected from the pond housing the In-pond Raceway System in Browns, Alabama.*

	% of air-dried weight	
Date	Nitrogen (%)	Phosphorus (%)
March	0.20 ± 0.09	0.10 ± 0.04
November	0.26 ± 0.10	0.12 ± 0.02

The quantities of feed and fish added to the raceways of the IPRS, amounts of fish harvested, and composition of fish and feed are presented in Table 5. The FCR of 1.50 in the IPRS indicated good feed use efficiency. The lowest FCRs usually reported in channel catfish research are 1.3–1.4 (Boyd 1985a; Gross et al. 2000), but commercial producers often obtain FCRs of 2.0 or more.

Each kilogram of live catfish required 1.50 kg of feed, and released into the water column 51.7 g nitrogen and 9.7 g phosphorus. Harvest of catfish removed 34.0% of added nitrogen and 37.1% of added phosphorus applied to the system in feed (Table 6). The additional harvest of paddlefish and tilapia increased removal to 40.0% of added nitrogen and 47.5% of added phosphorus. Boyd (1985a) reported that 26.8% of nitrogen and 30.1% of phosphorus applied to traditional channel catfish ponds in feed were removed in fish at harvest. In striped bass ponds with low feeding rates, fish harvest accounted for 22.2% of nitrogen and 56.7% of phosphorus applied in feed (Daniels and Boyd 1989). Harvest of tilapia from ponds in the dry tropics accounted for 19.5% nitrogen and 17.0% phosphorus added in feed (Green and Boyd 1995). Hybrid catfish incorporated 40.7% nitrogen and 49.0% phosphorus from the feed input in both nonintegrated and natural and artificial

TABLE 5. *Average weights of channel and hybrid catfish stocked, feed applied, and fish harvested, and data on the composition of fish and feed from an In-pond Raceway System (IPRS). The pond of the IPRS was 2.43 ha in surface area. Values represent average and standard deviations.*

Item	Feed	Small fish	Large fish
Quantity added (kg)	47,000	18,506	
Quantity harvested (kg)			49,913
Dry matter (%)	90.7 ± 0.30	27.6 ± 1.69	29.2 ± 2.75
Nitrogen (% of dry weight)	5.77 ± 0.06	8.89 ± 0.46	8.85 ± 0.79
Phosphorus (% of dry weight)	1.14 ± 0.05	2.15 ± 0.34	1.99 ± 0.14

TABLE 6. *Average gains and losses (kg) for nitrogen and phosphorus from an In-pond Raceway System in Browns, Alabama.*

Item	Nitrogen	Phosphorus
Gains		
Fish stocked (catfish)	454.1	109.8
Fish stocked (paddlefish)	5.6	1.9
Fish stocked (tilapia)	0.3	0.1
Feed	2459.7	486.0
Nitrogen fixation	?	
Inflow from well	9.5	1.9
Rainfall	3.7	0.0
Runoff	1.9	0.0
Total	2934.8	599.7
Losses		
Fish harvested (catfish)	1289.9	290.0
Fish harvested (paddlefish)	58.3	19.9
Fish harvested (tilapia)	96.0	32.8
Overflow	50.8	5.2
Seepage	2.9	0.3
Denitrification and diffusion of ammonia	1126.7	
Sediment absorption and accumulation	310.2	251.5
Total	2934.8	599.7

water circulation treatments, respectively (Yi et al. 2003). Green and Boyd (1995) found that fish harvest accounts for a larger percentage of added nutrients in ponds when they received concentrated feeds as compared with ponds that received organic fertilizers.

The primary source of nitrogen was from fish feed which was 83.8% of the measured nitrogen input (Table 6). Nitrogen fixation was assumed to be nil, because higher concentrations of combined nitrogen in channel catfish ponds should suppress biological nitrogen fixation (Boyd and Tucker 1998). Fish harvest was the greatest measured loss of nitrogen, but ammonia volatilization and denitrification were a close second accounting for 38.4% of nitrogen loss (Table 6). The amount of phosphorus added in feed greatly exceeded the quantities removed in effluent and harvested fish (Table 6).

On a dry weight basis, 42,629 kg of feed resulted in 9467 kg of fish – an actual feed conversion of 4.50. The difference between dry feed and dry fish (33,162 kg) represents chemical substances contained in uneaten feed, feces, and metabolic wastes. Catfish in raceways consumed nearly all the feed offered, because they were confined in a small area and easily visible. Feed barriers reduced the chance of feed floating out of the tail end of the raceways, and a negligible quantity of uneaten feed settled to the pond bottom. Despite the low FCR (1.50), considerable amounts of metabolites were released into the water column by fish. Each kilogram of dry substance in feed produced 0.22 kg of dry fish and yielded 0.78 kg dry metabolic wastes.

Conclusions

This study demonstrates that Ictalurid catfish were successfully cultured in an IPRS with co-culture of paddlefish and Nile tilapia in the outside pond. Paddlefish and tilapia recycle nutrients in wastes that would normally be only partially assimilated by the pond ecosystem thereby lessening the nutrient load discharged into receiving waters. This study also provides information useful to the development of integrated, intensive and semi-intensive culture systems for both small- and large-scale production. Obviously, fish survival affects the amount of nutrients recovered at harvest. Poor fish survival would increase the amount of nutrients lost to the ecosystem and decrease the recovery of those nutrients as whole fish. To maximize production efficiency and nutrient utilization mortalities must be minimized in this system.

By using an IPRS, the in-pond raceways can be used to produce the primary species (catfish), and the rest of the pond to produce co-cultured species such as paddlefish and tilapia. This favors more efficient utilization of feed through recycling wastes to filter-feeding species. Optimization of the catfish to paddlefish to tilapia ratio (catfish production in raceways : pond area), and length of the culture period would maximize efficiency, enhance nutrient utilization efficiency, minimize environmental impacts of effluents, and increase profit potential.

Acknowledgments

This research was supported by the Alabama Catfish Producers, Dean Wilson Farms, the Alabama Agriculture Experiment Station, and the Alabama Cooperative Extension System. The assistance of Dr. Luke A. Roy with fish sampling was gratefully appreciated. Thanks also are extended to the Alabama Fish Farming Center for providing laboratory and office space. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

Literature Cited

Andrews, J. W., L. H. Knight, J. W. Page, Y. Matsuda, and E. E. Brown. 1971. Interactions of stocking density and water turnover on growth and food conversion of channel catfish reared in intensively stocked tanks. Progressive Fish-Culturist 33:197–203.

Bernardez, R. G. 1995. Evaluation of an in-pond raceway system and its economic feasibility for fish production. Master's thesis. Auburn University, Auburn, Alabama, USA.

Boyd, C. E. 1982. Hydrology of small experimental fish ponds at Auburn, Alabama. Transactions of the American Fisheries Society 111:638–644.

Boyd, C. E. 1985a. Chemical budgets for channel catfish ponds. Transactions of the American Fisheries Society 114:291–298.

Boyd, C. E. 1985b. Pond evaporation. Transactions of the American Fisheries Society 114:299–303.

Boyd, C. E. 2000. Water quality: an introduction. Kluwer Academic Publishers, Norwell, Massachusetts, USA.

Boyd, C. E. 2009. Assessing, reducing pond seepage. Pages 62–63 *in* D. Jory, editor. The global aquaculture advocate. Global Aquaculture Alliance, St. Louis, Missouri, USA.

Boyd, C. E. and B. W. Green. 1998. Dry matter, ash, and elemental composition of pond-cultured tilapia *Oreochromis aureus* and *O. niloticus*. Journal of the World Aquaculture Society 29:125–128.

Boyd, C. E. and C. S. Tucker. 1992. Water quality and pond soil analysis for aquaculture. Alabama Agriculture Experiment Station, Auburn, Alabama, USA.

Boyd, C. E. and C. S. Tucker. 1998. Pond aquaculture water quality management. Kluwer Academic Publishers, Norwell, Massachusetts, USA.

Brown, E. E., J. L. Chesness, and S. R. Chapman. 1971. Raceway and pond economics. Producing and marketing catfish in the Tennessee Valley. Tennessee Valley Authority, Tennessee, USA.

Brown, T. W., J. A. Chappell, and C. E. Boyd. 2011. A commercial-scale, in-pond raceway system for *ictalurid* catfish production. Aquacultural Engineering 44:72–79.

Brune, D. E. 1991. Engineering aspects of intensive aquaculture. Pages. 118–130 *in* M. B. Timmons, editor. Pond aquaculture. Natural Resources, Agriculture, and Engineering Service Publication NRAES-49, Natural Resources, Agriculture, and Engineering Service, New York, New York, USA.

Brune, D. E., G. Schwartz, A. G. Eversole, J. A. Collier, and T. E. Schwedler. 2003. Intensification of pond aquaculture and high rate photosynthetic systems. Aquaculture Engineering 28:65–86.

Brune, D. E., G. Schwartz, A. G. Eversole, J. A. Collier, and T. E. Schwedler. 2004a. Partitioned aquaculture systems. Pages 561–584 *in* C. S. Tucker and J. A. Hargreaves, editors. Biology and culture of channel catfish. Elsevier, New York, New York, USA.

Brune, D. E., G. Schwartz, A. G. Eversole, J. A. Collier, and T. E. Schwedler. 2004b. Partitioned aquaculture systems. SRAC Publication No. 4500.

Daniels, H. V. and C. E. Boyd. 1989. Chemical budgets of polyethlene-lined, Brackishwater Ponds. Journal of the World Aquaculture Society 20:53–59.

Davis, J. A. and C. E. Boyd. 1978. Concentrations of selected elements and Ash in Bluegill (*Lepomis macrochirus*) and certain other freshwater fish. Transactions of the American Fisheries Society 107:862–867.

Drapcho, C. M. and D. E. Brune. 1999. The partitioned aquaculture system: impact of design and environmental parameters on algal productivity and photosynthetic oxygen production. Aquacultural Engineering 21:151–168.

Eaton, A. D., L. S. Clesceri, E. W. Rice, and A. E. Greenberg. 2005. Standard methods for the examination of water and wastewater, 21st edition. American Public Health Association, Washington, D.C., USA.

Fast, A. W. 1977. Floating fish rearing system. U.S. Patent No. 4,044,720.

Fast, A. W. 1991. A floating fish cage with solid plastic membrane and pumped water exchange. Journal of Applied Aquaculture 1:99–110.

Fremont, H. J. 1972. Floating fish growing tank. U.S. Patent No. 3,653,358.

Glover, D. C., D. R. DeVries, R. A. Wright, and D. A. Davis. 2010. Sample preparation techniques for determination of fish energy density via bomb calorimetry: an evaluation using largemouth bass. Transactions of the American Fisheries Society 139: 671–675.

Green, B. W. 1993. Water and chemical budgets for organically fertilized fish ponds in the dry tropics. PhD dissertation. Auburn University, Auburn, Alabama, USA.

Green, B. W. and C. E. Boyd. 1995. Chemical budgets for organically fertilized fish ponds in the dry tropics. Journal of the World Aquaculture Society 26:284–296.

Gross, A. and C. E. Boyd. 1998. A digestion procedure for the simultaneous determination of total nitrogen and total phosphorus in pond water. Journal of the World Aquaculture Society 29:300–303.

Gross, A., C. E. Boyd, and C. W. Wood. 2000. Nitrogen transformations and balances in channel catfish ponds. Aquacultural Engineering 24:1–14.

Hakanson, L., L. Carlsson, and T. Johansson. 1998. A new approach to calculate the phosphorus load to lakes from fish farm emissions. Aquacultural Engineering 17:149–166.

Hawcroft, B. A. 1994. Development and evaluation of an in-pond raceway and waste removal system. Master's thesis. Auburn University, Auburn, Alabama, USA.

Hill, T. K., J. L. Chesness, and E. E. Brown. 1974. Growing channel catfish, *Ictalurus punctatus*, in raceways. Proceedings of the Annual Conference Southeastern Association of Game and Fish Commissioners 28:488–499.

Krom, M. D. and A. Neori. 1989. A total nutrient budget for an experimental intensive fish pond with circularly moving seawater. Aquaculture 83:345–358.

Lemarie, G., J. L. M. Martin, G. Dutto, and C. Garidou. 1998. Nitrogenous and phosphorous waste production in a flow-through land-based farm of European seabass (Dicentrarchus labrax). Aquatic Living Resources 11:247–254.

Long, C. E. 1990. Raceway culturing of fish. U.S. Patent No. 4,915,059.

Martin, J. 1997. Effluent control of an in-pond raceway system. Master's thesis. Auburn University, Auburn, Alabama, USA.

Masser, M. P. 1995. Intensive catfish systems. World Aquaculture 26:60–64.

Masser, M. P., and A. Lazur. 1997. In-pond raceways. Southern Regional Aquaculture Center (SRAC), Publication No. 170. Mississippi State University, Stoneville, Mississippi, USA.

Masser, M. 2004. Cages and in-pond raceways. Pages 530–544 *in* C. S. Tucker and J. A. Hargreaves, editors. Biology and culture of channel catfish. Elsevier, New York, New York, USA.

Masser, M. P., and S. Duarte. 1994. The Alabama piedmont catfish cage farming industry. World Aquaculture 25:26–29.

Masuda, K. and C. E. Boyd. 1994. Effects of aeration, alum treatment, liming and organic matter application on phosphorous exchange between pond soil and water in aquaculture ponds at Auburn, Alabama. Journal of the World Aquaculture Society 25:405–416.

Munsiri, P., C. E. Boyd, and B. J. Hajek. 1995. Physical and chemical characteristics of bottom soil profiles in ponds at Auburn, Alabama, and a proposed method for describing pond soil horizons. Journal of the World Aquaculture Society 26:346–377.

NADP data report precipitation chemistry. 2008. Blackbelt Research and Extension Center, Auburn University, Selma, Alabama, USA.

Naylor, R. L., R. J. Goldburg, J. H. Primavera, N. Kautsky, M. C. M. Beveridge, J. Clay, C. Folke, J. Lubchenco, H. Mooney, and M. Troell. 2000. Effect of aquaculture on world fish supplies. Nature 405:1017–1024.

Nhan, D. K., A. Milstein, M. C. J. Verdegem, and J. A. V. Verreth. 2006. Food inputs, water quality and nutrient accumulation in integrated ponds systems: a multivariate approach. Aquaculture 261:160–173.

Rigler, F. H. 1964. The phosphorous fractions and the turnover time of inorganic phosphorous in different types of lakes. Limnology and Oceanography 9:511–518.

Sanyal, S. K. and S. K. De Datta. 1991. Chemistry of phosphorous transformations in soils. Advances in soil science 16:1–20.

Schmittou, H. R. 1969. Intensive culture of channel catfish, *Ictalurus punctatus* (Rafinesque), in cages suspended in ponds. PhD dissertation. Auburn University, Auburn, Alabama, USA.

Schneider, O., V. Sereti, E. H. Eding, and J. A. J. Verreth. 2005. Analysis of nutrient flows in integrated intensive aquaculture systems. Aquacultural Engineering 32:379–401.

Southworth, B. E., N. Stone, and C. R. Engle. 2006a. Production characteristics, water quality, and costs of producing channel catfish *Ictalurus punctatus* at different stocking densities in single-batch production. Journal of the World Aquaculture Society 37:21–31.

Southworth, B. E., C. R. Engle, N. Stone. 2006b. Effect of multiple-batch catfish, *Ictalurus punctatus*, stocking density and feeding rate on water quality, production characteristics, and costs. Journal of the World Aquaculture Society 37:452–463.

Tucker, C. S. and S. Kingsburg. 2010. High-Density Split-Pond Systems Offer High Output, Low Maintenance. Global Aquaculture Advocate 13:64–54.

Tucker, C. S. and E. H. Robinson. 1990. Channel catfish farming handbook. Van Nostrand Reinhold, New York, New York, USA.

United States Department of Agriculture (USDA). 2006. 2005 Census of Agriculture. Washington, D.C., USA.

United States Department of Agriculture/National Agricultural Statistics Service USDA/NASS). 2009. Production and Inventory of Channel Catfish. Washington, D.C., USA.

United States Environmental Protection Agency (USEPA). 1974. Pollution aspects of catfish production-review and projection. EPA, Report 660/2-74-064. Washington, D.C., USA.

U.S. Soil Conservation Service. 1972. Hydrology. In SCS national engineering handbook, Sec. 4, SCS: Washington, D.C., USA.

Westers, H. 2000. A fourteen-year dispute about phosphorous effluent contribution and its impact on Platte Lake. Recirculating Aquaculture, Roanoke, Virginia, USA.

Wilcox, M. D. 1998. Effects of an in-pond raceway on fish production performance and water quality. Master's thesis. Auburn University, Auburn, Alabama, USA.

Yi, Y., C. K. Lin, and J. S. Diana. 2003. Hybrid catfish (*Clarias macrocephalus* × *C. gariepinus*) and Nile tilapia (*Oreochromis niloticus*) culture in an integrated pen-cum-pond system: growth performance and nutrient budgets. Aquaculture 217:395–408.

Yoo, K. H. and C. E. Boyd. 1994. Hydrology and water supply for pond aquaculture. Chapman & Hall, New York, New York, USA.