Effluents from an Aquaculture Research Station and Stream Water Quality

by

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Abstract

Lower Station of the E. W. Shell Fisheries Center discharges into Saugahatchee Creek. Ponds of the Fish Genetics Research Unit and the Aquaculture Production Research Unit are the main sources of anthropogenic pollution to Lower Station Creek. However, the Fish Genetics Research Unit effluent enters the stream above the water supply reservoir (FP-11). Natural, biological and physiochemical processes in FP-11 improve water quality, and outflow from FP-11 is of superior quality to water in Lower Station Creek upstream of the Fish Genetics Research Unit. Thus, the main source of pollution to Lower Station Creek is discharge from the Aquaculture Production Research Unit.

Concentrations of total nitrogen, total phosphorus, chloride, total alkalinity, total hardness, specific conductance, total suspended solids, turbidity, and biochemical oxygen demand increase between the outflow of FP-11 and the entrance of Lower Station Creek into Saugahatchee Creek. The major increases in concentrations of the variables tend to occur during fall and early winter when ponds of the Aquaculture Production Research Unit are drained for harvest. The highest concentrations of potential pollutants are discharged in the final stages of draining a pond for harvest. Effluents from ponds at different stages of drawdown are combined in the common drains tending to mash the concentration peaks at the outfalls of the common drains. Because a large portion of the pollution is discharged during pond draining, measures to reduce overflow from ponds during the rest of the culture period do not have a large effect on annual pollution loads.

Water quality at the mouth of Lower Station Creek is better than water quality in Saugahatchee Creek. Thus, discharge from the Lower Station does not contribute to further water quality degradation in the already-polluted Saugahatchee Creek. Discharge of Lower Station Creek has higher concentrations of several possible pollutants than typically found in less-polluted streams, but only total suspended solids and turbidity exceeded concentration limits typically imposed on effluents discharged into Alabama streams classified for fish and wildlife propagation.

The Lower Station produces over 45,454 harvest kilograms of fish annually and discharges 30 days or more per year. According to the U.S. Environmental Protection Agency rules, it is a concentrated aquatic animal production (CAAP) facility and qualifies for National Pollutant Discharge Elimination System (NPDES) permitting. In Alabama, NPDES permits for effluents from CAAP (aquaculture) facilities apparently will require implementation of best management practices (BMPs). The only practical means of removing suspended solids and turbidity from the discharge of the Aquaculture Production Research Unit would be retention for at least 24 hours in a sedimentation basin before final discharge.

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List of Abbreviations

ACP	Alabama Catfish Producers
ADEM	Alabama Department of Environmental Management
BMPs	Best Management Practices
BOD_5	5-day biological oxygen demand
CAAP	Concentrated aquatic animal production
ELGs	Effluent limitations guidelines
FCR	Feed conversion ratio
NPDES	National Pollutant Discharge Elimination System
NRCS	Natural Resources Conservation Service
U.S.EPA	The United States Environmental Protection Agency

CHAPTER 1

INTRODUCTION

The United States Environmental Protection Agency (U.S.EPA) recently developed an effluent rule for the US aquaculture industry (Federal Register 2004). This rule defined a concentrated aquatic animal production (CAAP) facility and stated that CAAP facilities must obtain National Pollutant Discharge Elimination System (NPDES) permits. However, U.S.EPA did not establish effluent limitations guidelines (ELGs) for effluents from CAAP facilities.

A warm water CAAP facility is defined as a pond, raceway, or other system that produces at least 44,454 kg (100,000 lb) of harvest biomass per year. Ponds or other open systems that discharge less than 30 days per year except for excess runoff are excluded from the NPDES permit requirement. However, U.S.EPA chose not to define excess runoff (Boyd et al. 2008).

Implementation and enforcement of the U.S.EPA aquaculture effluent rule is delegated to the individual states. States must be as strict as the U.S.EPA rule, but they may be stricter if they desire. For example, the U.S.EPA rule does not include ELGs for pond effluents, but it recommends use of best management practices (BMPs). Individual states could require ELGs and mandate BMPs, but in Alabama, compliance with the U.S.EPA effluent rule likely will be based on voluntary adoption of BMPs by farmers (Boyd and Hulcher 2001).

Considerations of aquaculture effluents and their possible impacts on receiving water bodies have focused on commercial production facilities (Tucker and Hargreaves 2008). For example, C. E. Boyd and his graduate students have collaborated with the Alabama Department of Environmental Management (ADEM), the Natural Resources Conservation Service (NRCS), and the Alabama Catfish Producers (ACP) to conduct several studies of channel catfish farm effluents and to develop BMPs for reducing the volume and improving the quality of these effluents (Boyd et al. 2002). However, these studies have not considered the influence of discharge from the E. W. Shell Fisheries Center (the place where much of the research on channel catfish culture in Alabama is conducted) on water quality in the receiving streams.

One of the main purposes of aquaculture research stations is to develop information for use by the private sector. Aquaculture is under increasing scrutiny related to environmental regulations. In order to provide a model for the private industry, efforts should be made to estimate pollution loads and environmental impacts of effluents from aquaculture research stations. Moreover, methods for reducing pollution loads also should be installed at research stations. It is particularly important for aquaculture research facilities such as the E. W. Shell Fisheries Center to demonstrate compliance with U.S.EPA effluent regulations.

The primary objective of this study was to evaluate the influence of effluents from the E. W. Shell Fisheries Center at Auburn University on water quality in receiving streams. Secondary objectives were: (1) to determine production level and enumerate discharge days and ascertain whether or not the station is a CAAP facility; (2) to measure water quality of effluents during pond draining for harvest; (3) to compare two methods of pond-water level management with respect to overflow discharge volume; (4) to discuss measures for improving effluent quality. The findings of this study should be useful to the staff on the E. W. Shell Fisheries Center in future efforts to comply with U.S.EPA regulations and to promote environmentally-responsible aquaculture in Alabama.

CHAPTER 2

LITERATURE REVIEW

US commercial catfish farming began in the 1960s. The commercial production of catfish grew rapidly from its inception to approximately 594 million pounds for a market value of $446 million in 2000. Catfish production increased to 662 million pounds in 2003, but the market value dropped to $384 million (National Agricultural Statistics Service 2009). Because of the rising price of fish feed and fuel, competition from fish imported from Asia, US catfish production has continued to decline and in 2008, production was only 513 million pounds. However, prices improved slightly and the farm-gate value was $421 million in 2008 (Anonymous 2009). The area remaining in production in 2008 was 112 thousand acres (National Agricultural Statistics Service 2009). Despite these obstacles, catfish remains the major aquaculture species in the US. It accounts for 68% of total, US aquaculture production (National Oceanic and Atmosphere Administration 2009).

Because of higher demands for food and limitations in natural food resources, we continually seek better strategies for food production. As with the green revolution in agriculture, there is a blue revolution in aquaculture. In the blue revolution, technology and research over the past four decades has improved aquaculture production. In 2006, world aquaculture production was about 51.7 million tonnes, and almost 15 times greater than 1970 production of 3.6 million tons (FAO 2009; Asche et al. 2009).

Trends in modern aquaculture are shifting more toward intensive aquaculture. Feed, aeration, fertilizer, and chemical substances help farmers overcome limitations in natural aquaculture productivity and improve both quantity and quality of aquaculture production. On the other hand, the increasing intensity of production has caused a large impact on the environment. Environmental impacts resulting from aquaculture include:

- Destruction of mangrove and wetlands
- Excessive use of chemicals
- Inefficient utilization of fish meal
- Salinization of land
- Excessive use of water
- Spread of aquatic animal disease
- Reduction of biodiversity
- Conflicts with other resource users
- Water pollution

Of the above listed environmental impacts, water pollution is the most common concern for most nations (Boyd and Gautier 2000; Boyd and Tucker 2000).

Catfish Farm Management Inputs

Most of the catfish farms in Alabama have watershed ponds that are supplied by rainfall and runoff or embankment ponds which are supplied by well water (Boyd and Tucker 1998). Water is seldom drained from catfish ponds, and fish are harvested by seining (Boyd et al. 2000). Catfish farming activities that affect water quality are liming, fertilization, feeding, mechanical aeration, and miscellaneous chemical treatment.

Liming

Liming usually is practiced in ponds that have alkalinity lower than 20 mg/L or pH less than 7.0. The purpose of liming is to neutralize soil acidity and increase both total alkalinity and total hardness which will help increase pond productivity and fish production (Boyd and Tucker 1998). Catfish farmers use approximately 1,000-2,000 kg/ha of agriculture limestone for ponds that have less than 20 mg/L total alkalinity. Hydrated lime is sometimes applied at 50 to 100 kg/ha to remove excessive carbon dioxide from pond waters (Boyd et al. 2000).

Fertilization

Chemical and organic fertilizers increase availability of natural food and control underwater weeds. Chemical fertilizers are substances that contain nitrogen, phosphorus, and potassium compounds (Boyd and Tucker 1998). Fertilizers used in channel catfish ponds include urea, ammonium nitrate, ammonium phosphate, and triple superphosphate. Nitrogen fertilizers also help to compose organic matter with a wide C: N ratio (Boyd and Tucker 1998). Organic fertilizers such as chicken litter and other animal manure are sometimes used in place of chemical fertilizers, but catfish farmers seldom use organic fertilizers.

Feeding

Ambient food in ponds is not enough to sustain high fish densities. Normally, catfish at high stocking densities are provided a 28% to 32% crude protein floating pellet. Suggested feeding rate is 3% of the fish weight per day. Most farmers feed catfish once a day from blower-equipped, truck-mounted hoppers. Usually, 8,000-16,000 kg of feed will be applied annually per hectare of pond surface (Silapajarn 2004). Besides wasting money, feeding fish more than they will eat can degrade water quality and cause disease (Boyd et al. 2000). By-products of fish metabolism that may degrade water quality are carbon dioxide, ammonia, and nitrite.

Feed conversion ratio (FCR) of commercial catfish farms were approximately 2.0-2.4, while FCR of research ponds are usually in the range of 1.2-1.6. The reasons for lower FCR in research ponds are less stocking rate and better feeding management which result in improved water quality (Boyd and Tucker 1998).

Mechanical aeration

Part of the feed applied to catfish ponds is uneaten, and some of it is expelled as feces. This organic waste decomposes to release carbon dioxide, ammonia, and phosphate into the water and stimulate phytoplankton productivity. Fish absorb much of the nutrients in feed. However, only a relatively small amount, 8-12% of carbon and 20-30% of nitrogen and phosphorus, of the nutrients are incorporated in fish biomass that is harvested (Boyd and Tucker 1998).

Oxidation of uneaten feed, feces, ammonia, and dead phytoplankton consume a lot of fissolved oxygen. This is especially true at night because ponds have dense blooms of phytoplankton (eutrophic conditions), and the respiration of these organisms often cause nighttime dissolved oxygen concentration to fall drastically. Thus, catfish ponds require mechanical aeration (Boyd et al. 2000). Aeration is applied mostly in summer because of high plankton density and rapid degradation of organic matter. Aerators are operated whenever dissolved oxygen falls below 2 or 3 mg/L. Low oxygen events that may warrant the use of aerators usually occur at night during cloudy weather and after phytoplankton died-offs (Boyd et al. 2002). There are several kinds of aerators in the US catfish industry. Some popular models of aerators are tractor-powered paddle wheels, floating electric paddlewheel aerators, and diffused-air aeration systems. Aerator-generated water currents erode pond earthwork and stir up sediment from the bottom to increase turbidity in the water (Boyd 1998).

Miscellaneous chemical treatments

Sodium chloride (NaCl) is used on channel catfish farms to help fish acclimate during stocking and also to prevent brown blood disease caused by high nitrite concentration. Nitrite combines with hemoglobin to form methemoglobin that is not effective in transporting oxygen. The combination of low dissolved oxygen and high nitrite can be extremely detrimental to fish. However, chloride interferes with nitrite uptake by fish and by increasing the chloride concentration to 50 to 100 mg/L, nitrite toxicity can be avoided (Boyd and Tucker 1998). Oxytetracycline, formalin, potassium permanganate, and malachite green, are used to treat fish diseases (Plumb 1979; Gordon et al. 2007). Copper sulfate is used to control blue green algae that are common in catfish ponds and can cause off-flavor in catfish (Tucker 1996). Total use of copper sulfate in catfish ponds is about 3-4 mg/L annually (Boyd et al. 2000). Chemicals used for disease control in catfish farming tend to be degraded by natural processes in ponds. For example, Silapajarn (2004) observed that concentrations of copper were no higher in a stream receiving the discharge from about 5,000 ha of catfish ponds than in control streams without catfish ponds in their catchments.

Catfish Pond Effluents

There are numerous publications on the subject of catfish pond effluents. These studies were mostly conducted over short periods of time and in experimental ponds (Tucker 1998). It is difficult to draw conclusions from these studies because the quality of catfish pond effluents varies with location, season, farm management practice, amounts of overflow after rains, and amounts of water drained during harvest.

Draining effluent discharged during harvest has a greater potential for causing pollution than overflow from ponds after rains (Boyd 1978; Schwartz and Boyd 1994a). Effluents that are released last during pond harvest are most concentrated in pollutants because of resuspension of sediment by seining efforts. Water samples from three catfish ponds were collected during draining and analyzed (Tucker 1998). The results were: 0.1-0.5 mg/L for total ammonia nitrogen; 0.002-0.007 mg/L for nitrite-nitrogen, 0.36-0.64 mg/L for nitrate-nitrogen; <5.01 mg/L for total Kjeldahl nitrogen; 0.001-0.16 mg/L for soluble reactive phosphorus; 0.15-1.3 mg/L for total phosphorus; 10-296 mg/L for 5-day biochemical oxygen demand; 0-60 mg/L for total settleable solids.

Overflow effluents in Alabama normally occur after rains in winter or early spring when catfish ponds have low concentrations of nutrients and high dissolved oxygen, and when streams also have high flow. Thus, the impact of catfish farm overflow effluents on natural streams is low. In summer when pond waters have high algal abundance and elevated concentrations of potential pollutants in response to high feed input, ponds seldom overflow after rainfall events (Boyd and Tucker 1998; Boyd et al. 2008). Composition of overflow after rains is similar to that of pond water (Tucker 1998). Water samples from 25 catfish ponds were collected and analyzed during winter through fall 1991 (Schwartz and Boyd 1994b). The results were: 0.01-7.71 mg/L for total ammonia-nitrogen; 0.58-14.04 mg/L for total nitrogen; 0.001-1.37 mg/L for nitrite-nitrogen; 0.18-16.8 mg/L for nitrate-nitrogen; 0.001-0.017 mg/L for soluble reactive phosphorus; 0.05-1.48 mg/L for total phosphorus; 1.28-35.54 mg/L for 5-day biochemical oxygen demand; 0-1.80 mg/L for total settleable solids; 0.7-329 mg/L for total suspended solids; 9-16.8 mg/L for dissolved oxygen; 6.0-9.3 for pH.

The primary sources of nutrients in pond water are uneaten feed, feces, fertilizer, and metabolic excretions. About 70% of the nitrogen and phosphorus from feed and fertilizer in aquaculture are left in pond water and can potentially be discharged to the environment (Boyd and Tucker 1998).

Erosion of embankments, pond bottoms, and discharge ditches are the main sources of suspended solids in catfish pond effluents (Boyd et al. 2000). Suspended solids create turbidity in water, and turbidity is likely to exceed concentrations typically allowed in effluent discharge permits (Ozbay 2002). Catfish farms in Alabama were placed on former row crop land. Compared with cotton, soybeans, and other crops, catfish ponds discharge similar loads of suspended solids per hectare. The conversion from cultivated land to catfish farms would not be expected to increase the input of suspended solids in streams (Boyd et al. 2000)

The quality of catfish pond effluents is usually better than quality of the effluents from municipal and industrial effluents (Tucker 1998). Two studies, Boyd (1978) and Tucker and Lloyd (1985), found that catfish pond water had worse water quality than stream waters into which they discharged. Boyd et al. (2000) found no differences between upstream water quality and downstream water quality in eight streams receiving catfish farm effluents in Alabama. Catfish pond effluents had a small but significant impact on water quality in Big Prairie Creek that receives the discharge of about 50% of catfish farms in Alabama (Silapajarn 2004).

Silapajarn stated in her study that water quality of downstream Big Prairie Creek did not exceed stream classification standards despite the fact that catfish farms discharged nutrients, chloride, and organic matter into it.

Catfish ponds usually have high dissolved oxygen concentration because of rapid rates of phytoplankton photosynthesis during daytime and extremely low dissolved oxygen concentration at night is avoided by aeration. Catfish pond effluents actually may increase dissolved oxygen levels in natural streams (Boyd et al. 2000).

Sodium chloride treatment to prevent nitrite toxicity can increase salinity, and hydrated lime used to remove carbon dioxide can increase pH. However, at concentrations of these two substances used in catfish ponds, no adverse effects on receiving water bodies were noted (Boyd et al. 2000).

Chemicals for disease treatment and algae control should be used for a short period of time and applied as recommended on product labels to avoid fish mortality and assure food safety. Toxic chemicals usually are not present in aquaculture effluents (Tucker 1998). Copper sulfate, which is widely used to control blue green algae and off-flavor in catfish ponds, disappears quickly from the water column and is sequestered in pond sediment (Masuda and Boyd 1993; Boyd et al. 2000). Within 72 hours after applying copper sulfate, concentrations in pond water usually have returned to pre-treatment levels.

Regulations and Guidelines for Aquaculture Effluents

Several countries have strict effluent regulations (Tucker and Hargreaves 2008). These effluent regulations often contain concentration, volume, and load restrictions for pond effluents. However, some countries enforce these regulations, but others do not. Besides the regulations, there are many guidelines for aquaculture effluents that producers may voluntarily adopt. An example of these may be found on the Aquaculture Certification Council website (aquaculturecertification.org). The worldwide concern about negative effects of aquaculture effluents has caused many aquaculture producers to follow these guidelines.

Aquaculture has been growing rapidly in the US, but until recently there was no national effluent regulation for aquaculture. Some states had their own regulations, but these states did not have large aquaculture industries (Boyd 2003). U.S.EPA announced its intent to establish effluent regulations for aquaculture as far back as 1976 (Boyd 1978). However, other industries were considered more important as polluters, and U.S.EPA delayed action on the aquaculture industry. In 1997, Environmental Defense lobbied U.S.EPA to make an effluent regulation for aquaculture. After that, in 2000, U.S.EPA responded and started the process by consulting with aquaculture producers, environmental advocacy groups, and aquaculture researchers (Kreeger 2000). The draft effluent regulations for aquaculture were developed in June 2002 (Lutz et al. 2003). Finally, U.S.EPA released the national effluent guideline for aquaculture in June 2004 (U.S.EPA 2004a). However, this regulation does not apply to every aquaculture facility. National effluent guidelines for aquaculture only apply to CAAP facilities which are the facilities that produce more than 9,090 kilograms of cold water fish or produce more than 45,454 harvest kilograms of warm water fish and discharge more than 30 days a year. This regulation requires only CAAP facilities to obtain a National Pollutant Discharge Elimination System (NPDES) permit and follow the rules which simply are best management practices for aquaculture. It did not contain effluent limitation guidelines. Implementation and enforcement are the authority of individual states (U.S.EPA 20004b). The US aquaculture effluent regulation could be a boom to environment management worldwide because it likely will serve as a guideline for government effluent regulations in developing countries. Many developing countries have more aquaculture and use more intensive production methods than the US (Boyd 2003).

Research for Reducing Impacts from Effluents

Much research has been conducted in order to find possible and efficient ways to improve the quality of aquaculture effluents. Examples of aquaculture effluent improvement include: aeration and circulation, reuse of water for irrigation (integrated system), reuse of water for multiple fish crops, natural filtration (grass strips and construction wetlands), and sedimentation basins (Tucker and Hargreaves 2008).

A high dissolved oxygen concentration is an indicator of good water quality. Oxygen is necessary for aquatic animals, and it also is essential for bacteria to completely oxidize organic matter and ammonia-nitrogen. The presence of oxygen prevents anaerobic conditions that can cause toxic concentrations of nitrite, sulfite, and other metabolites (Boyd and Tucker 1998). Aeration and circulation promote oxygen in water, and some aquaculture facilities use aerators in water treatment reservoirs to increase effectiveness of waste treatment (Boyd 2001).

Reuse of water for irrigation (integrated system) is another way to remove nitrogen and phosphorus from effluents and reclaim them for agricultural production. Lin and Yi (2003) concluded that rice crops removed 32% total nitrogen and 24% total phosphorus from catfish effluents. However, it was not clear whether the catfish effluents increased the production of crops. Tucker (1998) stated that nitrogen and phosphorus concentrations in catfish effluents are too low to increase crop production, but Meso et al. (2004) reported that effluents from polyculture of tilapia and African catfish which contained 6.03 mg/L nitrogen and 3.89 mg/L phosphorus increased production of French beans significantly from 4,300 kg/ha in normal canal irrigation to 7,700 kg/ ha in aquaculture effluent irrigation.

Few catfish producers harvest fish every year by draining all water from the pond. After seining, the pond is refilled for the next crop year. Tucker (1998) demonstrated that it is not necessary to drain ponds and refill them every year to maintain good water quality and satisfactory levels of fish production. The research showed that water quality in ponds that were drained every year was only slightly different from that in ponds that were not drained for 3 years. Moreover, there was no difference in fish production between ponds that were drained every year and in ponds that were harvested by seining without draining. Reusing water for multiple fish crops is possible because natural processes in the pond remove potential pollution from the water. For example, organic matter is degraded by bacteria, ammonia is oxidized to nitrate by denitrifying bacteria, nitrate is denitrified by certain anaerobic bacteria in sediment, and phosphorus is absorbed by sediment (Boyd and Tucker 1998).

Plants such as common and coastal Bermuda, Dallis grass and Bahia grass are recommended for grass strips for filtering effluents from aquaculture ponds. Effluents were applied as overland flow across the grass surfaces. Bahia grass filter strips can reduce concentrations of suspended solids as much as 62%, BOD as much as 34%, and nitrogen as much as 22%. Effluents, after being treated by grass filter strips, may be reused for fish crops or released to natural waters (Ghate et al. 1997).

Catfish effluents also can be treated by constructing wetlands and sedimentation basins (Boyd et al. 2000; Sonnenholzner et al. 1997). Constructed wetlands improve water quality through several processes. Wetland plants absorb nutrients from the water and convert them to plant biomass. The roots and detritus from dead wetland plants serve as a biological filter that has both aerobic zones and anaerobic zones. Nitrification occurs in the aerobic part of wetlands while denitrification progresses where the system is anaerobic. Decomposition of organic matter occurs in both aerobic and anaerobic zones. In addition, wetland soils absorb phosphorus and sedimentation occurs in wetlands. Schwartz and Boyd (1995) constructed an artificial wetland and planted it with cattails and bull rush. They evaluated the capacity of the wetland to purify catfish pond effluents. After 2 days, the wetland reduced BOD by 92.6-94.8%, total suspended solids by 92.1-97.6%, total nitrogen by 60.7-80.5%, and total phosphorus by 37.4-62.3%. Treatment of effluent for only 1 day in the wetland reduced BOD to 66%, total suspended solids to 88%, nitrogen to 55%, total phosphorus to 66%, and settleable solids to 57%. Increasing retention time to 4 days reduced phosphorus by 80% and settleable solids by 100%. However, removal of BOD, total suspended solids, and nitrogen were no greater after 4-day retention than after 1-day retention.

Sedimentation basins are easier to build than wetlands and can be as effective as wetlands in treating catfish farm effluents (Seok et al. 1995). Even though sedimentation basins remove little phytoplankton and detritus, basins with 8- to 12-hour retention times can be very effective in removing coarse, suspended mineral particles (Boyd et al. 2000). Ozbay (2002) reported that holding draining effluent for catfish ponds in sedimentation basins for 72 hours can improve water quality significantly, but such basins are not effective in improving water quality in overflow that occurs after rains. The reason for less effective results for overflow than for draining effluent is that the composition of these effluents is different. Overflow effluents after rain events are less concentrated in coarse mineral particles than effluents drained during harvest events. Boyd and Queiroz (2001) also found that it would not be feasible for catfish farms in

Alabama to treat effluents after rains by sedimentation basins because it would require an enormous amount of space to build basins of adequate hydraulic retention time.

Aluminum sulfate or alum can be used as a coagulant aid in sedimentation basins to improve efficiency, but the cost of alum is too high to use in actual practice (Ozbay 2002).

There is a paucity of information on the economic feasibility of reducing impacts from catfish effluents. Kouka and Engle (1996) demonstrated that constructed wetlands would increase the cost of catfish by $0.12/kg. Use of filter feeding fish to remove particulate organic matter from pond waters costs $0.075/kg, while application of effluents to irrigate rice costs nothing. Rice irrigation would result in water conservation and more efficient water use. Unfortunately, in practice, catfish ponds do not normally discharge effluents during dry weather when water is required for irrigation (Boyd and Queiroz 2001). This is another case of a methodology that is effective in research but that cannot be applied because conditions within the research setting do not occur at production facilities.

Even though Engle and Valderrama (2003) reported that it would cost 19-367$ per hectare annually for constructed sedimentation basins, sedimentation basins remain the most feasible way to treat catfish effluents because sedimentation basins are cheaper and they are easier to operate as compared to wetlands (Boyd and Queiroz 2001). However, sedimentation basins for catfish facilities require 10-20% of the volume of the largest pond on the facility, and most catfish facilities in Alabama do not have enough space for settling basins of this size (Boyd et al. 2000; Boyd and Queiroz 2001).

At present, best management practices (BMPs) are considered the most practical approach to control effluent volume and quality from aquaculture farms because effluents from these farms are both non-point source and point source pollution. It is not possible to control non-point source pollution by standard regulations (Boyd and Queiroz 2001; Lutz et al. 2003).

Aquaculture BMPs can be used by producers to control the sources and delivery of pollutants in order to reduce the amount of pollutants reaching natural water resources (Lutz et al. 2003). Aquaculture BMPs are available from many organizations. These BMPs are all similar in concept (Boyd 2003), and their objectives can be categorized into five groups (Boyd and Queiroz 2001).

The five groups of BMPs and some examples of individual BMPs in each group are provided below:

1. Reduce effluent volume.
    - Control the volume of inflow to lessen overflow.
    - Harvest fish without completely draining ponds.
    - Maintain storage capacity in ponds to store rainfall and avoid overflow.
2. Minimize suspended solids through erosion control.
    - Control erosion on watersheds by providing vegetative cover, eliminating gully erosion, and constructing terraces.
    - Eliminate steep slopes on roads and cover roads with gravel.
    - Provide grass cover on earthwork and position aerators to avoid water currents from impinging on earthwork.
3. Improve pond water quality.
    - Do not overfeed.
    - Use high quality feed that are not excessive in nitrogen and phosphorus content.
    - Use plenty of mechanical aeration.

4. Use therapeutic agents and other chemicals correctly.
   - Carefully follow instructions for use on labels of therapeutic agents and other chemicals.
   - Store chemicals under a roof to prevent them from washing into rainfall.
   - Diagnose diseases and obtain recommendations for treatment before applying therapeutic agents.
5. Build new farms or farm expansions correctly.
   - Construct new ponds according to Natural Resources Conservation Service (NRCS) standards.
   - New ponds should be located on watersheds that are not disturbed by subdivisions, industry, or row crops.

It should be stressed that BMPs are not fixed rules. BMPs change as knowledge, technology, and site location change, so they need to be reviewed and updated to reflect these changes (Boyd 2003).

CHAPTER 3

MATERIALS AND METHODS

Stream Water Quality

Study Area

The E. W. Shell Fisheries Center is located on Alabama Highway 147 about 5 km north of Auburn, Alabama. It consists of 935 ha of land with several units of watersheds separated into three catchments (Fig. 1). The upper and middle catchments are referred to as the Upper Station. These two catchments contain 28 watershed ponds – 11 on the middle catchment and 17 on the upper catchment. These ponds are used for various fish production studies, but most of them do not receive large inputs of feed. The lower catchment is known as the Lower Station. There is a Fish Genetics Research Unit with 70 ponds ranging from 0.04 ha to 0.1 ha in area, and an Aquaculture Production Research Unit with 192 ponds ranging from 0.02 ha to 0.4 ha in area. The small research ponds average about 1 m in depth. The total water surface area for the two, small, research pond units is 14.28 ha of which 10.88 ha are contained in the Aquaculture Production Research Unit. The lower catchment has nine watershed ponds that are used solely as water supply for the small, research ponds. The small research ponds, and especially the ones of the Aquaculture Production Research Unit, usually receive large inputs of feed.

A small un-named stream (called the Lower Station Creek in this report) receives overland flow and base flow of the lower catchment. This creek is the source of water for the small, research ponds, and to facilitate this use, its flow is partially diverted into underground pipes that supply each pond. The discharge from the small, research ponds re-enters Lower Station Creek before it flows into Saugahatchee Creek. The watershed ponds on the lower catchment have discharge structures to allow release of stored water into Lower Station Creek when its flow is not adequate to supply the small, research ponds.

The lower catchment has a total area of 352 ha with 36.33 ha of pond water surface area. The catchment is in the Piedmont Plateau area which is characterized by numerous hills and narrow valleys. Soils of the E. W. Shell Fisheries Center are Typic, Kandiudlults (clayey, kaolinitic, and thermic). They are acidic, reddish-brown soils of low cation exchange capacity and base saturation less than 35% (McNutt 1981). Watersheds are covered primarily by woodland, and there are no residential, agricultural, or industrial activities.

Sampling stations

Sampling stations for water quality measurements (Fig. 2) were located along Lower Station Creek and Saugahatchee Creek as follows: above the two units of small, research ponds (Stations 1, 2, and 4); below the outfall of the Fish Genetics Research Unit (Station 3); at the discharge of the water supply reservoir known as Pond FP-11 which is immediately above the Aquaculture Production Research Unit (Station 5); near the midpoint of the Aquaculture Production Research Unit (Station 6); at the entrance of Lower Station Creek into Saugahatchee Creek (Station 7); in Saugahatchee Creek upstream of the entrance of Lower Station Creek (Station 9); in Saugahatchee Creek downstream of the entrance of Lower Station Creek (Station 8).

Four reference streams in the Piedmont Plateau region within 10 km of the E. W. Shell Fisheries Center also were selected for sampling (Fig. 3). These streams were on wooded watersheds that did not have aquaculture production facilities, agricultural activities, or industrial sites. There were some rural dwellings on the watersheds. Each reference creek was sampled at a single location where it flows beneath a highway bridge. A surface water sample was collected by aid of a plastic bucket attached to a rope. Sampling dates and variables for analysis coincided with those for Lower Station Creek.

Water quality analyses

Analyses were initiated on the same day that samples were taken. Most variables were analyzed according to protocol given by the "Standard Methods for the Examination of Water & Wastewater" (Eaton et al. 2005). These methods were: air and water temperature (mercury thermometer); pH (electronic meter with glass electrode); specific conductance (conductivity meter); dissolved oxygen (polarographic dissolved oxygen meter); total alkalinity (titration to pH 5.1 with 0.02 N sulfuric acid); total hardness (titration to the erichrome black T endpoint with 0.01 M EDTA); chloride (titration to the 5-diphenylcarbozone endpoint with 0.0141 N mercuric nitrate); total ammonia-nitrogen (phenate method); total suspended solids (filtration through a 2-μm glass fiber filter and gravimetry); 5-day biochemical oxygen demand or BOD_5 (dissolved oxygen loss in undiluted sample incubated at $20^{o}C$ in dark for 5 days); turbidity (laboratory turbidimeter). Total nitrogen and total phosphorus were analyzed by spectrophotometry following digestion in potassium persulfate solution (Gross and Boyd 1998).

Hydrologic data

Rainfall and Class A pan evaporation were measured by standard gauges installed in an open area covered by short grass at the Aquaculture Production Research Unit. Potential evapotranspiration from the catchment was estimated by the Thornthwaite method (Thornthwaite and Mather 1957) using air temperature data for Auburn, Alabama (Alabama Weather Information Service, Auburn, Alabama). Stream flow from the catchment was estimated by subtracting potential evapotranspiration from rainfall (Boyd et al. 2009).

The catchment for Lower Station Creek was mapped by Boyd and Shelton (1984) using standard land surveying techniques. Land use on the catchment was ascertained from 2007 Landsat satellite imagery using GIS technology (ERDAS and Arc GIS), and the information obtained from the satellite imagery was ground-truthed by visual observations made while walking across selected areas of the catchment.

Pond Draining Effluent Study

Six, 0.04-ha ponds of the Aquaculture Production Research Unit were selected in fall 2006. During draining for harvest, water samples were collected at the water surface as the water level fell. Samples were taken when maximum pond depths were estimated to be 125, 100, 75, 50, 25, and 10 cm. Water samples also were collected from a nearby, common drain that collected effluent from a block of ponds for discharge into Lower Station Creek. The samples were analyzed for water temperature, dissolved oxygen, BOD_5, specific conductance, pH, turbidity, total suspended solids, total ammonia-nitrogen, total nitrogen, and total phosphorus by methodologies described above.

Pond Overflow Study

Eight, 0.04-ha ponds on the Aquaculture Production Research Unit and three, watershed ponds on the middle catchment (Ponds S-10, S-11, and S-14) were visited daily in 2007 and 2008. It was noted whether or not water was overflowing from ponds on each day.

Water Level Management Study

Six, 0.04-ha ponds on the Aquaculture Production Research Unit were stocked with channel catfish fingerlings (6 to 10 cm total length) at the rate of 12,000/ha in March 2007. The fish were fed daily with a 32% crude protein, pelleted feed at 3% of body weight per day. Five grass carp fingerlings (15 to 20 cm total length) also were stocked in each pond for aquatic weed control. Ponds were aerated with 0.33-hp vertical pump aerators each night.

Water meters were installed on the inlet pipes of each pond and read at monthly intervals between March and October 2007. Water levels in three ponds were maintained within 2.5-cm of the tops of the standing, overflow pipes by frequent additions. Water levels in the other three ponds were allowed to fall to 15 cm below the tops of the overflow pipes before water was added to bring water levels to within 7.5 cm of the tops of the overflow pipes. This procedure is called the drop-fill method (Cathcart et al. 1999).

Water samples were collected at weekly intervals and analyzed for total ammonia nitrogen, total nitrogen, soluble reactive phosphorus, total phosphorus, BOD_5, and total suspended solids by methodologies given above. Ponds were drained and fish harvested in October 2007.

CHAPTER 4

RESULTS AND DISCUSSION

Catchment Discharge

Installation of a flow monitoring structure in Lower Station Creek was cost prohibitive. Therefore, discharge from the catchment was estimated from the relationship that stream flow in a humid region is approximately equal to annual precipitation minus potential evapotranspiration (Boyd et al. 2009; (www.gwri.gatech.edu/conferences/previous-gwrc-conferences/gwrc-2009). This method does not account for the influence of ponds on water balance. Ponds are filled with water from the catchment, and all water applied to ponds annually either seeps out, overflows, becomes draining effluent, or evaporates. It follows that all water captured in ponds except evaporation will become catchment discharge. Thus, the primary hydrologic effect of ponds on discharge from the catchment is the increase in evaporation from the continuous, free water surface created by ponds as compared to evapotranspiration from an equal area of land. Evapotranspiration often is limited by a shortage of soil moisture, whereas a pond provides a constant water surface for evaporation.

Pond evaporation was calculated as Class A pan evaporation × 0.81 (Boyd 1985). Pond evaporation was 114 cm in 2006 and 130 cm in 2007 as compared to PET (potential evapotranspiration) values of 93 and 97 cm, respectively (Table 1). The reduction in discharge was about 21 cm in 2006 and 33 cm in 2007 for the area covered by ponds. Pond area was only

10.32% of catchment area, so the reduction in stream flow for the entire catchment was 2.2 cm in 2006 and 3.4 cm in 2007.

Lower Station Creek discharge adjusted for evaporation increase caused by the ponds was 2.64 m^3/min in 2006 and 2.91 m^3/min in 2007 (average = 2.77 m^3/min/yr). Without ponds, the stream discharge would have been 2.79 m^3/min in 2006 and 3.14 m^3/min in 2007 (average = 2.96 m^3/min/yr).

Water Quality in Lower Station and Saugahatchee Creeks

There was no difference in water quality between Stations 1 and 2 above the Fish Genetics Research Unit, and the data from the two stations were pooled and reported as Station 1. On most sampling dates, there was no flow in the small tributary entering the Lower Station Creek at Station 4. Therefore, data for this station were pooled with data for Station 3 and reported as Station 3.

Seasonal patterns

Monthly concentrations of water quality variables at Station 1, Station 7, and for the four reference streams are provided in Figs. 4-6. Water temperature closely followed air temperatures, but water was cooler than air and especially in the summer. There were no striking differences in either air or water temperature among the stations (Fig. 4).

Dissolved oxygen concentration ranged from about 4 mg/L to nearly 10 mg/L. There was no difference in dissolved oxygen concentration between Station 1 above the small research pond areas and the mouth of Lower Station Creek at Station 7 (Fig. 4). Moreover, Station 1 and the reference streams had similar dissolved oxygen concentrations. Higher concentrations of dissolved oxygen occurred during cool months because of the increasing solubility of oxygen with decreasing temperature. The reason for the particularly low DO concentrations in spring 2007 at all stations is not known.

The pH of stream water tended to increase between Station 1 and Station 7 indicating that effluent from the small, research ponds was basic in reaction relative to normal stream flow from the lower catchment. The reference streams usually had slightly higher pH than water at Station 1, but they tended to be similar in pH to water at Station 7. However, the difference between Station 1 and reference streams was probably not related to anthropogenic inputs as the catchments above Station 1 and the reference catchments were wooded and not thought to have been impacted by agricultural or industrial effluents.

Station 1 and reference streams tended to have BOD_5 concentrations below 2 mg/L, while on several dates; BOD_5 was above 3 mg/L at Station 7. BOD_5 concentration at Station 7 peaked in the fall during pond draining for harvest (Fig. 4).

Specific conductance (Fig. 4) was similar in value and trend of change over time between Station 1 and the reference streams. Specific conductance tended to be elevated at Station 7 relative to Station 1 and reference streams – particularly from June 2006 through April 2007. Both 2006 and 2007 were dry years, and the prolonged drought likely caused the increase in specific conductance in reference streams in August 2007 and at Station 1 between April and December 2007.

Turbidity and total suspended solid (TSS) concentrations fluctuated considerably in Lower Station Creek and in reference streams, but concentrations for these two variables often were greatest at Station 7 (Fig. 5). Peak turbidity and TSS concentration at all sampling stations were above 50 NTU and 40 mg/L TSS. The peak turbidity values exceeded the limit for this variable in streams classified for fish and wildlife propagation (Boyd 2000).

Total alkalinity and total hardness concentrations exhibited considerable temporal fluctuation (Fig. 5). Nevertheless, Station 1 and reference streams usually had similar concentrations of these two variables while Station 7 tended to have higher concentrations.

Total ammonia-nitrogen concentration usually was below 0.4 mg/L, but it fluctuated between 0.05 and 0.78 mg/L. There was no clear trend in concentration among the stations (Fig. 6). Total nitrogen concentration, however, was similar between Station 1 and the reference streams, and these stations typically had less than 1 mg/L total nitrogen. Large peaks in total nitrogen concentration were observed at Station 7 during the fall harvest period of both years.

Total phosphorus concentrations were relatively similar and highly variable at all three stations (Fig. 6). Concentrations of this variable tended to be less in the spring and highest during summer and early fall at all stations. The greatest peaks in total phosphorus were found at Station 1 during the fall.

Chloride concentration was similar (1-5 mg/L) and exhibited similar trends of change over time at Station 1 and in the reference streams. Chloride was elevated (5 to 16 mg/L) at Station 7.

Water quality data also were provided over time for the outfall of Lower Station Creek (Station 7) and locations in Saugahatchee Creek just upstream (Station 9) and just downstream (Station 8) of Station 7 (Figs. 7 and 8). Station 7 had lower concentrations of most variables on most sampling dates than found at either Station 9 or Station 8.

Averages for selected stations

Data in Figs. 4-8 suggest that Station 1 did not differ greatly from the reference streams with respect to most water quality variables. Moreover, Station 7, the outfall for the catchment containing the Lower Station also was similar in concentration to Station 1 and reference streams for several variables. Station 7, however, appeared to have greater concentrations of BOD_5, specific conductance, total nitrogen, chloride, and possibly total alkalinity and total hardness than Station 1 and reference streams. Moreover, the Lower Station discharge did not appear to negatively impact water quality in Saugahatchee Creek.

In order to obtain a better assessment of the effects of the Lower Station effluent on water quality in Lower Station Creek, grand means of variables were estimated and compared. First, water quality variables for the stations above (Station 1) and below (Station 3) the Fish Genetics Research Unit and below the water supply reservoir (Station 5) were compared (Table 2). There were only three differences ($P < 0.2$) among the means for water quality data when Stations 1 and 3 are compared. Water temperature increased because water was detained in ponds where it heated from insolation, and total alkalinity and total hardness concentrations increased because ponds received agricultural limestone applications.

The reference streams did not differ from Station 1 except for pH and total suspended solids, and turbidity (Table 2). Logging operations had been conducted on the Lower Station catchment in 2005 and early 2006. This is probably the reason that Lower Station Creek had greater concentration of total suspended solids and turbidity than reference streams. The difference in pH between Station 1 and the reference streams possibly is related to differences in soils on catchments of the streams.

The water from Station 3 enters the water supply reservoir. Water at Station 5 had been held in the reservoir for a considerable period – the annual hydraulic retention time for the reservoir was estimated to be about 3 months (Boyd and Shelton 1984). Water at Station 5 was similar in quality to water at Station 3 with a few exceptions. Total alkalinity and total hardness concentrations declined ($P < 0.2$) because of dilution by runoff from areas of the catchment not affected by aquacultural inputs to the Fish Genetics Research Unit. Total suspended solids and turbidity also decreased ($P < 0.2$) because of sedimentation of solids while the water was retained in the reservoir. Water at Station 5 was even lower in total suspended solids and turbidity than water at Station 1 that had not received aquaculture effluents. The increase in pH in the reservoir likely resulted from increased phytoplankton photosynthesis while the water was impounded.

The changes in water quality between Stations 5 and 7 are depicted in Table 4. There were no differences in temperature, pH, and concentrations of total ammonia nitrogen and total phosphorus among these sampling stations ($P > 0.2$). However, specific conductance, turbidity, and concentrations of total alkalinity, total hardness, chloride, total suspended solids, total nitrogen, and BOD_5 increased ($P < 0.05$) between Station 5 and Station 7. Obviously, these variables also increased between Station 1 and Station 7.

Total alkalinity and total hardness concentrations were higher as a result of liming the research ponds. Chloride increased because salt (sodium chloride) was applied to ponds to counteract nitrite toxicity. Greater specific conductance was caused by the increases in alkalinity, hardness, and chloride concentrations. Nitrogen and phosphorus concentrations rose in response to use of feeds and fertilizers in the ponds. Greater plankton growth in ponds resulting from nutrient inputs and resuspension of sediment by aeration is an obvious source of suspended particles and turbidity. The small research ponds have very small watersheds (about

50% of surface area) and they are operated with water levels about 7.5-cm below tops of overflow pipes in order to capture direct rainfall and runoff from heavy rains (Boyd 1982; Cathcart et al. 1999). The research ponds normally discharge little water except in winter when precipitation may exceed evaporation plus seepage (Boyd and Shelton 1984). Thus, most discharge from the production research area occurs in fall and early winter when ponds are drained for harvest.

It is not surprising that the Aquaculture Production Research Unit had a greater impact than the Fish Genetics Research Unit on water quality in Lower Station Creek (compare differences between Stations 1 and 3 with differences between Stations 5 and 7). The production unit is larger and employs more intensive culture procedures than does the genetics unit.

Lower Station Creek empties into Saugahatchee Creek. The catchment of Saugahatchee Creek includes commercial and residential areas in Auburn and Opelika, Alabama, and the stretch that passes the Lower Station has a history of relatively poor water quality. The quality of water at Station 7 is compared with the quality of water in Saugahatchee Creek (Table 5). The discharge of Lower Station Creek (Station 7) was not different from water collected from Saugahatchee Creek above the outfall (Station 9) with respect to temperature, dissolved oxygen, turbidity, and total suspended solids ($P > 0.2$). Station 7 was lower in pH, specific conductance, total alkalinity, total hardness, chloride, total ammonia nitrogen, total nitrogen, total phosphorus, and BOD_5 than Station 9. Station 8 below the outfall of Lower Station Creek into Saugahatchee Creek did not differ from Station 9 above the outfall with respect to temperature, dissolved oxygen, turbidity, total alkalinity, total hardness, chloride, total suspended solids, total nitrogen, and total phosphorus. Station 8, however, lower in pH, specific conductance, total ammonia nitrogen, and BOD_5 than Station 9. The distance between Station 9 and Station 8 is only about

600 m, and there is no inflow to Saugahatchee Creek along this stretch other than overland flow from the surrounding wooded area. It can be concluded that discharge from the E. W. Shell Fisheries Center has no negative impact on Saugahatchee Creek, and to the contrary, may actually improve water quality in Saugahatchee Creek by dilution.

Although the aquaculture station discharge did not have higher concentrations of most water quality variables than Saugahatchee Creek, a better understanding of the pollution potential of the station effluents can be obtained by comparing Station 7 with the reference streams (Table 6). The discharge from the E. W. Shell Fisheries Center was higher than reference streams in specific conductance, turbidity, total alkalinity, total hardness, chloride, total suspended solids, total nitrogen, and BOD_5. Nevertheless, the differences were small, and small increases in these variables are not detrimental to stream water quality. The increase in water temperature is less than the 2.8°C rise allowed in Alabama streams classified for fish and wildlife propagation (Boyd 2000). Dissolved oxygen concentration and pH at Station 7 typically exceeded 6 mg/L and 7.0, respectively – stream standards are 5.0 mg/L for dissolved oxygen concentration and 6 to 8.5 for pH. There are no standards for total alkalinity and total hardness concentrations for stream waters in Alabama, but the small increases in these two variables did not raise pH significantly. In many areas of Alabama, stream waters are naturally acidic and poorly buffered (Arce and Boyd 1980). Thus, increases in total alkalinity and total hardness would be viewed as improvements in stream water quality in most areas of Alabama. The in-stream limit for chloride concentration is 230 mg/L (Benoit 1988). This limit greatly exceeds the maximum chloride concentration of 16.56 mg/L measured at Station 7. The variables of most concern in effluent from the Lower Station were suspended solids (and associated turbidity), total nitrogen and phosphorus, and BOD_5.

Pollutant loads from the Lower Station can be calculated from the stream discharge at Station 5 and water quality data for Stations 5 and 7 as follows:

Pollutant load (kg/yr) = $Q_{7A}C_7\text{-}Q_7C_5$

where Q_{7A} = estimated discharge at Station 7 adjusted for pond water surface (m^3/yr),

C_7 = concentration of water quality variable of interest at Station 7 (mg/L = g/m^3),

Q_7 = estimated discharge at Station 7 unadjusted for water surface area (m^3/yr),

C_5 = concentration of water quality variables of interest at Station 5 (mg/L = g/m^3)

(represents background concentration)

The estimates for the pollutant loads are provided in Table 7.

Water Quality during Draining

Ponds were drained during a single day; the initial samples were taken in the morning and the final samples about mid afternoon. Water temperature increased because air temperature increased during the day warming the pond water (Fig. 1). Specific conductance remained about the same as the water depth declined from 125 cm to 25 cm; at lesser depth, there was a marked increase in this variable. Dissolved oxygen concentration decreased from about 8 mg/L to 6 mg/L after water depth fell to 25 cm (Fig. 9). The pH increased as water level declined from 125 to 75 cm, and then, pH tended to decline. This change as well as the decline in dissolved oxygen concentration resulted from greater photosynthesis during midday than later in the afternoon, and were not related to the draining operation. Concentrations of BOD_5, turbidity, total suspended solids, total ammonia-nitrogen, and total nitrogen tended to increase with increasing water-level drawdown and particularly during the final stage of drawdown (Fig. 9-10). These increases were related to the resuspension of sediment by out-flowing water, and by the activity of the fish that were crowded into a continually diminishing volume of water. The BOD_5 concentration did not exceed 9 mg/L; considerably less than the limit of 20 to 25 mg/L typically allowed in limitations for effluents from other kinds of facilities (Carter 1984; Boyd and Gross 1999). Total ammonia-nitrogen and total nitrogen concentrations also were not particularly high, 2.0 mg/L and 3.4 mg/L, respectively, during the final drawdown. Turbidity and total suspended solids concentrations, however, reached extremely high values of 920 NTU and 5,200 mg/L, respectively, in the final phase of drawdown. These concentrations were much greater than turbidity values of 25 to 100 NTU and total suspended solids concentrations of 25 to 50 mg/L usually allowed in effluent limitation guidelines for other industries. In Alabama, there is no stream standard for TSS concentrations, but the turbidity standard is 50 NTU (Boyd 2000). It is interesting that total phosphorus concentration did not increase during drawdown.

These results agree with earlier studies of drawdown in preparation for harvest of larger production ponds in which concentrations of selected water quality variables increased drastically in the final 20 to 25% of discharge (Boyd 1978; Schwartz and Boyd 1994a; Teichert-Coddington et al. 1999). Moreover, the conclusion that total suspended solids and turbidity were the major water quality variables of concern in draining effluent from production ponds (Schwartz and Boyd 1994a) applies equally well to smaller, research ponds.

The ponds discharged into a few common drains that emptied into Lower Station Creek. The averages and standard errors for measured variables in the discharge of the common drain were as follows: water temperature, $22 \pm 0.86^{o}C$; dissolved oxygen, 8.15 ± 0.12 mg/L; BOD_5, 7.70 ± 1.43 mg/L; specific conductance, 106 ± 6 µs/cm; pH, 6.93 ± 0.10; turbidity, 367 ± 104 NTU; total suspended solids, 380 ± 154 mg/L; total ammonia-nitrogen, 0.396 ± 0.065 mg/L; total nitrogen, 1.21 ± 0.06 mg/L; total phosphorus, 0.64 ± 0.04 mg/L. The common drain effluent was not as concentrated in potential pollutants as the final effluent from individual ponds, because effluents from different stages of pond draining are mixed in the common drain.

The research ponds did not overflow appreciably during the fish production season when liming materials, salt, fertilizer, and feed are applied to ponds. They discharged primarily in response to draining during fall and early winter. Therefore, the volume of ponds in the production research area and the average concentrations of variables listed in the previous paragraph were used to estimate pollutant loads from the ponds (Table 8). It is interesting to note that these estimates do not differ greatly from those made based on estimates of stream flow and concentrations of water quality variables at Station 5 and Station 7 (Table 7). However, there is less uncertainty in estimates of pollutant loads provided in Table 8 than in those given in Table 7.

It is interesting to note that the percentages of feed inputs of potential pollutants that are discharged from ponds of the Lower Station in effluent were quite small: 2.9% for nitrogen and 6.6% for phosphorus. The feed BOD is presented as ultimate BOD (Table 9), and ultimate BOD may be twice the BOD_5 (Boyd and Gross 1999). Thus, around 1.2% of the feed BOD may have been discharged in effluent. Most of the suspended solids load resulted from resuspension of sediment during pond draining. The load was equal to 3,800 kg solids/ha (at total of 41,344 kg from the Production Research Pond Area). A discharge of 3,800 kg TSS/ha is much greater than the amount of solids discharged in runoff from wooded land and similar to solids discharged from cultivated land (U.S.EPA 1973). Therefore, it must be concluded that total suspended solids and associated turbidity are the major contaminants in effluents from pond aquaculture research facilities.

Pond Discharge Days

Ponds at Aquaculture Production Research Unit are allocated for numerous experiments each year, and it was not possible to obtain a reliable estimate of total production for either year. Accurate records on feed purchases and inventory were available. Some ponds were removed from use in 2007 for renovation, and feed use that is typically more than 150 tonne/yr declined to 120 tonne/yr (Table 9). The feed conversion ratio (FCR) varies among experiments, but it usually will be about 2. At this FCR, use of 120 tonnes feed would result in 60,000 harvest kg of fish – 45,454 kg/yr is the lower limit for a CAAP facility.

Discharge days include any days that ponds release water in response to draining or overflow after rains – excluding excess runoff. The discharge days are for the facility not for individual ponds. The E. W. Shell Fisheries Center has 260 small ponds, and if only one pond is discharging, a discharge day results. In 2007, ponds overflowed on 26 days, while in 2008, there were only 14 days with overflow (Table 10). Although the facility could be excluded as a CAAP facility based on overflow days, draining for harvest is done over several weeks – the peak period is mid September to early November. Draining for harvest alone would result in the center being classified as a CAAP facility.

The E. W. Shell Fisheries Center also has 37 watershed ponds ranging in size from 0.29 ha to 10.52 ha. The watersheds on the facility are situated in three catchments (Fig. 1), and watershed ponds on the catchment supplying the Fish Genetics Research Unit and the Aquaculture Production Research Unit are used only for water supply. However, watershed ponds on the other catchments are used for fish culture experiments. The three watershed ponds observed in this study discharged on 168 days in 2007 and 132 days in 2008 (Table 11). There is sufficient pond area in both of the catchments to produce more than 45,454 harvest kg of fish per year. However, on most years, production does not reach this level.

Water-level Management

The study was conducted during an unusually dry period. Normal rainfall at Auburn, Alabama is 93.3 cm between March and October (Alabama Weather Information Service, Auburn, Alabama, personal communications). However, in 2007, rainfall for this period was only 40.1 cm. Class A pan evaporation for the 8-month period totaled 131.2 cm (Table 1). Based on a pan coefficient of 0.81 (Boyd 1985), pond evaporation was 109 cm and 68.9 cm greater than direct rainfall into ponds.

Average, measured water additions (Table 12) were greater for ponds operated by the full-pool method than for ponds managed by the drop-fill technique. However, seepage rates among ponds located side-by-side on the E. W. Shell Fisheries Center often differ considerably (Boyd 1982; Stone and Boyd 1989). Because of variable seepage, water use did not differ ($P>0.05$) between the two methods of water-level management. Normal rainfall is greater than rainfall during the study period, and the excess of pond evaporation over precipitation would be much less on most years than in 2007. Thus, a water savings and reduction in discharge days could be expected on a normal year. Nevertheless, ponds at the E. W. Shell Fisheries Center seep considerably, and the potential water savings from use of the drop-fill method is less than at locations where ponds do not seep at a high rate. For example, commercial channel catfish ponds in the Blackland Prairie region of Alabama have seep rates 5 to 10 times less than ponds in the Piedmont Plateau where the EWS Fisheries Center is located (Yoo and Boyd 1994).

Water quality variables did not differ between the two methods of pond water-level management (Table 13). Moreover, fish production data were similar between treatments (Table 14).

Solids and Turbidity Control

The findings reported above suggest that pond aquaculture research facilities such as the E. W. Shell Fisheries Center will discharge more than 30 days per year because of overflow after rains and draining of ponds for harvest. Thus, large facilities that produce more than 45,454 harvest kg of fish per year will be CAAP facilities and require NPDES permits. High concentrations of total suspended solids and turbidity in pond draining effluent appear to be the two water quality variables of most concern. Concentrations of these two variables can be reduced by sedimentation (Boyd 1995; Boyd et al. 1998).

Settling ponds for removing coarse, suspended clay particles from aquaculture pond effluent should have a hydraulic retention time (HRT) of 24 hr (Ozbay and Boyd 2003, 2004). The maximum number of ponds drained at the Aquaculture Production Research Unit in 24 hr does not exceed 12, 0.04-ha ponds of 1 m average depth. Thus, the maximum volume of effluent should not exceed 4,800 m^3. Because of the layout of the Aquaculture Production Research Unit, it would not be practical to pass effluent from the pond through a settling basin before it enters Lower Station Creek. The sedimentation basin would have to be installed in Lower Station Creek before the creek discharges into Saugahatchee Creek. Average flow of Lower Station Creek should not exceed 1 m^3/min during low flow conditions that occur during late summer, fall, and early winter in Alabama (Boyd et al. 2009). At this flow rate, the steam would discharge 1,440 m^3 in 24 hr. A settling basin volume of 6,240 m^3 would be the minimum size necessary for a 24-hr HRT. However, it is expected that the basin might remove up to 28,000 kg solids per year. At a particle density of 1.5 tonne/m^3, the annual deposition of solids might exceed 18.6 m^3/yr. Additional solids of natural origin also would be removed by the basin because the Lower Station Creek stream would flow through it. The basin size probably should be twice the minimum size to assure a service life of many years. A 2-m average depth basin of 6,000 m^2 area or a 1.5-m depth basin of 9,000 m^2 area should be adequate.

Sedimentation basins should receive inflow at the surface on one side and discharge from the surface on the opposite side. A baffle can be installed to avoid short circuiting of flow across the basin from inlet to outlet (Boyd 1995). The embankments should be covered with grass, geofabric liners, or stone to minimize erosion. Mechanical aeration should not be applied in settling basins, for water currents from aerators resuspend solids.

This study revealed that the E. W. Shell Fisheries Center does not discharge a large amount of pollution and it discharges into a polluted stream; nevertheless, it qualifies as a CAAP facility. Moreover, the center should be operated in a manner that demonstrates and promotes good production practices to commercial producers. The center should apply best management practices described by Boyd et al. (2003, 2004), and the settling basin described above should be constructed.

CHAPTER 5

CONCLUSIONS

The findings of this study can be summarized as a few conclusions.

(1) The E. W. Shell Fisheries Center is a CAAP facility because both the small, aquaculture research ponds on the Lower Station discharge and the large, production ponds on the Upper Station exceed the USEPA minimum criteria for a CAAP facility, i.e., discharge 30 days or more per year and produce over 45,454 harvest kg (100,000 lb) per year..

(2) The facility discharges water with elevated concentrations of alkalinity, hardness, chloride, specific conductance, total nitrogen, total phosphorus, BOD_5, total suspended solids, and turbidity relative to Lower Station Creek. However, water in Lower Station Creek is of better quality than water in Saugahatchee Creek, and discharge from Lower Station Creek does not negatively impact water quality in Saugahatchee Creek.

(3) Concentrations of potential pollutants in discharge from the Aquaculture Production Research Unit are elevated in comparison to background concentration of these variables in nearby reference streams. However, the only variables that appear elevated enough for concern are total suspended solids and associated turbidity.

(4) Use of the drop-fill method would not appreciably reduce discharge from small, research ponds because most discharge occurs when ponds are drained for harvest.

(5) Sedimentation appears to be the only practical means of improving water quality in discharge from the E. W. Shell Fisheries Center or other pond aquaculture research facilities.

Table 1. Monthly rainfall and Class A pan evaporation measured at the Aquaculture Production Research Unit at the E. W. Shell Fisheries Center.

	2006		2007		2008		2009	
Month	P	E	P	E	P	E	P	E
Jan	8.86	2.98	14.53	1.50	8.00	8.42	6.77	6.43
Feb	7.37	4.58	21.97	2.16	20.09	11.04	3.73	8.15
Mar	14.43	9.25	2.11	13.62	12.17	13.54	9.12	14.24
Apr	5.51	13.33	3.67	15.34	7.64	18.30	14.43	17.21
May	7.21	16.06	0.15	21.46	8.23	22.25	8.58	17.43
Jun	12.34	19.75	13.89	21.00	2.08	16.89	9.91	19.70
Jul	8.53	18.41	9.63	20.36	6.91	21.57		
Aug	3.48	17.53	7.26	22.69	22.12	15.82		
Sep	5.05	16.29	5.69	15.37	7.17	16.83		
Oct	11.84	11.72	6.46	11.53	16.50	13.54		
Nov	14.48	6.90	8.01	9.03	7.37	5.88		
Dec	4.47	4.22	9.40	6.12	9.82	9.14		
Total	103.58	141.02	102.78	160.20	128.08	173.22	52.53	83.16

Table 2. Grand means for concentrations of water quality variables at different sampling stations in Lower Station Creek. Data represent averages for monthly samples taken between April 2006 and March 2008.

	Station[1]		
Variable	1	3	5
Air Temp (°C)	24.76 a	23.45 a	23.51 a
Water Temp (°C)	19.83 a	21.23 b	23.50 b
pH	6.77 a	7.02 a	7.33 b
DO (mg/L)	6.84 a	7.57 a	7.85 a
SC (µs/cm)	82.69 a	102.52 a	74.63 a
Turbidity (NTU)	59.34 a	49.27 a	16.81 b
TA (mg/L)	34.84 a	40.50 b	26.67 a
TH (mg/L)	30.65 a	36.89 b	26.51 a
Cl (mg/L)	4.34 a	5.91 a	5.93 a
TSS (mg/L)	26.27 a	29.09 a	8.14 b
TAN (mg/L)	0.09 a	0.08 a	0.07 a
TN (mg/L)	0.38 a	0.73 a	0.47 a
TP (mg/L)	0.16 a	0.15 a	0.13 a
BOD (mg/L)	1.42 a	1.58 a	1.52 a

[1]Means indicated by the same letter did not differ (P = 0.2) according to Duncan's multiple range test (horizontal comparisons only.

Table 3 .Grand means for concentrations of water quality variables at Station 1 in Lower Station Creek and in four reference streams. Data represent averages for monthly samples taken between April 2006 and March 2008.

Variable	1[1]	Reference streams
Air temp (°C)	24.76 a	22.86 a
Water temp (°C)	19.83 a	18.85 a
pH	6.77 a	7.23 b
DO (mg/L)	6.84 a	6.98 a
SC (µs/cm)	82.69 a	88.63 a
Turbidity (NTU)	59.34 a	31.08 b
TA (mg/L)	34.84 a	33.40 a
TH (mg/L)	30.65 a	30.25 a
Cl (mg/L)	4.34 a	4.10 a
TSS (mg/L)	26.27 a	12.26 b
TAN (mg/L)	0.09 a	0.18 a
TN (mg/L)	0.38 a	0.54 a
TP (mg/L)	0.16 a	0.13 a
BOD (mg/L)	1.42 a	1.43 a

[1]Means indicated by the same letter did not differ (P = 0.2) according to t-test (horizontal comparisons only).

Table 4. Grand means for concentrations of water quality variables at different sampling stations in Lower Station Creek. Data represent averages for monthly samples taken between April 2006 and March 2008.

	Station[1]		
Variable	5	6	7
Air Temp (°C)	23.51 a	23.79 a	23.37 a
Water Temp (°C)	23.50 a	21.39 a	21.31 a
pH	7.33 a	7.12 a	7.23 a
DO (mg/L)	7.85 a	7.26 a	7.11 a
SC (µs/cm)	74.63 a	115.97 b	116.23 b
Turbidity (NTU)	16.81 a	31.75 b	34.81 b
TA (mg/L)	26.67 a	37.31 b	42.07 b
TH (mg/L)	26.51 a	36.65 b	40.44 b
Cl (mg/L)	5.93 a	10.83 b	9.85 b
TSS (mg/L)	8.14 a	19.32 b	29.30 b
TAN (mg/L)	0.07 a	0.12 a	0.13 a
TN (mg/L)	0.47 a	0.62 a	1.06 b
TP (mg/L)	0.13 a	0.14 a	0.16 a
BOD (mg/L)	1.52 a	1.71 a	1.98 b

[1]Means indicated by the same letter did not differ (P = 0.2) according to Duncan's multiple range test (horizontal comparisons only.

Table 5. Grand means for concentrations of water quality variables at the outfall of Lower Station Creek into Saugahatchee Creek (Station7) and concentrations of these variables 550 m above (Station 9) and 10 m below (Station 8) the outfall. Data represent averages for monthly samples taken between April 2006 and March 2008.

	Station[1]		
Variable	9	7	8
Air temp (°C)	23.67 a	23.37 a	23.19 a
Water temp (°C)	20.23 a	21.31 a	20.60 a
pH	7.65 a	7.23 b	7.56 b
DO (mg/L)	6.89 a	7.11 a	6.97 a
SC (µs/cm)	605.99 a	116.23 c	485.16 b
Turbidity (NTU)	43.54 a	34.81 a	32.42 a
TA (mg/L)	106.64 a	42.07 b	96.38 a
TH (mg/L)	47.29 a	40.44 b	46.52 a
Cl (mg/L)	51.40 a	9.85 b	46.62 a
TSS (mg/L)	24.78 a	29.30 a	17.78 a
TAN (mg/L)	0.48 a	0.13 c	0.31 b
TN (mg/L)	4.71 a	1.06 b	4.50 a
TP (mg/L)	0.54 a	0.16 b	0.48 a
BOD (mg/L)	3.07 a	1.98 c	2.53 b

[1]Means indicated by the same letter did not differ (P = 0.2) according to Duncan's multiple range test (horizontal comparisons only.

Table 6 .Grand means for concentrations of water quality variables at sampling Stations 7 in Lower Station Creek and in four reference streams. Data represent averages for monthly samples taken between April 2006 and March 2008.

	Station[1]	
Variable	Reference streams	7
Air temp (°C)	22.86 a	23.37 a
Water temp (°C)	18.85 a	21.31 a
pH	7.23 b	7.23 b
DO (mg/L)	6.98 a	7.11 a
SC (μs/cm)	88.63 a	116.23 b
Turbidity (NTU)	31.08 a	34.81 a
TA (mg/L)	33.40 a	42.07 b
TH (mg/L)	30.25 a	40.44 b
Cl (mg/L)	4.10 a	9.85 b
TSS (mg/L)	12.26 a	29.30 b
TAN (mg/L)	0.18 a	0.13 a
TN (mg/L)	0.54 a	1.00 b
TP (mg/L)	0.13 a	0.16 a
BOD (mg/L)	1.43 a	1.98 b

[1]Means indicated by the same letter did not differ ($P = 0.2$) according to t-test (horizontal comparisons only).

Table 7. Amounts of four water quality variables in discharge from the Lower Station at the E. W. Shell Fisheries Center. Calculated as the annual amounts of variables at Station 7 of Lower Station Creek minus the amounts of variables at Station 5 in the Creek.

Variable (kg/yr)	2006 [a]	2007 [b]	Average
Total suspended solids	19,560.56	32,428.14	25,994.35
Total nitrogen	353.13	1,149.53	751.33
Total phosphorus	19.26	27.86	23.56
Biological oxygen demand	589.75	384.08	486.91

Table 8. Pollutant loads discharged from the Aquaculture Production Research Unit of the E. W. Shell Fisheries Center during the 2007 harvest.

Variable	Quantity (kg)	Percentage feed input
Total suspended solids	41,344	---
Total nitrogen	132	2.9
Total phosphorus	69	6.6
Biochemical oxygen demand	838	1.2

Table 9. Feed used, fish harvested, and nitrogen (N) and phosphorus (P) waste loads in tonnes/year.

			Waste load		
Year	Feed [a]	Fish [b]	N [c]	P [c]	BOD [d]
2006	177.70	88.85	6.65	1.55	213
2007	120.24	60.12	4.50	1.05	144

[a] 5.12% N; 1.2% P
[b] FCR = 2.0; 2.75% N; 0.65% P
[c] N and P inputs in feed minus N and P outputs in fish
[d] Feed BOD = 1.2 feed input (Boyd 2009)

Table 10. Data on overflow days for eight, 0.04-ha embankment ponds at the E. W. Shell Fisheries Center.

Month	No. ponds with overflow	No. of days per pond	No. of days with overflow from any pond
Jan-07	8	0-5	5
Feb-07	8	0-7	7
Mar-07	8	0-1	1
Apr-07	3	0-1	1
May-07	0	0	0
Jun-07	1	0-1	1
Jul-07	1	0-2	2
Aug-07	2	0-1	1
Sep-07	2	0-3	3
Oct-07	1	0-1	1
Nov-07	5	0-2	2
Dec-07	6	0-2	2
Total 2007	45		26
Jan-08	6	0-6	6
Feb-08	7	0-8	8
Mar-08	6	0-5	0
Apr-08	5	0-3	0
May-08	2	0-4	0
Jun-08	2	0-1	0
Jul-08	4	0-2	0
Aug-08	2	0-1	0
Sep-08	0	0	0
Oct-08	3	0-2	0
Nov-08	2	0-1	0
Dec-08	4	0-1	0
Total 2008	43		14

Table 11. Data on overflow days for three watershed ponds on the E. W. Shell Fisheries Center.

Month	No. ponds with overflow	No. of days per pond	No. of days with overflow from any pond
Jan-07	2	0-28	28
Feb-07	2	28	28
Mar-07	2	0-31	31
Apr-07	1	0-30	30
May-07	1	0-31	31
Jun-07	1	0-19	20
Jul-07	0	0	0
Aug-07	0	0	0
Sep-07	0	0	0
Oct-07	0	0	0
Nov-07	0	0	0
Dec-07	0	0	0
Total 2007	9		168
Jan-08	0	0	0
Feb-08	1	0-9	9
Mar-08	2	0-21	25
Apr-08	1	0-13	13
May-08	2	0-31	31
Jun-08	1	0-30	30
Jul-08	1	0-2	2
Aug-08	1	0-3	3
Sep-08	0	0	0
Oct-08	2	0-8	8
Nov-08	2	0-10	10
Dec-08	1	0-1	1
Total 2008	14		132

Table 12. Average volumes of water added for two pond water level management methods.

There were three replications per treatment.

Month	Average water added (gallon)		SD		t-value
	Drop-fill	Full pool	Drop-fill	Full pool	
March-April	189836	259105	97372	106384	---
April-May	245634	220161	72182	38623	---
May-June	137955	265860	96356	117659	---
June-July	63306	183780	65965	179303	---
July-August	268155	288296	107193	187680	---
August-September	99310	123083	11717	45086	---
September-October	24381	42108	13193	20374	---
Total	1,028,578	1,382,399	311,150	559,619	0.203

Table 13. Averages of water quality data for two pond water level management methods. There were three replications per treatment.

	Water level management		
Variable	Drop-fill	Full pool	t-value
5-day biochemical oxygen demand (mg/L)	5.06	4.88	0.347
Total suspended solids (mg/L)	13.45	11.78	0.232
Total ammonia-nitrogen (mg/L)	0.25	0.23	0.309
Total nitrogen (mg/L)	1.96	2.06	0.295
Soluble reactive phosphorus (mg/L)	0.02	0.02	0.063
Total phosphorus (mg/L)	0.28	0.24	0.179

Table 14. Summary of fish production data for two pond water level management methods. There were three replications per treatment.

Variable	Water level management Drop-fill	Full pool	t-value
Catfish			
Survival (%)	91.0	69.1	0.110
Marketable (%)	63.3	78.2	0.038
Harvest weight (kg/ha)	4,558	4,202	0.054
FCR	1.29	1.41	
Carp			0.074
Survival (%)	80.0	76.7	
Harvest weight (kg/ha)	342	406	0.417

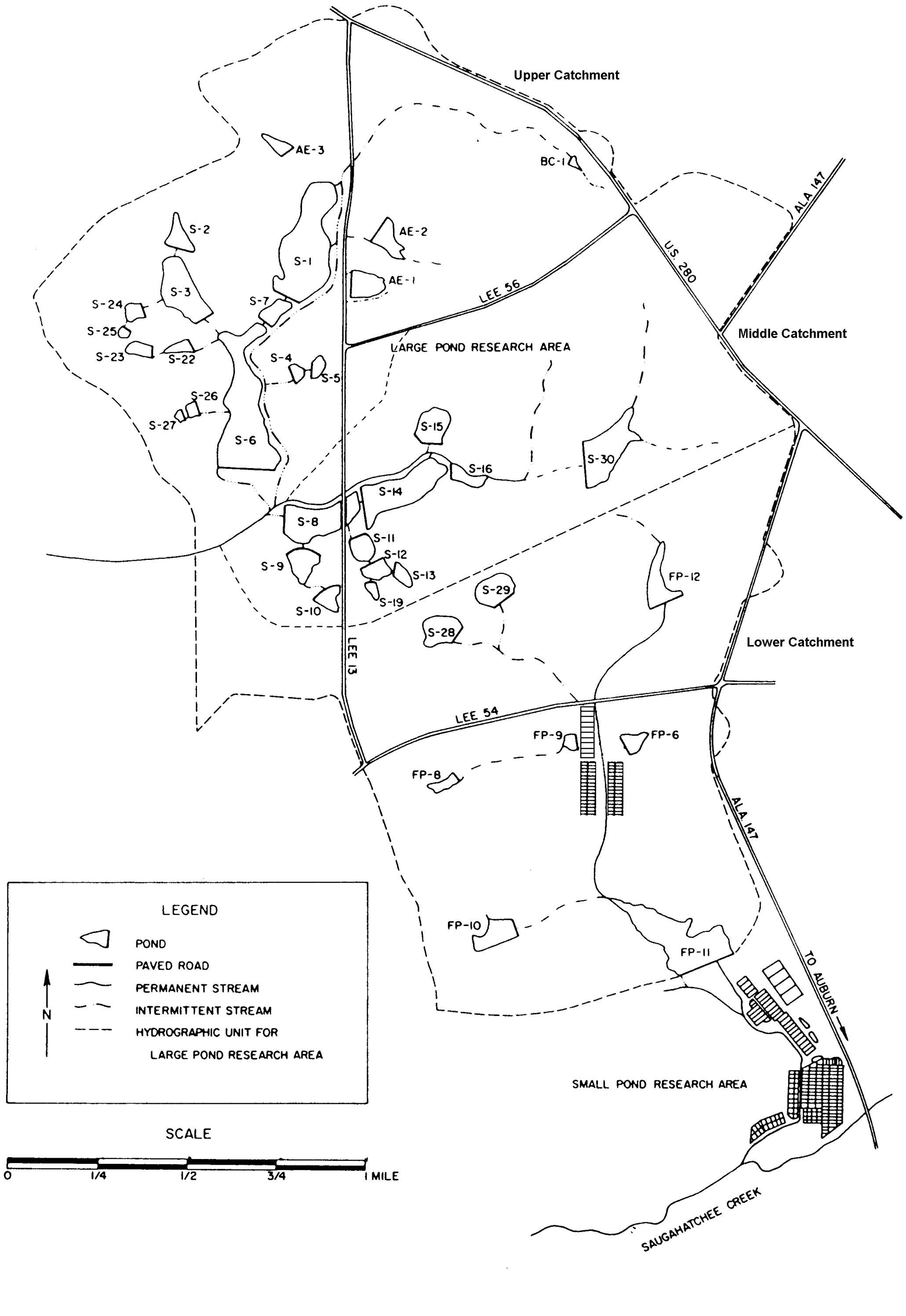


Figure 1. The E. W. Shell Fisheries Center with depiction of the three catchments and locations of watershed ponds and units of small, research ponds.

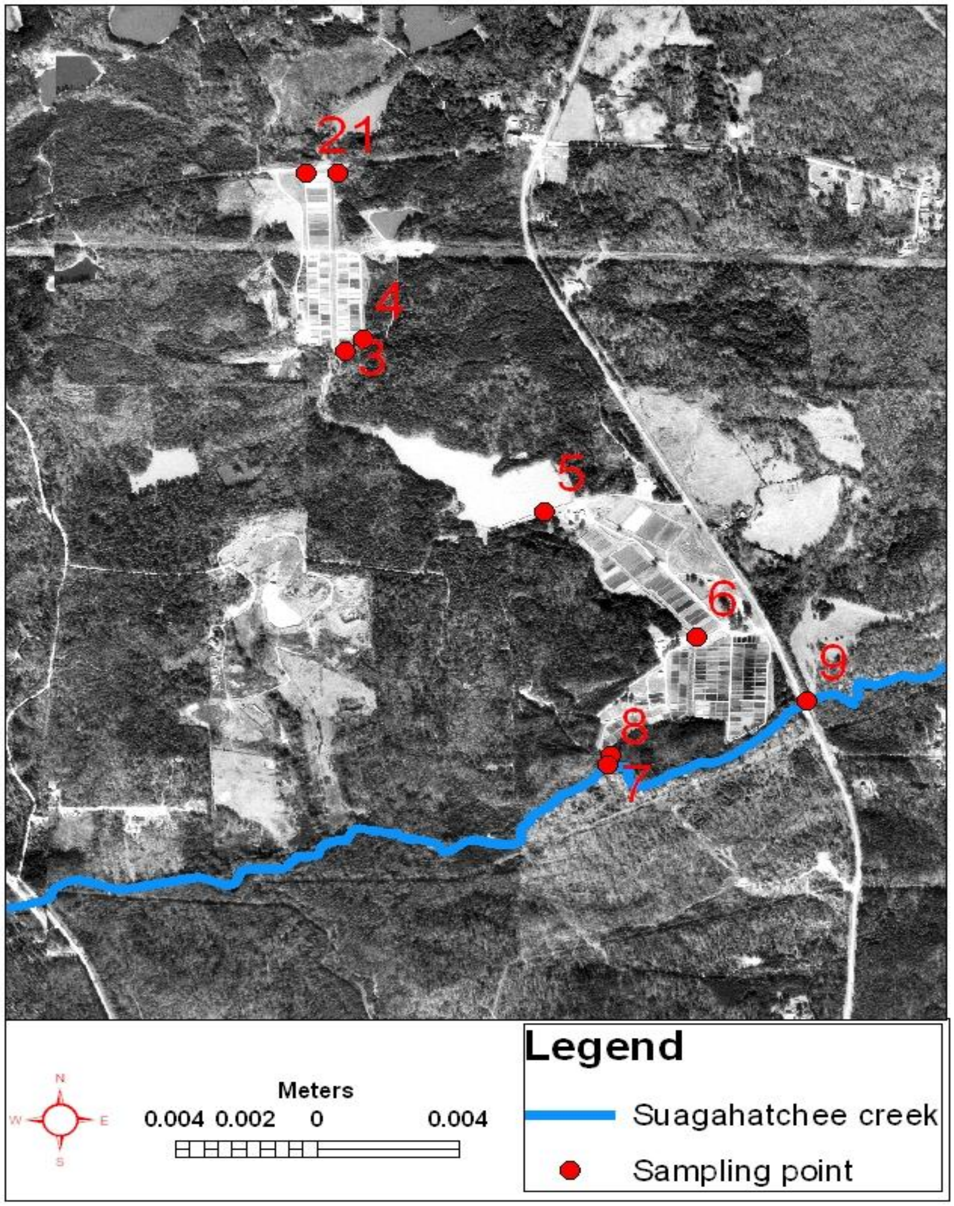


Figure 2. Location of water quality sampling stations in Lower Station and Saugahatchee Creeks.

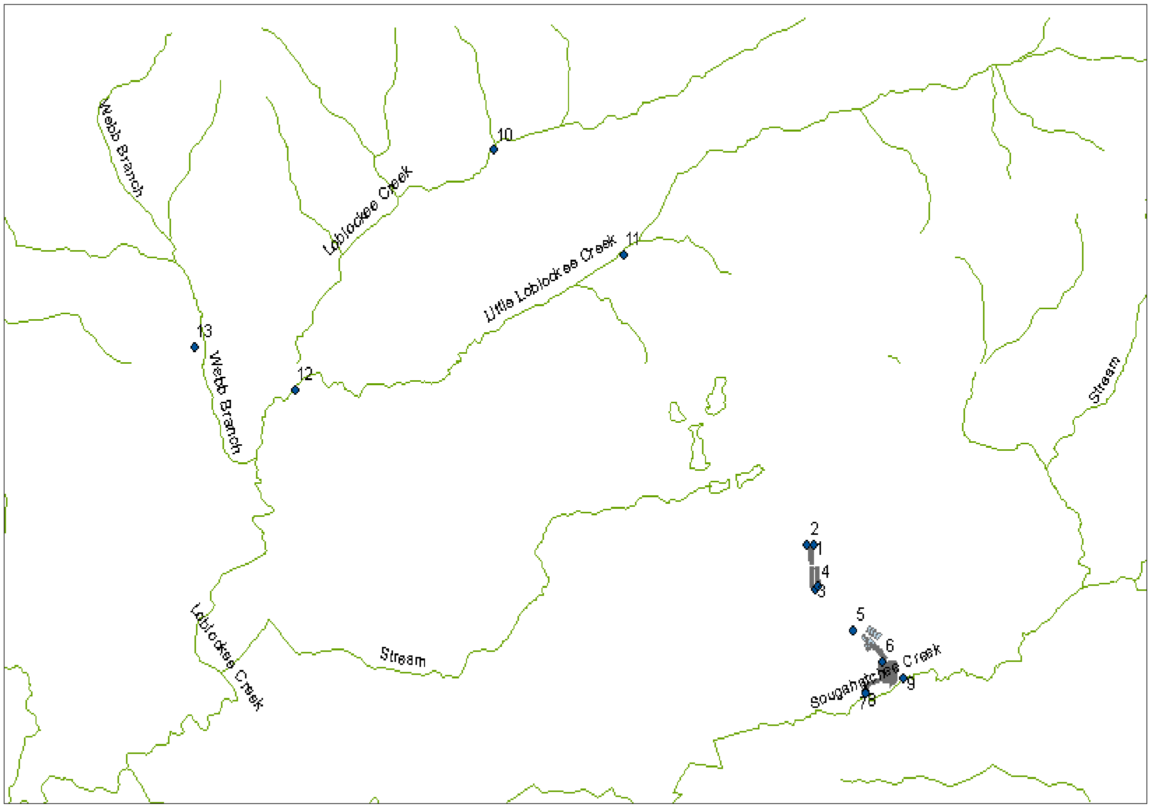


Figure 3. Locations of reference streams and sampling stations in streams.

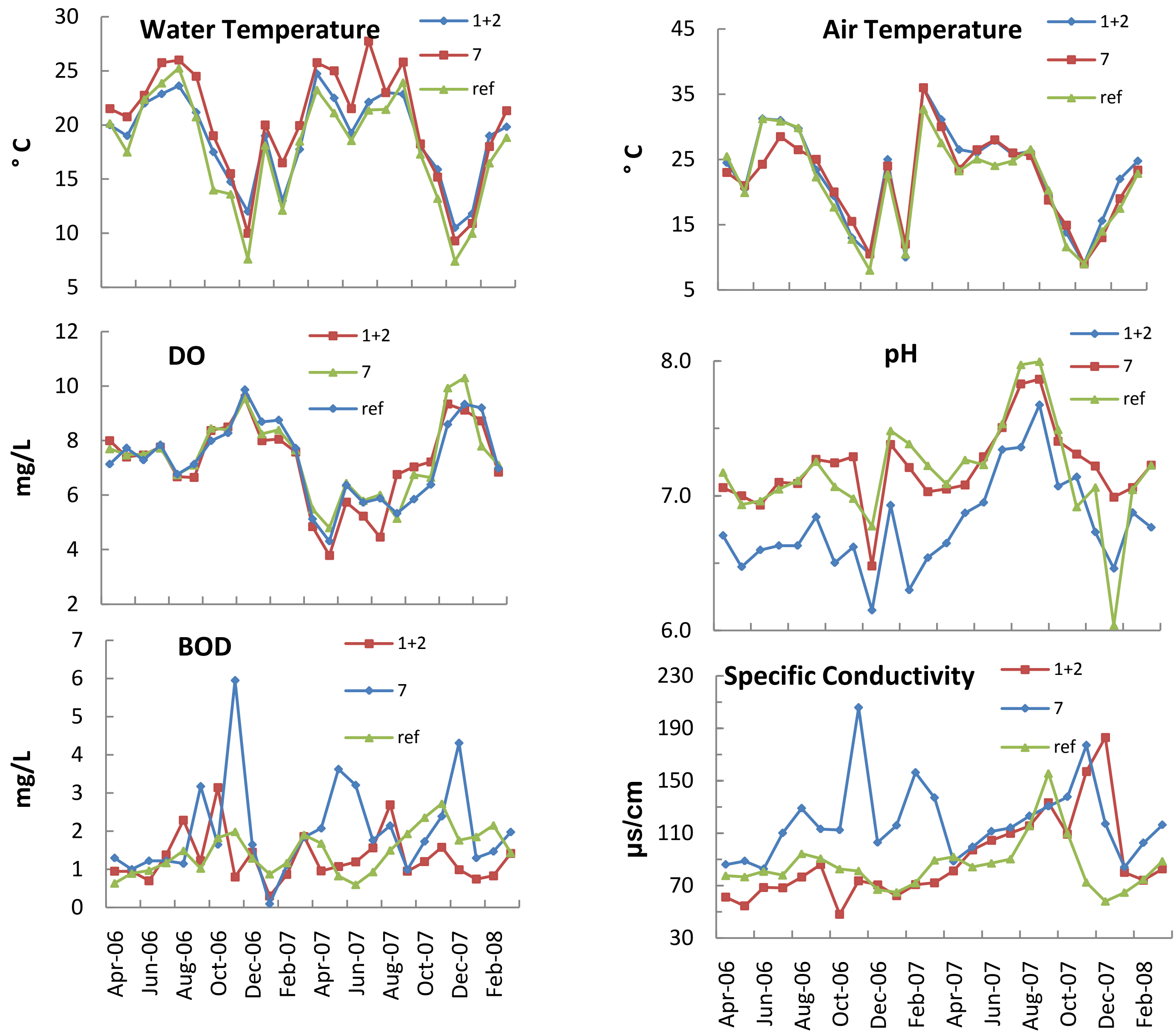


Figure 4. Concentration of water quality variables at monthly intervals in Lower Station Creek upstream of small research pond area (1), at outfall into Saugahatchee Creek (7), and reference (ref) streams.

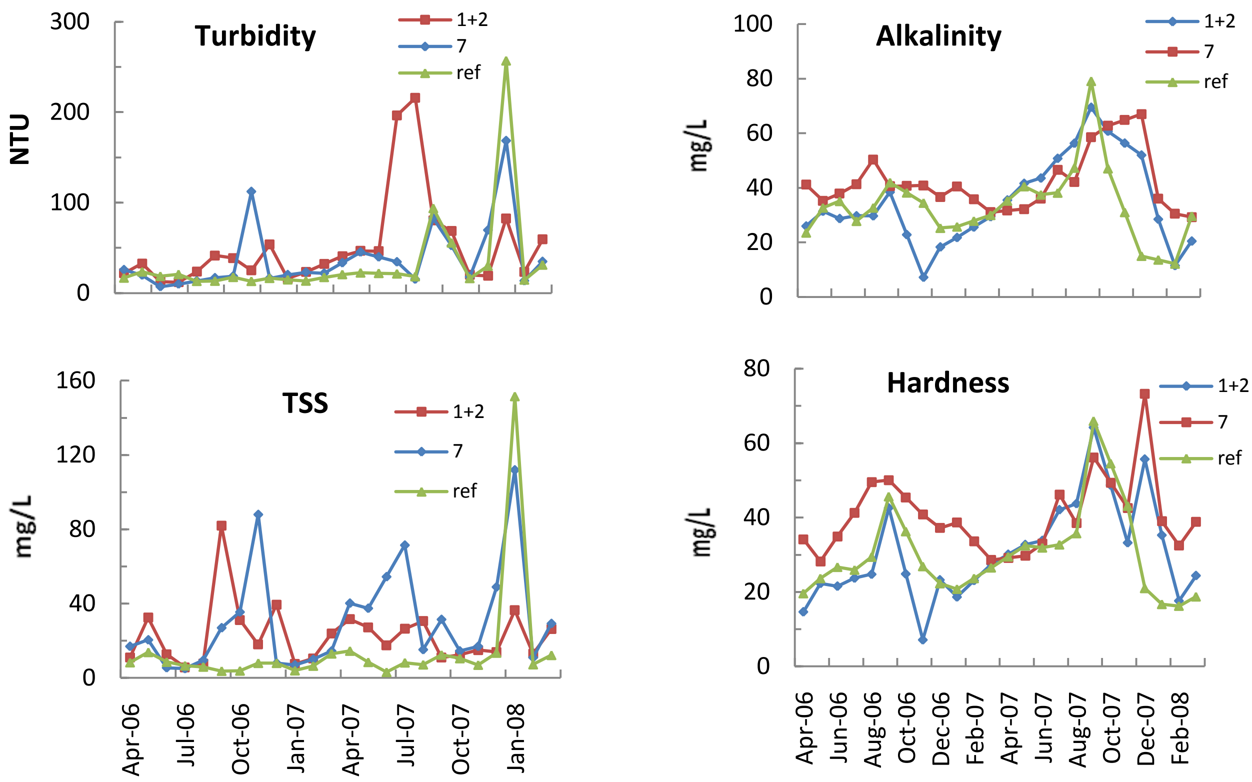
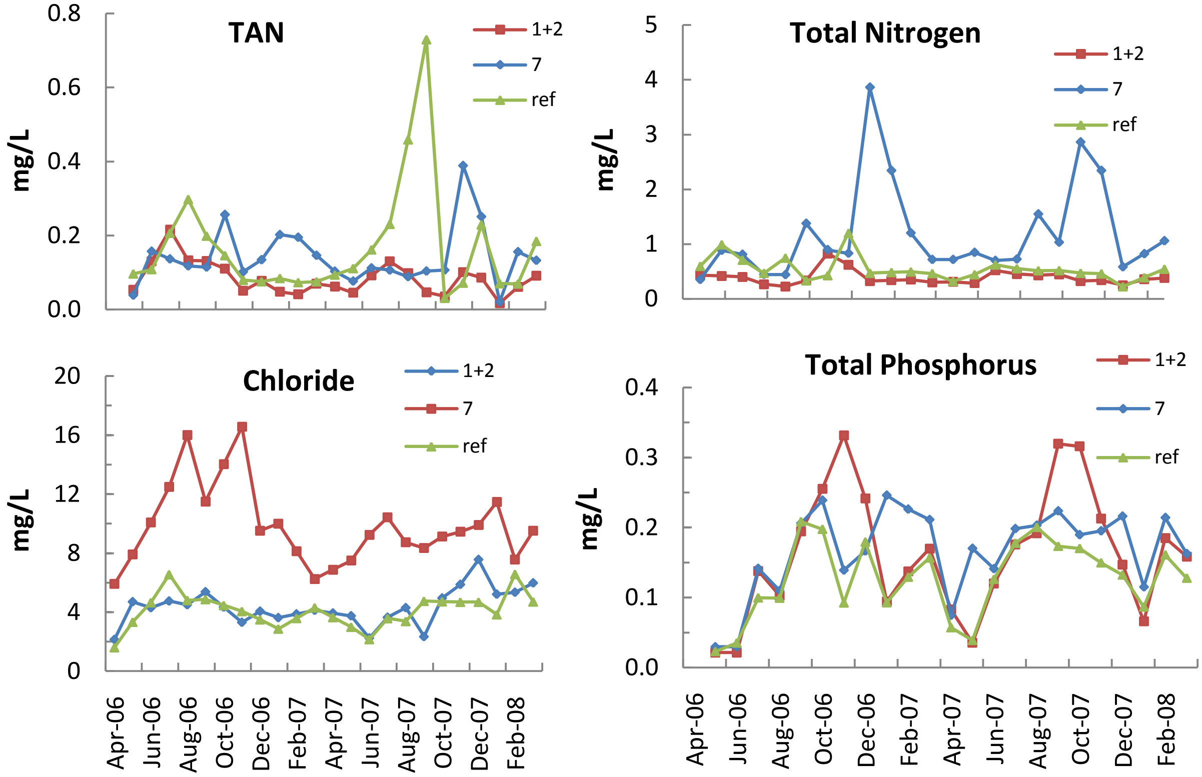


Figure 5. Concentration of water quality variables at monthly intervals in Lower Station Creek upstream of small research pond area (1), at outfall into Saugahatchee Creek (7), and reference (ref) streams.



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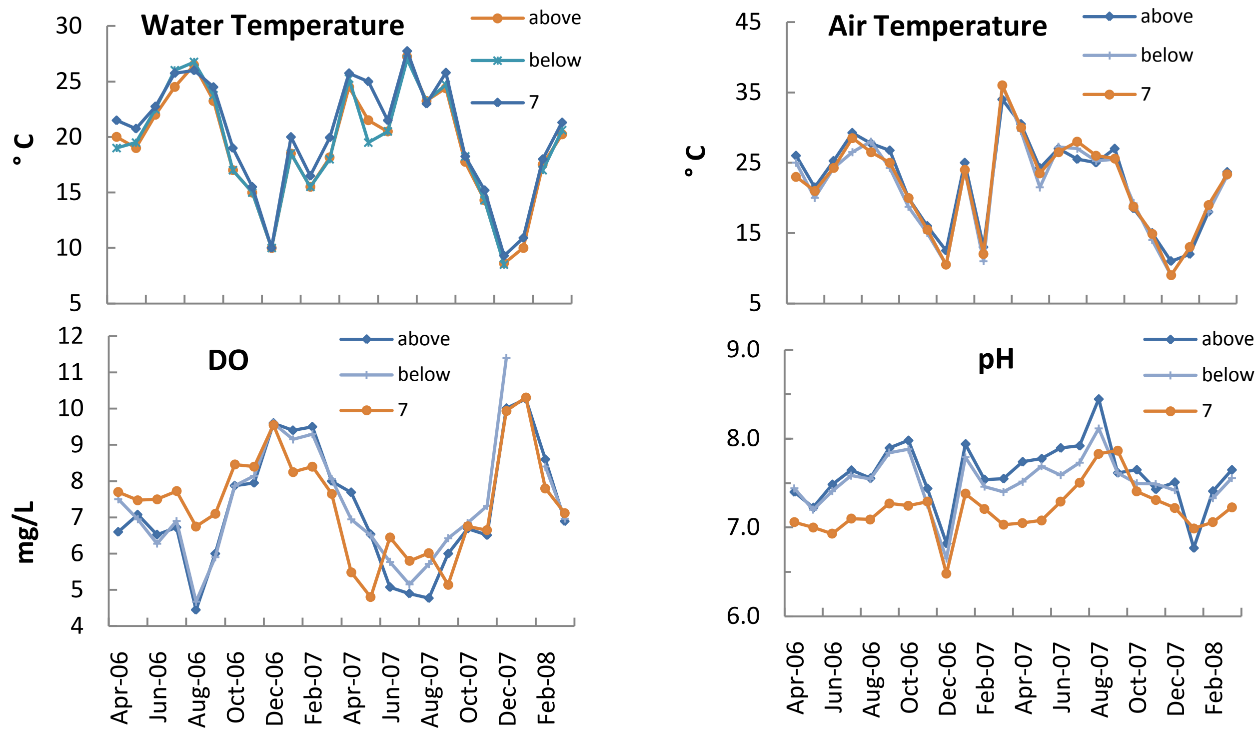

Figure 7. Concentration of water quality variables at monthly intervals at outfall of Lower Station Creek (Station7) and at station in Saugahatchee Creek about 550 m upstream (above) and 10 m downstream (below) the outfall.

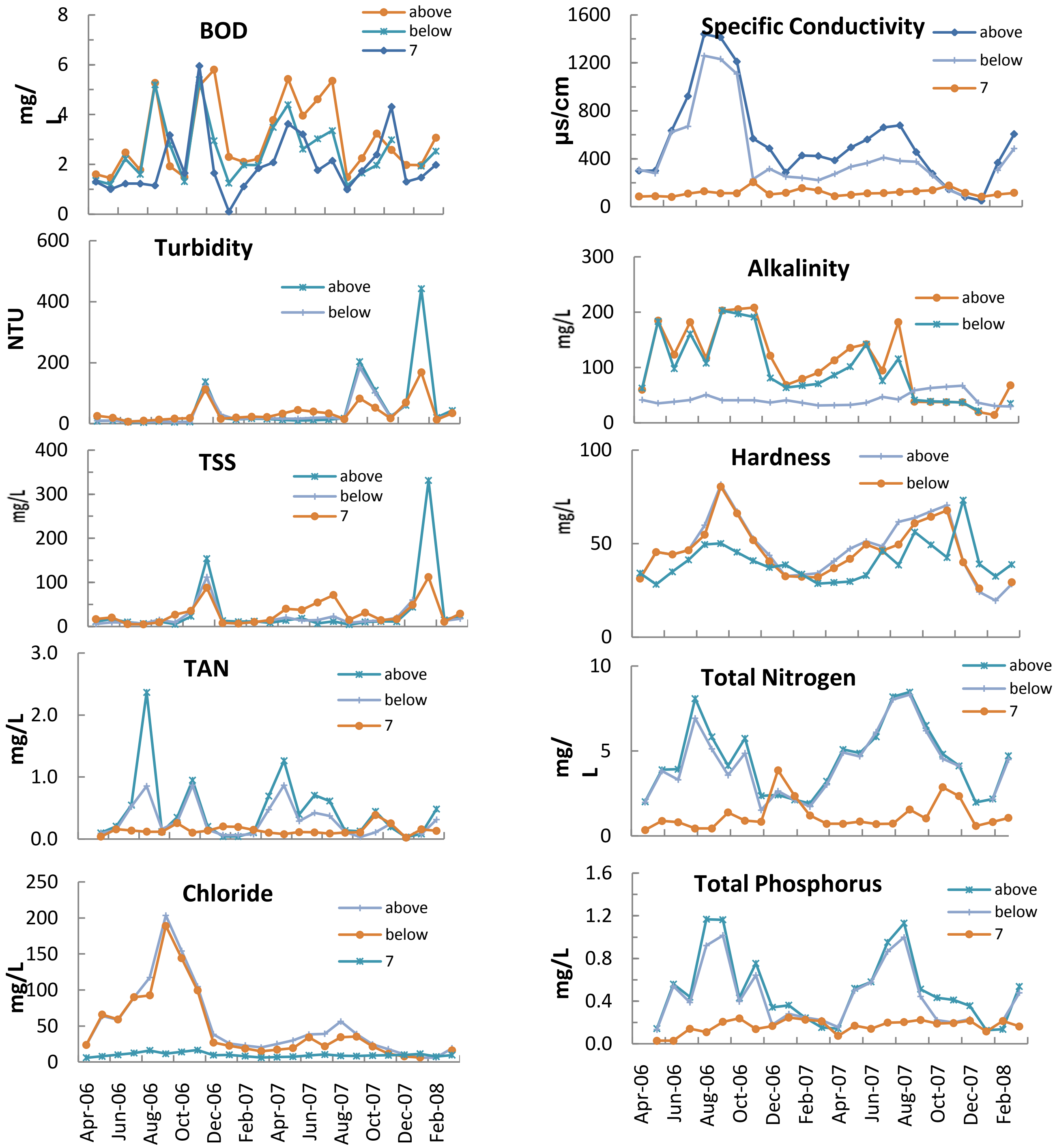

Figure 8. Concentration of water quality variables at monthly intervals at outfall of Lower Station Creek (Station7) and at station in Saugahatchee Creek about 550 m upstream (above) and 10 m downstream (below) the outfall.

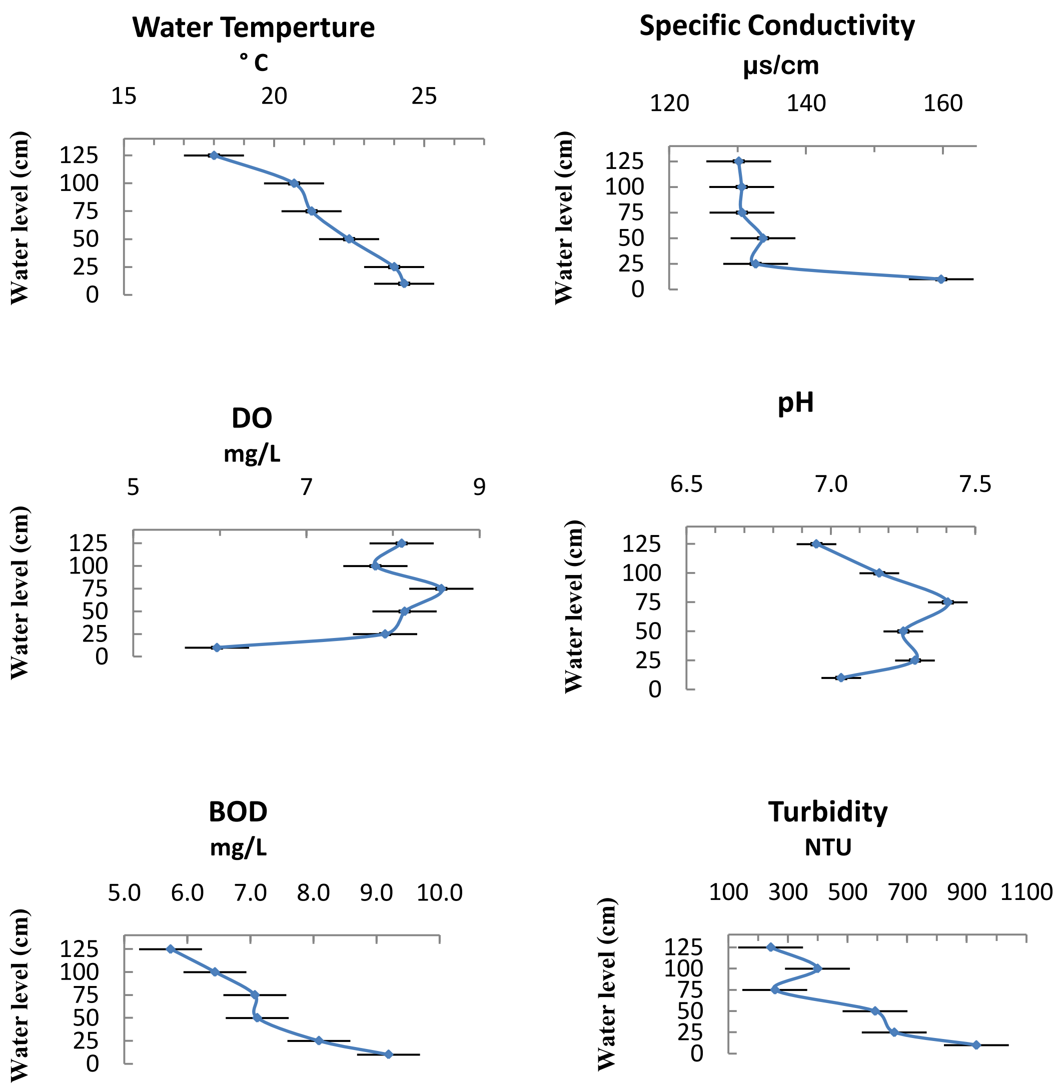

Figure 9. Means and standard errors for concentration of water quality variables during drawdown for harvest of six ponds at the Aquaculture Production Research Unit of the E. W. Shell Fisheries Center.

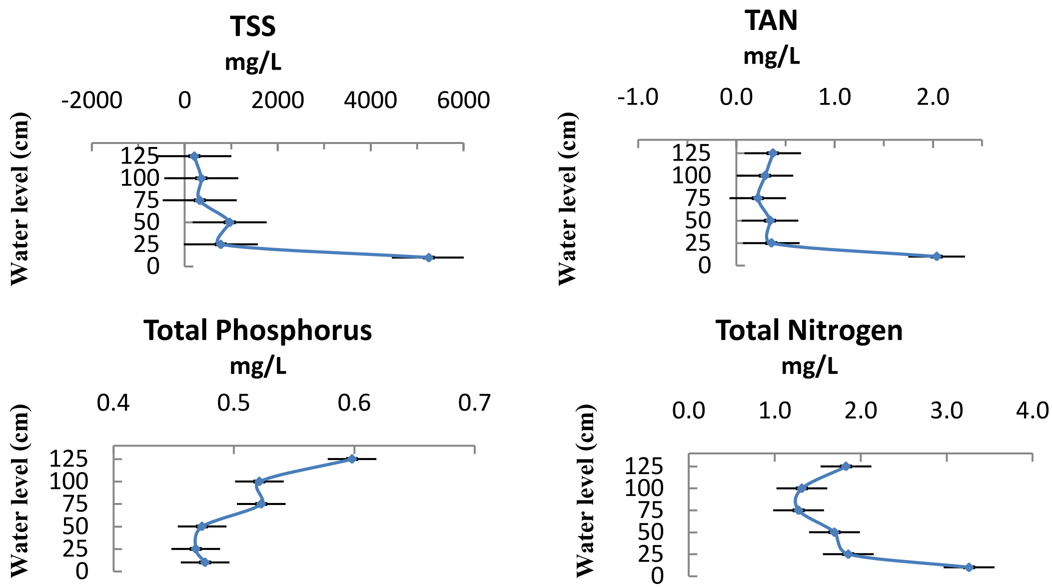

Figure 10. Means and standard errors for concentration of water quality variables during drawdown for harvest of six ponds at the Aquaculture Production Research Unit of the E. W. Shell Fisheries Center.

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