INVESTIGATIONS OF WATER SUPPLY AND WATER QUALITY ISSUES RELATED TO INLAND SHRIMP FARMING IN WESTERN ALABAMA

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INVESTIGATIONS OF WATER SUPPLY AND WATER QUALITY ISSUES RELATED TO INLAND SHRIMP FARMING IN WESTERN ALABAMA

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Christopher Andrew Boyd, son of Glenda and Claude Boyd, was born in Aiken, South Carolina USA on March 23, 1971. He has a wife, a sister and a brother, Mary, Stacy, and Claude. He earned his bachelors degree in agronomy and soil science at Auburn University, Auburn, Alabama in 1994. He earned his masters degree in crop soil and environmental science at Clemson University, Clemson, South Carolina in 1997. He has completed his research and earned his Ph.D. from the Department of Fisheries and Allied Aquacultures, Auburn University on August 7, 2006.

DISSERTATION ABSTRACT

INVESTIGATIONS OF WATER SUPPLY AND WATER QUALITY ISSUES RELATED TO INLAND SHRIMP FARMING IN WESTERN ALABAMA

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Examination of data on chloride concentrations in well waters revealed that an area in Greene, Sumter, Hale, Marengo, and Wilcox Counties had the greatest potential for inland culture of marine shrimp. A few places in Tuscaloosa and Lowndes Counties also have access to groundwater of adequate salinity. Highly saline groundwater in Washington, Clarke, and Choctaw Counties did not appear as acceptable for shrimp culture.

Studies conducted at an existing inland shrimp farm in Greene County showed that potassium applied to ponds as fertilizer to correct a potassium deficiency in pond waters was lost from ponds by bottom soil adsorption, seepage, and discharge of water for harvest. Estimates of potassium adsorption by bottom soil revealed that the capacity of the soil to exchange other ions for potassium in the water was mostly filled during a single shrimp crop. However, the bottom soils contained 2:1 type clay minerals with high capacity to fix potassium through noncationic exchange processes. Pond soils likely will remove added potassium from water for several years, and the only reliable way to determine when potassium fertilizer should be applied to inland shrimp ponds in Alabama is to monitor potassium concentrations in the water.

The salt input to the shrimp farm in Greene County was saline well water, fertilizer, feed, rainfall, and runoff was 1,980.8 tonnes of salt over a 5-year period. A total of 1,588 tonnes of the added salt was lost to the environment with almost equal amounts lost exiting ponds in seepage and effluent (overflow and draining). The salinity of water in a small creek flowing through the farm and in the shallow aquifer beneath the pond area was elevated by saline water discharged from the ponds. However, chloride concentration in the receiving stream, Needham Creek, only exceeded the Alabama Department of Environmental Management "in stream" standard of 230 mg/L when water was discharged from ponds to facilitate shrimp harvest in the fall. Greater water reuse or more gradual release of pond effluents during harvest would reduce the peak in chloride concentration in Needham Creek during shrimp harvest.

Style manual or journal used Journal of the World Aquaculture Society

Computer Software used Microsoft Excel 2000, Microsoft Word 2000, SigmaStat 2.0, and SigmaPlot 8.0

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I. INTRODUCTION

Shrimp farming traditionally has been conducted in ponds constructed in coastal areas and supplied with seawater or brackish water from estuaries. Many conflicts have arisen between shrimp producers and other stakeholders because of mangrove destruction, water pollution, and other negative impacts of shrimp culture. Moreover, viral diseases and impaired water quality have had disastrous effects on coastal shrimp farming, and in some places shrimp farms have failed.

In view of the problems with coastal shrimp culture, innovative individuals in several Alabama counties are attempting to take advantage of saline groundwater resources in inland areas for use in shrimp production. There is a general consensus that problems associated with coastal aquaculture can be avoided in inland areas. There is groundwater in central and west-central Alabama with salinity suitable for marine shrimp. However, the water often has a low potassium concentration, and ponds must be treated with potassium fertilizer to improve survival and growth of shrimp. Several farmers have had enough success producing Panaeus vannemei (Pacific white shrimp) to stimulate considerable interest in the expansion of inland shrimp farming in the Blackland Prairie physiographic region.

Producers and prospective producers of shrimp in Alabama need assistance with several issues related to water supply and water quality as follows:

- Location of saline groundwater suitable for inland shrimp culture in central and west-central Alabama
- A better understanding of losses of added potassium from pond waters so that more efficient potassium fertilization is possible
- Evaluation of the possibility of salinization of shallow aquifers and streams receiving discharge from shrimp farms
- Development of techniques for preventing salinization

This study was initiated to investigate water supply and water quality issues mentioned above. Much of the research was conducted on a single shrimp farm in Greene County, but the findings will likely be applicable to other sites.

II. REVIEW OF LITERATURE

Aquacultural production of marine shrimp has been increasing for the past few decades. Aquaculture currently supplies about 30% of the world supply of shrimp (Anonymous 2006). Originally, shrimp were cultured in brackish water ponds filled by tidal action or pumping. Water in ponds was exchanged at 10 to 20% of volume per day to maintain good water quality (Fast 1992). Growth of the industry has been rapid and uncontrolled, and many mistakes were made related to site selection and management. There have been severe problems with diseases such as white spot syndrome and Taura syndrome viruses (Wickins and Lee 2002). Also, construction of shrimp farms in coastal areas has infringed on mangrove and other wetlands, and effluents from ponds have caused water pollution (Boyd and Clay 1998). Because of the many problems facing the industry, research has been conducted to improve methods of disease control, to prevent damage to coastal wetlands, and to lessen pollution in historical shrimp farming areas. Two examples of new shrimp farming technology are pond culture in lined ponds with no effluent discharge (zero-exchange systems) as described by (McIntosh 1999) and inland shrimp farming (Jory 1999; Samocha et al. 2002; Davis et al. 2003).

Inland shrimp farming could lower disease pressure because farms would not be as concentrated in one area or share a common water supply that often doubles as the effluent recipient. The isolated water sources for inland farms should be free of contaminated water created by neighboring shrimp farms or other water users. Prices tend to be less for land in inland areas because land is usually in much greater demand along the coast. Inland areas often are less ecologically sensitive than coastal areas. Moreover, biosecurity is easier to achieve at inland farms than at coastal ones (Samocha et al. 2002). Best management practices should nevertheless be followed in inland shrimp farming to reduce stream, soil, and aquifer salinization and to prevent eutrophication of streams and other water bodies (Musig and Boonnom 1988; Boyd 2001; Boyd et al. 2004).

Inland culture of *Penaeus vannamei* or Pacific white shrimp probably was done first in Texas by Smith and Lawrence (1990) using saline well water as a water source. Inland culture of marine shrimp became quite successful in Thailand in the early 1990s. Brine solution from seawater evaporation ponds is used as a source of salt in Thailand (Limsuwan et al. 2002). Farmers mix the brine solution with freshwater from irrigation systems or other sources to provide water with 2 to 5 ppt salinity for shrimp culture (Fast and Menasveta 2000). After the Thai's successful venture into inland culture of marine shrimp, producers in other nations began to attempt this endeavor. For example, inland shrimp farming has been done in China, United States, Ecuador, and several other nations indicating that inland culture of marine shrimp is occurring worldwide (Boyd and Thunjai 2003). Unlike in Thailand, producers in other nations are using saline groundwater pumped from wells instead of brine solution, because brine often is not available at a reasonable price.

The initial trial of inland shrimp culture in the United States was done in ponds supplied with groundwater containing 28 ppt salinity. Acclimation was easy, and good survival was achieved (Smith and Lawrence 1990). Today, inland shrimp farming is established in other areas of Texas, Alabama, Arkansas, Arizona, Florida, and possibly other states. However, the salinities of well water used in most inland shrimp ponds in the United States tend to be less than 10 ppt, acclimation is a critical step in the production process, and survival sometimes is low (Boyd and Thunjai 2003).

The Pacific white shrimp is a euryhaline species that can tolerate wide fluctuations in salinity throughout its life cycle (Atwood et al. 2003). In nature, shrimp do most of their growing in estuaries where salinities vary greatly. Post larvae for aquaculture can be acclimated to low salinity, but the acclimation procedure must be carefully controlled and done gradually. The age of the post larvae also is a big factor. Once post larvae are about 15-days old, they can be acclimated to salinity less than 4 ppt with little mortality (McGraw et al. 2002; Davis et al. 2004).

Although *P. vannamei* can survive low salinity water, it cannot survive cool water for extended periods of time. At low temperatures, metabolic processes slow down to the point that cellular processes do not work fast enough for survival (Lester and Pante 1992). In Alabama, water temperatures are adequate for shrimp production from mid May through late September or early October – about 4 or 5 months. Pacific white shrimp grow at a rate of 1 g or more per week under good conditions (Davis et al. 2004). Therefore, Pacific white shrimp can be reared to 20 to 25 g body weight during the growing season provided by Alabama climate. It is, however, impossible to produce more than one crop per year in outdoor ponds in Alabama or other sun belt states while two or more crops per year can be produced in tropical climates. Producers in the United States try to grow a larger shrimp to compensate for fewer crops per year. The larger sized shrimp will net higher prices and faster returns at the market (Wickins and Lee 2002).

The salinity of water can be evaluated in several ways. Salinity is equal to the sum of the concentration of all individual, inorganic ions in water (Wetzel 2001). Analyses to calculate salinity from the sum of ions are prohibitively expensive, and salinity usually is measured with a salinity refractometer. The total dissolved solids concentration usually is roughly equal to the salinity (Boyd 2000). This measurement is useful for low salinity waters but unsuitable for highly saline water. The specific conductance of water increases as concentration of ions increase, so specific conductance is a good indicator of salinity and total dissolved solids (Hem 1970). Meters that read total dissolved solids or salinity directly are modified conductivity meters. Many groundwater geologists have reported chloride concentration as an indicator of the degree of mineralization of groundwater (Cook 1993, 1997). In seawater, chloride multiplied by 1.8 is a good estimate of salinity (Strickland and Parsons 1972), but the factor is usually higher for low-salinity inland water (Boyd 2000). There is no good general agreement about the level of salinity, total dissolved solids, specific conductance, or chloride that delineates a freshwater form a saline one. Boyd (2002) suggested using 1 ppt salinity or a specific conductance of 1.5 mS/cm to make this separation. The world average concentration of total dissolved solids in river water is 120 mg/L of which chloride comprises 7.8 mg/L. Total dissolved solids and chloride often exceed 500 mg/L and 100 mg/L, respectively, in rivers of some arid climates (Livingstone 1963). Thus waters with over 100 mg/L chloride can be considered highly mineralized.

The groundwater used to fill production ponds should have salinity greater than 2 ppt, and the water should be tested to determine ionic deficiencies compared to that of seawater (Boyd 2003). The following elements are typically found in ground water: calcium, magnesium, sodium, potassium, bicarbonate, sulfate, chloride, nitrate, silica, and trace elements that include iron, manganese, zinc, copper, boron, and others (Bureau of Reclamation 1977). Of these elements, calcium, magnesium, potassium, sodium, chloride, and sulfate are the most important for shrimp culture. The minimum concentrations of these ions needed by shrimp in low-salinity culture are not known (Boyd et al; 2002). However, it is assumed that shrimp will survive and grow best if the ionic proportions are the same as those for seawater diluted to the same salinity as the low-salinity culture water. Conversion factors provided by Boyd et al. (2002) allow determination of the concentration of major ions that would be expected in normal seawater (34.5 ppt) diluted to the salinity of the culture water. The factors are as follows: calcium, 11.6; magnesium, 39.1; potassium, 10.7; sodium, 304.5; chloride, 551; sulfate, 78.3. For example, suppose a culture water of 2 ppt salinity contains 5 mg/L potassium and 10 mg/L magnesium. Seawater diluted to 2 ppt salinity should contain 21.4 mg/L potassium (2 ppt X 10.7) and 78.2 mg/L magnesium (2 ppt X 39.1). If possible deficiencies in ionic concentrations are noted, as in the example, mineral amendments can be added to pond water to improve the prospects for adequate shrimp growth (McNevin 2004).

The following ions are involved in shrimp osmoregulation: sodium, calcium, magnesium, potassium, chloride, and sulfate. When comparing the concentrations of these ions in various groundwaters to those of seawater held at the same salinity, magnesium, potassium, and sulfate often appear to be deficient (McGraw and Scarpa 2003, Boyd and Thunjai 2003). For inland farms in Alabama, it is thought that the pond water potassium concentration should be at least 30 mg/L, magnesium concentration should be greater than 20 mg/L, and sulfate concentration should be greater than 50 mg/L to obtain adequate survival. Applying muriate of potash (potassium chloride) and Kmag® (potassium magnesium sulfate) will increase potassium, magnesium, and sulfate concentrations of the pond water (McNevin et al. 2004, Prangnell and Fotedar 2005). Additions of these fertilizers greatly increased survival and production of shrimp at farms in Alabama, and potassium apparently provided most of the benefit (McNevin et al. 2004). Potassium is an essential mineral in animals because of its involvement in cellular metabolism (Kem and Trachewsky 1983). In order to reach concentrations comparable to those of diluted seawater, magnesium concentrations should actually be raised to around 130 mg/L and sulfate concentrations should be increased to around 240 mg/L in the pond water when the salinity is around 3 ppt (McNevin et al. 2004). It would be uneconomical to increase the concentrations of magnesium and sulfate to such high levels. Fortunately, it appears that increasing the potassium to the expected concentration of diluted seawater and effecting moderate increases in magnesium and sulfate concentrations is adequate to assume good yields of marine shrimp.

Typical applications of potassium fertilizers are 250 to 500 kg/ha of muriate of potash and 1,000 to 2,000 kg/ha of Kmag to inland ponds in Alabama (McNevin et al. 2004). Thus, the cost of increasing potassium concentrations in ponds is substantial. Research is needed to refine application rates of potassium fertilizer based upon salinity and background potassium levels of pond water and the capacity of bottom soil to adsorb this ion.

Potassium is an abundant element in the soil but the problem is that only 1 to 10% of total soil potassium is available to plants over the growing season (Brady 1990; Aikawa 1983). The soil contains potassium that is exchangeable, non-exchangeable, or combined in primary minerals (Brady 1990). Exchangeable potassium is in equilibrium with potassium in the soil solution, and potassium in the soil solution is readily available to plants. If plants do not take up soil solution potassium, it is leached out of the soil profile. Only 1 to 2 % of the total potassium in most soils is in the exchangeable form. The non-exchangeable potassium is fixed by soil colloids, especially in 2:1 type clay minerals such as those found in the Blackland Prairie region of Alabama (Dixon and Nash 1968). In many soils, the amount of fixed potassium exceeds the quantity of exchangeable potassium (Yuan et al. 1976). The non-exchangeable, fixed potassium is in equilibrium with the exchangeable and soil solution potassium, so it is a major factor in the potassium cycle. Non-exchangeable potassium can supply some of the potassium requirement of crops during the growing season (Brady 1990). Primary minerals contain most of the potassium in soil. Potassium in these minerals may be released slowly over time, but primary minerals are not considered a source of potassium during a single growing season (Brady 1990).

In inland shrimp ponds in Alabama, potassium concentration in well water declines when this water is placed in ponds. Also, potassium concentrations gradually decline following potassium fertilization (McNevin et al. 2004). Thus, it is apparent that inland shrimp pond soils in Alabama are a sink rather than a source for potassium.

Information in soil uptake of potassium from traditional agriculture can be useful in understanding the potassium uptake by pond bottom soils.

Factors that affect soil uptake of potassium are the type of parent material, clay mineralogy, particle size, and pH. Clay minerals are very reactive and give the soil the largest amount of its nutrient holding capacity. Clay minerals have a very small particle size which gives the particles a large surface area (Brady 1990). The negative charges in clay minerals attract cations, and the ability of soils to hold cations is referred to as cation exchange capacity. Soils with 2:1 type clay minerals such as those of the Blackland Prairie may have CEC values of 20 to 30 meq/100g or greater (Dixon and Nash 1968). Large amounts of potassium can be held on cation exchange sites in such soil. Potassium fixation occurs when potassium is held between adjacent tetrahedral layers of clay minerals (Sparks 2000). Clays of the 2:1 type also have a large capacity to fix potassium. As the soil increases in pH more potassium is fixed, but as the soil pH decreases less potassium is held by fixation (Sparks 2000).

When shrimp farmers apply potassium to their ponds, potassium will be removed from the water by cation exchange processes and through fixation by the soil colloids. The soils in the Blackland Prairie contain large amounts of 2:1 clay minerals. They have high cation exchange capacities and their pH usually is above 7. All these factors favor potassium adsorption. Eventually potassium fixation by bottom soils should slow down and less potassium fertilizer will need to be added. However, research and monitoring programs need to be conducted to thoroughly understand this process.

The small group of Alabama farmers who have initiated projects to produce marine shrimp in Lowndes, Greene, and Tuscaloosa Counties have been successful enough to suggest that a small-scale, shrimp farming industry could be sustainable in Alabama. This industry could be especially important in the economically depressed, Blackland Prairie region where the catfish farming has been the only expanding agricultural activity in several decades (Perez 2006). Diversification of the catfish industry by growing inland shrimp or other species of marine fish could make the aquaculture industry more sustainable.

Information on the saline ground water resource in Alabama is needed to support any effort to encourage saline-water aquaculture. The United States Geological Survey and the Geological Survey of Alabama have studied the ground water quality of the major aquifers in central and west-central Alabama. Data from these studies show that highly mineralized waters exist in several aquifers. Chloride concentrations in water from wells in some locations exceed the United States Environmental Protection Agency drinking water standard of 250 mg/L (Cook, 1993). The well water used at some catfish farms in Greene, Hale, Marengo, and Tuscaloosa Counties had salinities of 1.5 to 6 ppt (Boyd and Brown 1990). Available data on saline groundwater collected by the two geological survey agencies should be evaluated and organized in a form accessible and understandable to those interested in saline-water aquaculture.

Although inland shrimp farming is hailed as a possible new source of income for rural areas, it presents a risk of soil and water salinization. For example, Braaten and Flaherty (2001) reported an average salt loss per crop to the environment from 0.26-ha inland shrimp ponds in Thailand of 11.5 tones in seepage, 9.7 tones in harvest effluent, and 1.8 tones in sediment removed from ponds. Effluents from inland shrimp culture caused salinity in irrigation canals to increase above safe concentrations for the main crops of the region – irrigated rice and fruit trees. Therefore, the salinity of the streams, soils, and shallow aquifers in the vicinity of inland shrimp farms should be monitored to determine if negative environmental impacts are occurring. The United States Environmental Protection Agency recommended an in-stream water quality standard of 230 ppm of chloride (Benoit 1988), and the Alabama Department of Environmental Management (ADEM) has adopted this standard. In order to comply with the ADEM chloride standard, water in shrimp ponds should be reused and not discharged at harvest. Seepage and overflow from ponds should be minimized through pond design features and application of a best management practice plans during operation (Boyd et al. 2004).

The use of saline ground water to grow shrimp would make good use of a natural resource that normally is unwanted. It has been reported that two thirds of the continental United States has underground saline resources (Feth et al. 1965; Feth, 1970; Smith and Lawrence 1990). Thus, there may be a large potential for inland shrimp farming, and it should be encouraged especially in salt-affected land (Smith and Lawrence 1990). Effluents can be discharged onto unused land, in arid areas where they would evaporate and the salt residue would not be troublesome. Nevertheless, it has been shown that the water used for inland production can be used to grow shrimp along with growing other salt tolerant agronomic crops to promote the use of this resource while preventing salinization of our resources (Smith and Lawrence 1990; Samocha et al. 2002). In humid areas like Alabama, effluents probably cannot be used for irrigation, and they should not be discharged onto land areas because they could cause soil salinization.

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III. LOCATIONS AND CHLORIDE CONCENTRATIONS OF SALINE AQUIFERS IN CENTRAL AND WEST-CENTRAL ALABAMA

Abstract

Culture of shrimp and possibly other marine species in inland ponds supplied by well water from saline aquifers is a potential new industry in Alabama. Based on examination of 2,527 well records of the Geological Survey of Alabama and the United States Geological Survey and visits to 35 well sites, 238 saline water wells (125 mg/L chloride of more) were located in ten counties of central and west-central Alabama. Saline water occurred in eleven of the twelve counties and in aquifers of fifteen different geological formations. Chloride concentrations varied from 136 to 94,000 mg/L. The highest chloride concentrations were from wells in Washington, Choctaw, and Clarke Counties. However, 83% of the saline-water wells were supplied by aquifers of the Eutaw, Gordo, McShan, and undifferentiated Eutaw-McShan Formations within Dallas, Hale, Greene, Marengo, Wilcox, and Sumter Counties. Water from these wells had an average and standard deviation of 1,238 ± 615 mg/L chloride. Chloride concentrations in Dallas County did not exceed 620 mg/L; thus, this county is not considered a potential area for inland shrimp farming. These same aquifers also occur in Perry County, but no saline wells were found in this county. Wells in these aquifers often were less than 300 m deep, and Hale, Greene, Marengo, Wilcox, and Sumter Counties have the greatest potential for saline-water aquaculture. Contour maps for chloride concentrations and

depths of wells in these five counties were prepared to better delineate this potential water resource.

Introduction

Saline groundwater, when found in adequate quantities, can be used to fill and operate aquaculture ponds to produce marine shrimp (Boyd et al. 2002; McNevin et al. 2004). Several farmers in Alabama have initiated projects to produce Pacific white shrimp (Litopenaeus vannamei) in Lowndes, Greene, and Tuscaloosa Counties. These farms have been successful enough to suggest that a small-scale shrimp farming industry could be sustainable in the state. This endeavor could be especially important in the economically depressed, Blackland Prairie region. Diversification of the existing channel catfish industry by growing species of marine shrimp or fish could make aquaculture more sustainable and profitable in the region.

Survival of postlarval shrimp during acclimation is low at salinities below 1 ppt (Cawthorne et al. 1983; McGraw et al. 2002). Nevertheless, marine shrimp have been grown to marketable size in China in pond waters with salinities as low as 0.4 ppt (Boyd and Thunjai 2003). Shrimp survival and growth is much better in inland ponds when salinities are 2 to 5 ppt (Limsuwan et al. 2002). Based on previous studies, well waters with salinities below 0.3 to 0.4 ppt probably cannot be used successfully for inland culture of shrimp, while those with salinities above 2 ppt have the greatest potential.

In the United States, the chloride concentration typically is reported as an indicator of the degree of mineralization of well water (Briggs and Fielder 1975). According to findings of Tavares and Boyd (2003), a well water sample from the

Blackland Prairie region of Alabama with a salinity of 0.4 ppt should contain about 125 mg/L chloride, and a water with 2 ppt salinity should have over 700 mg/L chloride.

Considerable information is available on the locations and chloride concentrations of wells in saline aquifers in Alabama, but these data have not been organized into a readily accessible form. Ground water at certain locations in west-central Alabama has been noted to have such high chloride and total dissolved solids concentrations to make it unsuitable for drinking purposes (Cook 1993). However, this saline groundwater resource is highly prized as a source of water for channel catfish ponds because of the therapeutic value of chloride and other dissolved salts to fish (Boyd and Brown 1990; Boyd et al. 2004).

This study was conducted to assemble information for promoting inland shrimp farming in Alabama. Sites with saline groundwater were located through collecting well water samples and searching archived well data (USGS 2006). The maps produced from the findings of this study will be helpful in locating places that are suitable for inland culture of shrimp and possibly other marine species.

Materials and Methods

The study area for this research was located within twelve counties in west-central Alabama (Fig. 1,3). Data on chloride concentrations in well water within the study area were obtained from three sources: a) groundwater resource bulletins of the Geological Survey of Alabama, b) United States Geological Survey website, and c) field sampling conducted during this study. The samples collected for this study were analyzed for chloride concentration by titration to the diphenylcarbazone endpoint with standard mercuric nitrate (Clesceri et al. 1998). Wells with chloride concentrations of 125 mg/L or above were considered potential water sources for inland shrimp farms.

Depths and chloride concentrations of water were obtained for wells in the following counties: Choctaw, Clarke, Dallas, Greene, Hale, Lowndes, Marengo, Perry, Sumter, Tuscaloosa, Washington, and Wilcox. Well locations and accompanying data were entered into Geographic Information System geographic grid based on their coordinates (latitude and longitude) taken by a GPS handheld unit onsite (Garmin GPS 12) and coordinates listed for wells in databases of the Geological Survey of Alabama and United States Geological Survey. The computer software programs Excel and ArcGIS were used to create the maps and to display well locations, chloride concentrations, and well depths on them. Inverse distance weighting interpolation method, County Boundary, and Watershed Boundary identified on the Alabama Soil and Water Conservation committee website were superimposed onto the maps to allow additional perspective.

Results and Discussion

Aquifers in Study Area

A brief description of the water-yielding formations and general comments about the degree of mineralization of their waters will be provided.

Choctaw County

Major sources of groundwater are the Nanafalia, Hatchatigbee, and Lisbon Formations and the Gosport and Tuscahoma Sands. Most of the groundwater in Choctaw

County is not highly mineralized. In the northeastern corner of the county, there are areas of massive and relatively impermeable clay, silt, and chalk deposits that extend to depths of 380 to 440 m below the land surface. These deposits contain water that is highly mineralized. In the southeastern corner of the county, the Hatchetigbee Anticline also yields highly mineralized water (Newton and McCain 1972).

Clarke County

Two major subsurface geological features, the Hatchetigbee Anticline and the Jackson Fault, are found in the southwestern part of Clarke County. However, the principal aquifers capable of producing groundwater for wells are found in the Nanafalia, Hatchatigbee, and Lisbon Formations, Gosport Sand, and Miocene and Pliocene Series. The Naheola Formation will only yield small quantities of water to wells, but its water is highly mineralized with concentration of chlorides greater than 20,000 mg/L (Lawson and McCain 1971).

Dallas County

Large amounts of ground water are available from permeable beds of sand and gravel. The principal aquifers capable of producing ground water for wells are found in the Coker, Gordo, Eutaw, and Ripley Formations and in terrace deposits and alluvium. Within the Eutaw aquifer, the chloride concentration generally is low except for in the southeastern most part of the county where waters are more mineralized (Scott et al. 1981).

Greene County

Geologic units that yield water to wells are of sedimentary origin and consist of sand gravel, chalk, and clay. The Coker, Gordo, McShan, and Eutaw Formations, and alluvial and terrace deposits contain aquifers capable of sustaining wells. Chloride concentrations tend to be greater than 1,000 mg/L between Forkland and Boligee from east to west in the southern part of the county within the Gordo Formation. The Eutaw Formation also has locations with high chloride concentrations, but the samples tend to have slightly lower concentrations than found in the Gordo Formation (Wahl 1966).

Hale County

The major aquifers are contained in the Coker, Gordo, and Eutaw Formations. The groundwater in Hale County typically has moderate concentrations of dissolved solids, but the northwestern and west-central parts of the county have some wells with mineralized water of higher chloride concentration (Davis et al. 1975).

Lowndes County

Most of the groundwater in Lowndes County is supplied by sand beds found in the Gordo, Eutaw, and Ripley Formations, terrace deposits, and alluvium (Scott 1957). The Gordo and Eutaw Formations tend to have high chloride concentrations. The Gordo Formation is about 200 m below the surface in the north of the county and it is around 600 m below the surface in the south. In the northern part of the county, the Gordo aquifer contains chloride concentrations as low as 2 mg/L, but the concentration increases to as much as 5,000 mg/L in the southern portion. The chloride concentration of water from the Eutaw aquifer ranges from less than 100 mg/L in the eastern part of Lowndes County to greater than 3,500 mg/L in the central part of the county (Gillett and Hunter 1990).

Marengo County

The major sources of groundwater are the Eutaw and Nanfalia Formations and the Tuscahoma Sand. The Eutaw Formation is found in the northern part of Marengo County and the Tuscahoma Sand and Nanfalia Formation occur in the southern part of the county. In the northwestern and south-central parts of the county, the water is highly mineralized with chloride values exceeding 1,000 mg/L (Newton et al. 1971).

Perry County

Beds of sand and gravelly sand in the Coker, Gordo, and Eutaw Formations provide most of the available groundwater within Perry County. In general the groundwater in Perry County is of good quality and suitable for most uses, but some waters from some wells have high levels of iron and hardness (Reed et al. 1972).

Sumter County

The major aquifers that supply groundwater in Sumter County are the Coker, Gordo, and Eutaw Formations. These aquifers tend to have concentrations of chloride greater than 500 mg/L in all areas but the northern and eastern parts of the county (Davis et al. 1980).

Tuscaloosa County

Sand, gravel, clay, chalk, and coal underlie a large portion of Tuscaloosa County (Paulson et al. 1962). Important water-yielding geological units in this county are the Coker, Gordo, McShan, and Pottsville Formations, and alluvial and terrace deposits. Water in the Coker Formation tends to be low in chloride concentration except in down dip portions of the aquifer in the eastern part of the county. Water in the Pottsville Formation is more mineralized at greater depth (Hunter and Moser 1990).

Washington County

In the northern part of Washington County, geological outcrops containing beds of permeable sand and limestone that serve as natural reservoirs for water. The Hatchetigbee Anticline and Jackson Fault located along the northeast and eastern boundaries of the county are responsible for highly mineralized groundwater, but there are large variations in depth to the water table (Newton et al. 1972).

Wilcox County

The geologic units in Wilcox County are of sedimentary origin, and they consist mainly of sand, gravel, chalk, and clay (Lamoreaux and Taoulmin 1959). The major aquifers are comprised of sands found in the Eutaw, Ripley, and Nanafalia Formations. Chloride concentrations greater than 250 mg/L can occur in the down dip sections of aquifers and in areas of faults and folds (Chandler 1987).

Geological factors and water quality

Many of the groundwater samples high in chloride concentration from the western Alabama Blackland Prairie region are located in the Eutaw aquifer. The Eutaw aquifer has been thoroughly studied in western Alabama because of problems resulting from highly mineralized waters of wells drilled for domestic water supplies (Cook 1993). The United States Environmental Protection Agency set a chloride limit of 250 mg/L for drinking water. The chloride standard can be exceeded in well waters within a large portion of the western Alabama region (Cook 1993). In particular, water in the down dip portions of the Eutaw Aquifer tends to have high chloride concentrations. This is primarily related to the fact that salts tend to leach downwards from sediments as the water moves down an elevation gradient from the recharge area (Cook 1993). There are also wells with chloride concentrations more than 3,000 mg/L in or near the recharge area in the Eutaw aquifer in Lowndes County (central Alabama) and Hale, Greene, and Sumter Counties (west-central Alabama). Cook (1997) stated that "the most likely causes of high concentrations of chloride in up dip areas are retention of ions from connate water, selective concentration of ions by clays acting as semi-permeable membranes, and upwelling of deep mineralized water along faults and fractures associated with basement structures of the Piedmont and Valley and Ridge Physiographic Provinces."

Waters of the Eutaw Formation have a wide range of chloride concentrations depending on where samples are taken. The recharge areas usually are low in chloride concentration, but locally high chloride concentrations result from special geological forces that create an upwelling of chloride. This occurs because the chloride ion is negatively charged and soil with high clay content tends to have permanent net negative charges. These negative charges on clay lattices lead to the leaching of chloride ions and the adsorption of positively charged ions. In an aquifer, the cations will tend to be at a higher concentration at the top of the aquifer and the anions tend to be at higher concentrations at lower depths within the aquifer (Cook 1993; Hem 1985).

Seven major chemical classes of water have been documented for the Eutaw aquifer in Alabama (Cook 1993) as follows: calcium bicarbonate, sodium bicarbonate, sodium-calcium bicarbonate, sodium bicarbonate-chloride, sodium-calcium chloride, sodium chloride, and calcium chloride-sulfate.

The sodium bicarbonate-chloride groundwater is found in northern Sumter, southern Greene, and western Hale Counties. This water may have chloride concentration in excess of 1,200 mg/L (Cook 1993). The sodium-calcium chloride type water occurs in two isolated areas in western Lowndes County and eastern and southern Dallas County (Cook 1993). In some areas, the sodium-calcium chloride type water can contain chloride concentration greater than 1,400 mg/L. Waters of the sodium chloride type in the Eutaw aquifer are located in an eastward trending zone that extends from Sumter County in west Alabama to Barbour County along the eastern border of the state. These waters can exceed 5,000 mg/L chloride (Cook 1993).

Chloride Concentrations by County

The database search revealed chloride concentrations for 2,527 wells, and samples were collected from 35 wells for chloride analysis (Table 1). More than half of the wells were in Tuscaloosa, Hale, and Greene Counties, and there were comparatively few well records for Lowndes, Choctaw, Perry, and Washington Counties. Chloride concentration exceeded 125 mg/L in only 238 wells (9.3% of the wells). Eighty-two saline-water wells were found in Greene County followed by Sumter with 49, Marengo with 26, Wilcox with 23, and Hale with 17. Thus, about 83% of the saline water wells were in these five counties.

There was large variation in chloride concentrations of saline groundwater across the twelve counties. The average chloride concentration of 4692 mg/L for all samples had a standard deviation of 9,407 mg/L, and the data had a range of 136 to 94,000 mg/L (Table 1). The few saline wells in Washington, Choctaw, and Clarke Counties that tended to have very high chloride concentrations contributed greatly to the extreme variation, and data from these wells profoundly influenced the average. If data from these three counties are omitted, the average and standard deviation of chloride concentration for wells in the other counties was 935 ± 440 mg/L, and the range was much narrower – 136 to 6,540 mg/L.

In terms of chloride concentration, the counties can be divided into five groups as follows: (1) Washington, Clarke, and Choctaw; (2) Greene, Sumter, Marengo, Hale, and Wilcox; (3) Tuscaloosa and Lowndes (4) Dallas; (5) Perry. The saline wells in Washington, Clarke, and Choctaw Counties occurred in a narrow band extending from northeast to southeast through the three counties (Fig. 4). Variation in chloride concentration was extremely great for saline wells in Washington, Clarke, and Choctaw Counties with ranges of 480 to 12,180 mg/L, 7,700 to 94,000 mg/L, and 590 to 34,100 mg/L, respectively (Table 1). Chloride concentrations in some of the wells suggest that waters would be too saline for aquaculture. Comparatively few wells have been drilled for domestic purposes, and apparently no wells have been installed for aquaculture. Thus, few data on water quality could be found. Anecdotal evidence from well drillers and other local individuals having knowledge of groundwater in the area suggest that the high-chloride-content waters in these counties often have troublesome amounts of iron and other water quality problems.

A cluster of saline wells was centered in Greene and Sumter Counties. This group of wells also extended into the western edge of Hale County and swept southeastward across Marengo County and into the north and western parts of Wilcox County (Fig. 4). Sixty-two percent of the saline-water wells in Greene, Sumter, Marengo, Wilcox, and Hale Counties contained between 132 and 1,144 mg/L chloride, 23% had concentrations of 1,145 to 2,155 mg/L chloride, and the remaining saline wells contained greater than 2,155 mg/L chloride (Table 2). The highest chloride concentrations for saline wells in the five-county area were found in Greene and Sumter Counties. In Greene County, the greatest number of wells had chloride concentrations between 1,145 and 3,167 mg/L, while in Sumter County; the largest number of wells had chloride concentrations between 3,168 and 5,190 mg/L. Saline wells in Marengo County had chloride concentrations ranging from 175 mg/L to 2,370 mg/L, while in Wilcox County; the range was 136 to 1,760 mg/L. Hale County contained saline wells with chloride concentration ranging from 149 mg/L to 3,040 mg/L, but this county had fewer saline-water wells than Greene, Sumter, Marengo, or Wilcox County. The watershed in the northwestern and west-central parts of Hale County that is underlain by a saline-water aquifer extends into Wilcox County. Although more records of saline wells in this watershed were found for Wilcox County than for Hale County, chloride concentrations tended to be lower than for wells within this watershed in Hale County.

There were three additional areas with saline water wells: Dallas County, Tuscaloosa County, and Lowndes County (Fig. 4). The chloride concentrations for saline wells in Lowndes County ranged from 250 to 4,648 mg/L with an average of 1,336 mg/L (Table 1). Saline wells in Tuscaloosa County tended to have lower chloride concentrations with an average of 889 mg/L and range of 213 to 2,599 mg/L (Table 1). Dallas County had the lowest chloride content saline wells with an average of 264 mg/L and a range of 158 to 620. No records of saline wells could be found for Perry County.

Chloride Concentrations by Aquifer

The formation yielding water to individual wells was reported for only 178 of the 230 wells (Table 3). Thus, most saline wells can be grouped according to aquifer as well as by county. The percentages of wells with saline water were distributed across the water-yielding formations as follows: Eutaw, 45%; McShan, 24%; undifferentiated Eutaw- McShan, 7%; Gordo, 7%; Ripley, 4%; Coker, 4%; Hatchetigbee, 2%; Low Terrace Deposits, 2%; Pottsville, 2%; the Nanafalia, Naheola, Terrace Deposits, Clayton, Eocene Series, 3% (Fig. 2). The Eutaw, McShan, undifferentiated Eutaw-McShan, and the Gordo Formations contained 83% of the saline water wells. Wells in the Eutaw formation comprised 54% of saline wells in Sumter County, 20% in Greene County, 13% in Lowndes County, 7% in Marengo County, 5% in Wilcox County, and 1% in Hale County. The McShan Formation was only found to have saline wells in Greene County. The undifferentiated Eutaw-McShan Formation was a source of saline-water wells in

Marengo and Wilcox County. The Gordo Formation is the source of saline-water wells in Greene County, Lowndes, Marengo, and Sumter Counties.

As mentioned above, the highest and most variable chloride concentrations were reported for wells of the low terrace deposits, alluvium, Lower Cretaceous Series, and Hatchetigbee and Naheola Formations (Table 3). The average and standard deviation for chloride concentration in these three water-yielding units were 52,500 ± 58,690 mg/L, 11,495 ± 12,101 mg/L, and 21,000 mg/L, respectively.

The Eutaw, Gordo, McShan, undifferentiated Eutaw-McShan Formations had an average chloride concentration of 1,238 mg/L with a standard deviation of 615 mg/L. This concentration might be given as the normal chloride concentration for saline-water wells for the study area, because 83% of the saline groundwater was found within these four aquifers. Also, these four aquifers are found within watersheds of Greene, Hale, Marengo, Sumter, and Wilcox Counties, where catfish farming is a common activity. This area has the best potential for future saline-water aquaculture facilities. A chloride map was created to display the groundwater chloride concentrations for Greene, Hale, Marengo, and Sumter Counties (Fig. 5).

Well Depths

Saline wells in Greene County ranged between 30 and 474 m deep (Table 4), but most were shallower than 200 m. Sumter County had wells that ranged between 30 and 474 m deep, while wells in Marengo County ranged from 30 and 770 m in depth. Wilcox County also had a wide range in depth to saline groundwater of 30 to 770 m. In Lowndes County, the average well depth was 202 m. Well depths are provided for the same area for which chloride concentrations were mapped (Fig. 6). The less distance that must be drilled to reach the saline groundwater, the cheaper will be drilling and pumping costs.

Potential for Saline Water Aquaculture

Findings of this study revealed that groundwater with salinity high enough for culture of marine shrimp and fish can be found in eleven counties in central and west-central Alabama. This water source is most abundant and accessible in Hale, Greene, Marengo, Wilcox, and Sumter Counties from aquifers in the Gordo, Eutaw, McShan, and undifferentiated Eutaw-McShan Formations. A few farmers in these counties have been using saline wells to raise channel catfish for over three decades, and two farmers in Greene County are producing marine shrimp in saline well water. Other farmers in this area could raise inland shrimp in existing ponds, or they could expand their farms to raise inland shrimp as a second aquaculture crop with minimal investment. There are sites outside of the five-county area where conditions may be favorable for the use of saline well water to produce marine species. In fact, marine shrimp have been produced successfully in ponds supplied by saline well water at a site in Tuscaloosa County near Fosters and at another place in Lowndes County near Hayneville.

The sustainability of the water source obviously is of interest if a saline-water aquaculture industry develops. There has been little interest in the saline groundwater of central and west central Alabama in the past, because it was not useful for domestic, municipal, and agricultural purposes. Therefore, data on the volume of saline groundwater is largely unknown. The general opinion seems to be that the saline groundwater is fossil water trapped in the formations, and that the saline aquifers are not recharged. However, based upon the extent of the aquifers and their rather shallow depth below the land surface, it seems unlikely that no recharge occurs. In fact, at one of the shrimp farms in Greene County, the owner reported that the saline water source well exhibited a small volume of artesian flow following a period when rainfall was unusually high. This observation suggests that the piezometric surface in the aquifer had increased through recharge to allow artesian flow (Briggs and Fielder 1975). Studies to evaluate the volume and sustainable pumping rate for the major saline groundwater aquifers should be made before widespread promotion of saline-water aquaculture in the Blackland Prairie.

Ionic Composition

Adequate salinity is not the only water quality issue in selecting a water source for inland, saline-water aquaculture. Shrimp and other marine species can be expected to survive and grow best in waters with ionic proportions similar to those of normal seawater. Several major ions, and especially potassium, often are of low concentration in saline groundwater when compared to seawater diluted to the same salinity (Fielder et al. 2001; Boyd et al. 2002; Saoud et al. 2003).

Most wells in the Blackland Prairie were drilled to provide water for domestic purposes. Waters were analyzed for chloride, and if the concentration was too high, the well could not be used and was capped. Thus, other than wells for aquaculture, there are few places where samples of saline well water can be obtained for analysis.

Analyses of saline wells for aquaculture have demonstrated considerable variation in concentrations of major ions (Boyd et al. 2002), as illustrated in Table 5. The ionic proportions in water from a particular source can be easily compared with those of seawater. To facilitate this comparison, Boyd et al. (2002) presented factors that can be multiplied by the salinity of the water source to provide equivalent concentrations expected in seawater diluted to the same salinity. These factors are as follows: calcium, 11.6; magnesium, 39.1; potassium, 10.7; sodium, 304.5; chloride, 551.0; sulfate, 78.3 (Boyd et al. 2002). A factor for bicarbonate was not included, for this ion is responsible for total alkalinity, and total alkalinity concentration should not be allowed to fall below 75 mg/L (92 mg/L bicarbonate) in aquaculture ponds (Boyd and Tucker 1998). Ionic concentrations in water from a source well at an Alabama inland shrimp farm near Forkland, Alabama (McNevin et al. 2004) is compared with those expected in seawater diluted to the same salinity in Table 6. The well water was particularly low in sulfate, calcium, magnesium, and potassium. However, low potassium concentration is thought to be of more concern than the low concentrations of other ions (McNevin et al. 2004).

Concentrations and proportions of major ions in groundwater should be compared to those of seawater diluted to the same salinity for predicting ionic deficiencies in water sources that might influence shrimp survival and growth (Boyd et al. 2002). If groundwater is thought to be deficient in an ion, mineral amendments can be applied to supplement the deficiency. However, compositional changes in well water usually occur when it is held in earthen ponds (Boyd and Tucker 1998). Thus, decisions about applications of products to supplement ionic imbalances ultimately should be based on the composition of pond water.

Total alkalinity can be increased by treatment with agricultural limestone (Boyd and Tucker 1998). In some cases, alkalinity may be high, but calcium concentration may be low. Calcium concentration may be increased by applying agricultural gypsum (calcium sulfate). Gypsum also will increase sulfate concentration. Muriate of potash (potassium chloride) is the best source of potassium, and it will increase chloride. Kmag® (potassium magnesium sulfate) may be applied to increase potassium, magnesium, and sulfate. Magnesium and sulfate concentrations can be increased through additions of Epsom salt (magnesium sulfate). Ordinary industrial-grade salt, sodium chloride is the cheapest source of sodium and chloride. Some properties of mineral products are provided in Table 7, and Boyd (2003) discussed the practical use of these amendments in ponds.

In summary, maps presented in this report may be helpful in finding sites in Alabama where saline-water wells can be developed to supply inland shrimp farms. However, further testing of a particular water source should be conducted to determine its ionic composition and to predict if ionic imbalances are likely in ponds. It also is important to mention that factors other than the availability and ionic composition of saline groundwater, e.g., soil characteristics, terrain, vegetation type, available land, should be considered in selecting sites for inland culture of marine species in ponds.

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Table 1. Number of well records and means, standard deviations, and ranges for chloride concentration in waters from saline wells with 125 mg/L chloride or more in twelve Alabama Counties.

County	Number of well records	Number of saline wells	Chloride (mg/L) Mean ± SD	Chloride (mg/L) Minimum	Chloride (mg/L) Maximum
Choctaw	102	6	7,183 ± 13,226	590	34,100
Clarke	170	5	32,340 ± 35,397	7,700	94,000
Dallas	284	8	264 ± 154	158	620
Greene	261	82	1,346 ± 792	368	3,700
Hale	377	17	806 ± 766	149	3,040
Lowndes	86	12	1,336 ± 1,327	250	4,648
Marengo	183	26	710 ± 513	175	2,370
Perry	126	0	-	-	-
Sumter	185	49	1,550 ± 1,499	126	6,540
Tuscaloosa	531	6	889 ± 892	213	2,599
Washington	117	4	4,615 ± 5,740	480	12,800
Wilcox	140	23	578 ± 458	136	1,760
All counties	2,562	238	4,692 ± 9,407	136	94,000

Table 2. Chloride concentration classes for well waters from saline aquifers of Greene, Hale, Marengo, Wilcox, and Sumter Counties.

Concentration class	Wells	Wells per county[1]				
(mg/L)	(%)	G	H	M	S	W
132-1,144	62.2	43	15	20	32	12
1,145-2,155	22.7	29	---	6	9	1
2,156-3,167	8.6	7	2	1	1	---
3,168-4,178	3.8	3	---	---	4	---
4,179-5,190	2.7	---	---	---	5	---

[1] G = Greene, H = Hale, M = Marengo, S = Sumter, W = Wilcox.

Table 3. Chloride concentrations (mg/L) of well waters from saline aquifers of geologic formations in ten Alabama counties.

Water yielding unit	Number wells	Chloride (mg/L) Mean ± SD	Minimum	Maximum
Clayton	1	460		
Coker	7	448 ± 93	270	530
Eocene Series	1	480		
Eutaw	84	1,118 ± 1,019	158	5,190
Undifferentiated Eutaw-McShan	12	513 ± 323	240	1,320
Gordo	13	2,006 ± 1,062	507	3,700
Hatchetigbee	4	11,495 ± 12,101	780	28,000
Low terrace deposits, alluvium	3	52,500 ± 58,690	11,000	94,000
Lower Cretaceous Series	1	3,040		
McShan	45	1,313 ± 622	540	2,550
Naheola	1	21,000		
Nanafalia	2	800 ± 849	200	1,400
Pottsville	4	588 ± 381	213	1,020
Ripley	7	469 ± 234	260	890
Terrace deposits	1	510		

Table 4. Depths of saline-water wells in Greene, Hale, Marengo, Wilcox, and Sumter Counties.

Depth (m)	Wells (%)	Wells per county[1]				
		G	H	M	S	W
30-178	38.3	46	11	2	7	9
179-326	45.3	46	---	10	32	1
327-474	12.6	1	3	9	11	1
475-622	0.0	---	---	---	---	---
623-770	3.8	---	---	5	---	3

[1] G = Greene, H = Hale, M = Marengo, S = Sumter, W = Wilcox.

Table 5. Means, standard deviations, and minimum and maximum concentrations of major ions (mg/L) in saline well water used to fill inland shrimp ponds in Alabama.

Ion	Mean ± SD	Minimum	Maximum
Calcium	170 ± 135	11	296
Magnesium	30 ± 22	3	64
Potassium	9.1 ± 2.8	4.0	12.4
Sodium	1,508 ± 646	401	2,210
Bicarbonate	209 ± 104	70	376
Sulfate	4.5 ± 3.7	0.0	10.0
Chloride	2,441 ± 1,117	38	4,009

Table 6. Concentrations of salinity, total alkalinity, and major ions in well water used as a water supply for an inland shrimp farm compared with concentrations of major ions in seawater diluted to the same salinity.

Variable	Well water[1]	Diluted seawater
Salinity (ppt)	3.70	3.70
Total alkalinity (mg/L as $CaCO_3$)	272.6	10.5[1]
Chloride (mg/L)	1,982	2,039
Sulfate (mg/L)	0.46	289.7
Calcium (mg/L)	118.2	42.9
Magnesium (mg/L)	5.46	144.7
Potassium (mg/L)	11.6	39.6
Sodium (mg/L)	1,402	1,128

[1] Minimum recommended total alkalinity is 75 mg/L for shrimp ponds (Boyd et al. 2002).

Table 7. Some properties of mineral products that can be used to correct ionic imbalances in inland shrimp ponds.

Product	Chemical compound	Typical composition
Agricultural limestone:		
Calcitic	Calcium carbonate	38% calcium
Dolomitic	Calcium magnesium carbonate	20% calcium 12% magnesium
Gypsum	Calcium sulfate	22% calcium 53% sulfate
Muriate of potash	Potassium chloride	49.8% potassium 45.2% chloride
Kmag	Potassium magnesium sulfate	17.8% potassium 10.5% magnesium 63.6% sulfate
Epsom salt	Magnesium sulfate	10% magnesium 39% sulfate
Salt	Sodium chloride	38.7% sodium 59.4% chloride

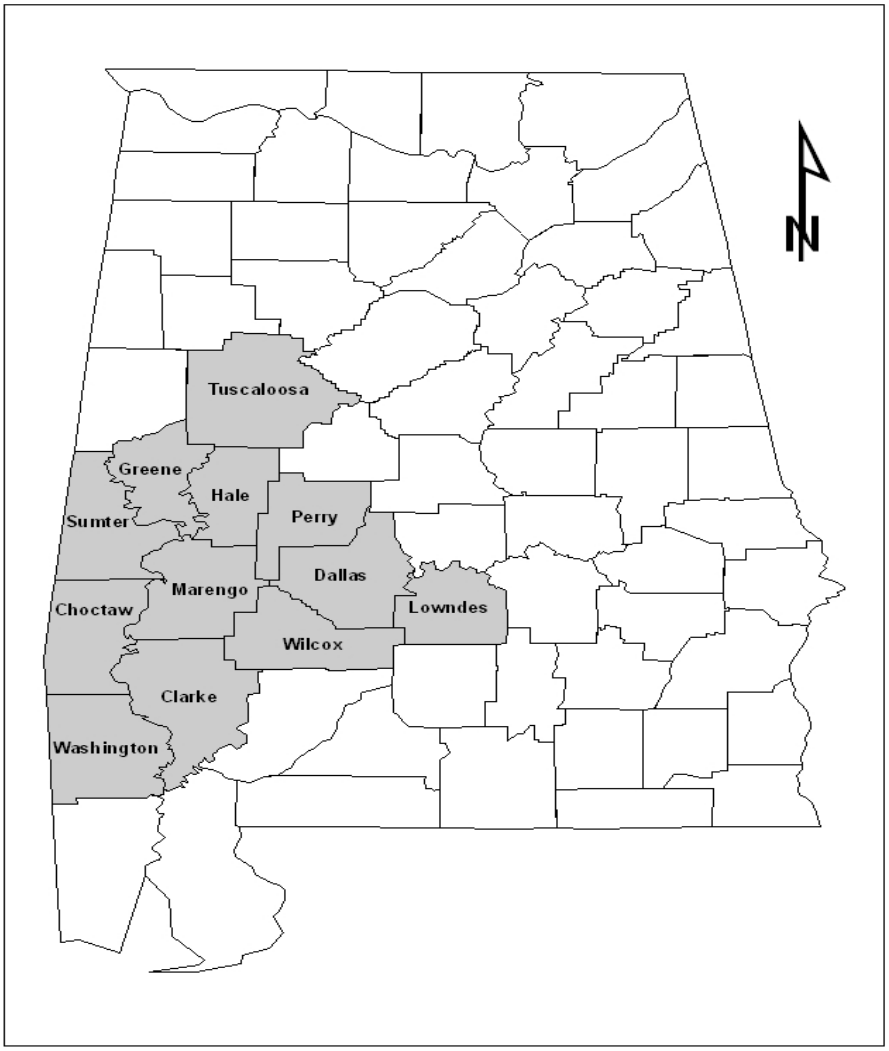
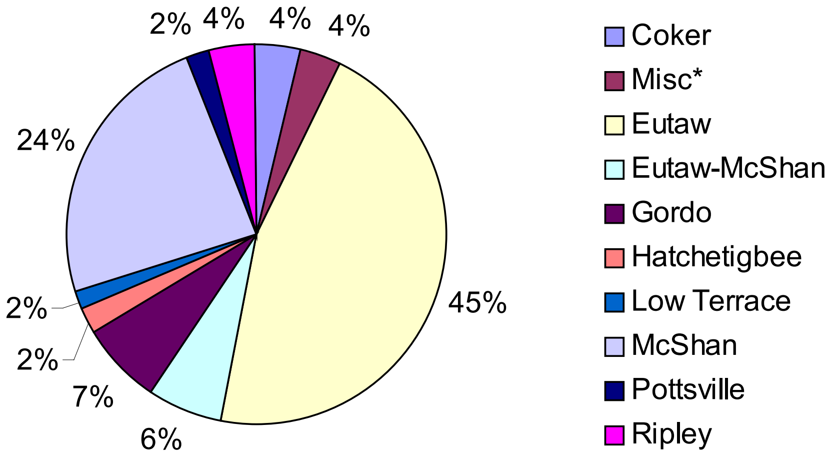


Figure 1. Saline ground water study area in central and west-central Alabama.



* Nanafalia, Naheola, Terrace Deposits, Clayton, and Eocene Series

Figure 2. Percentages of saline-water wells found in major geologic formations of twelve central and west-central Alabama counties.

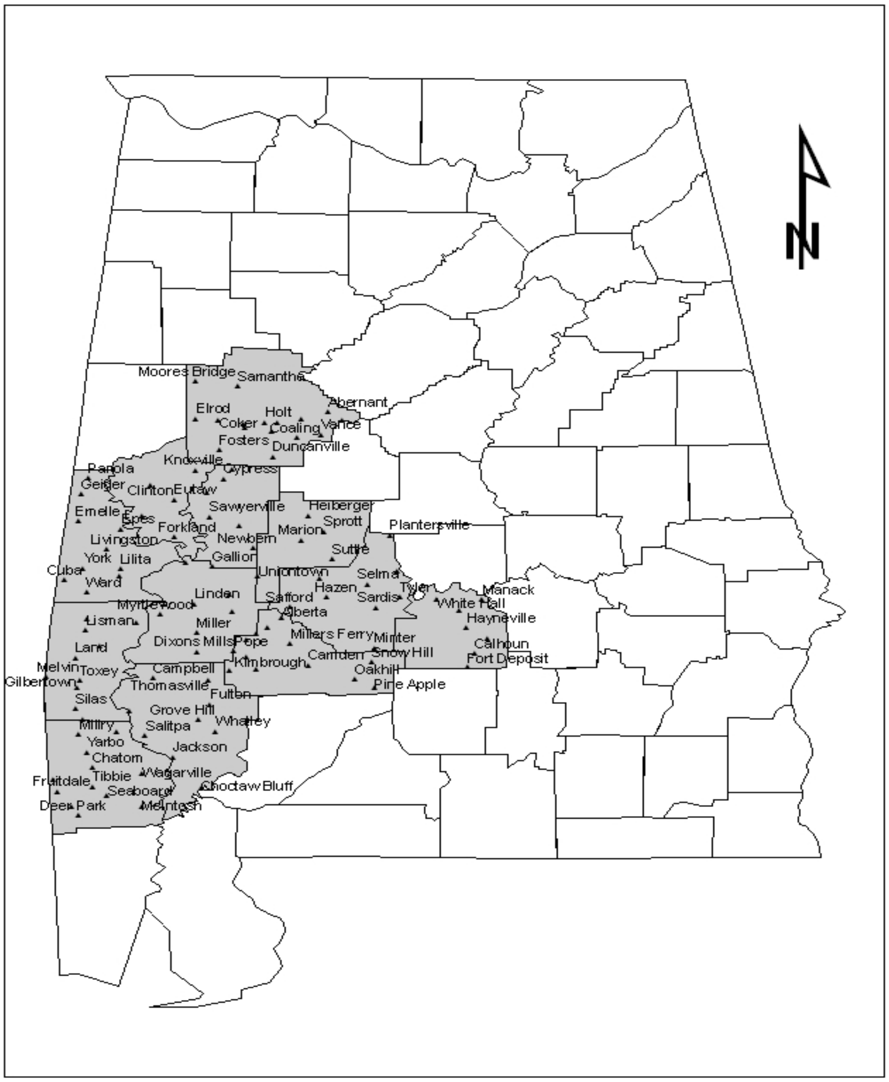


Figure 3. Cities located within the saline ground water study area in central and west-central Alabama.

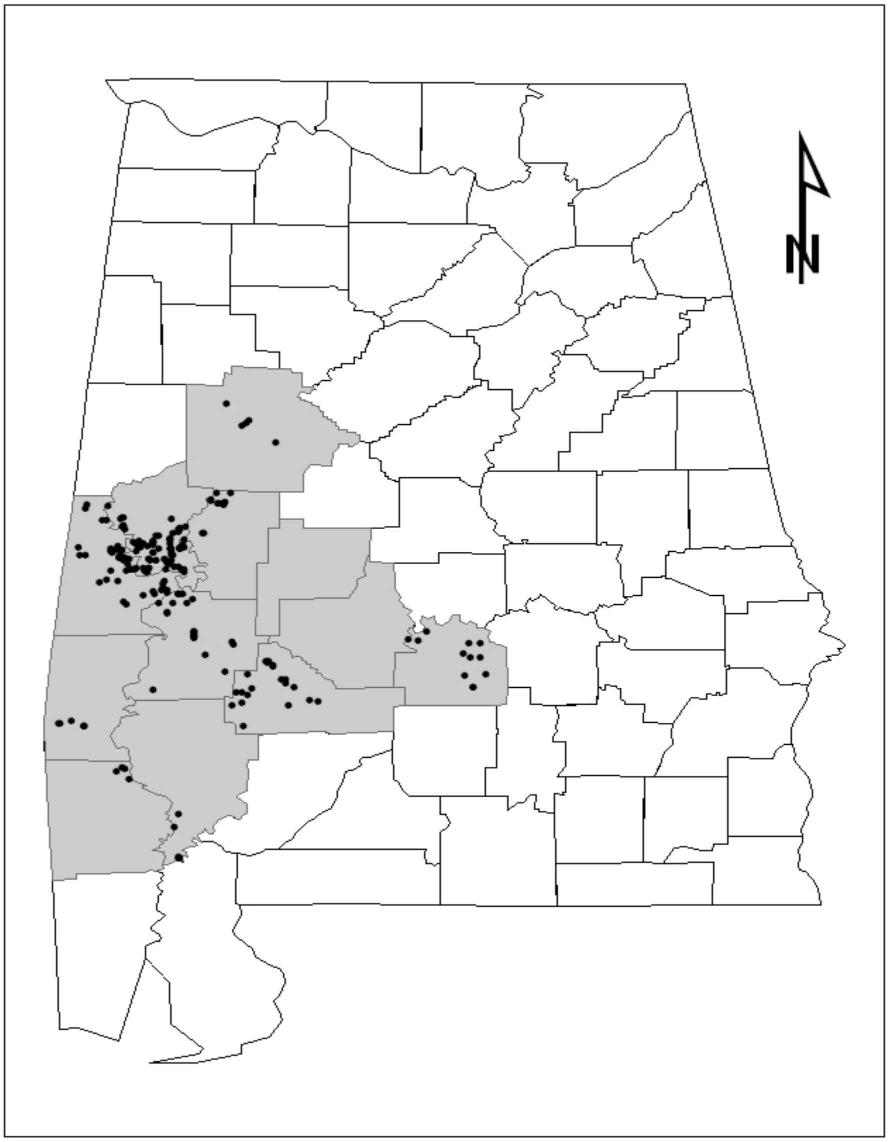


Figure 4. Locations of wells containing over 125 mg/L chloride in central and west-central Alabama.

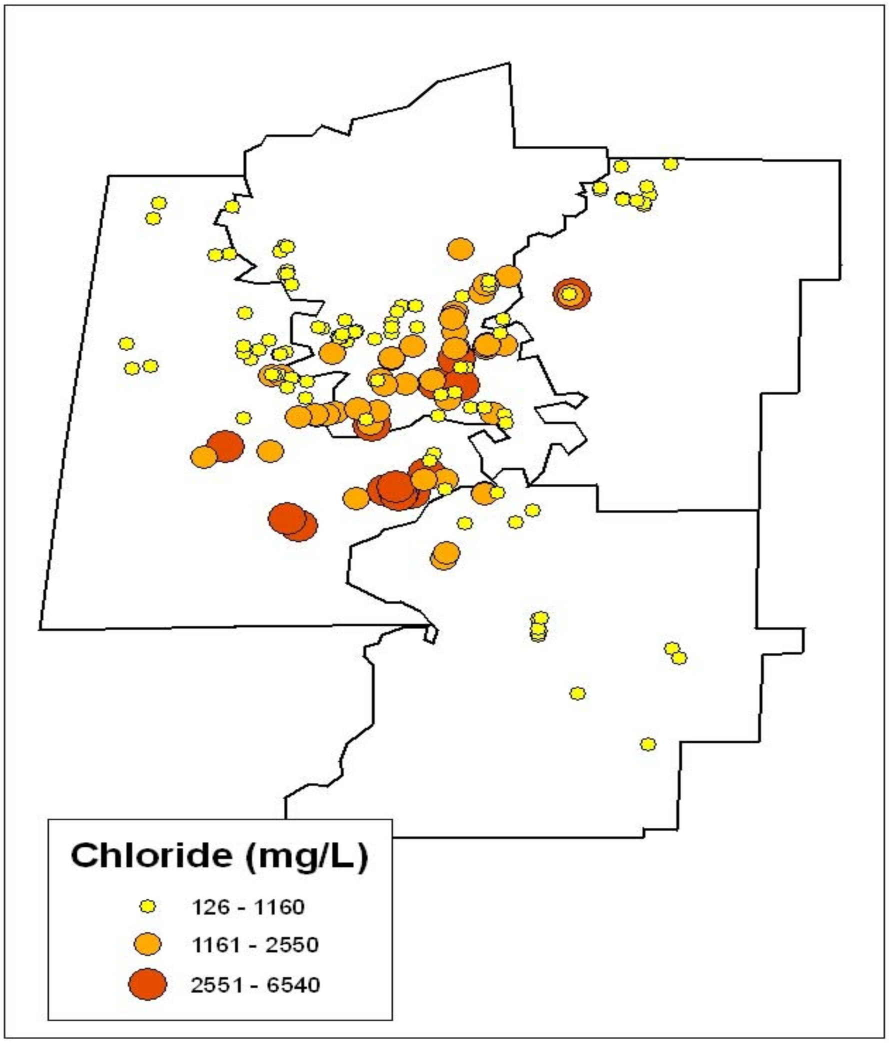


Figure 5. Chloride map for saline-water wells in Greene, Hale, Marengo, and Sumter Counties in west-central Alabama.

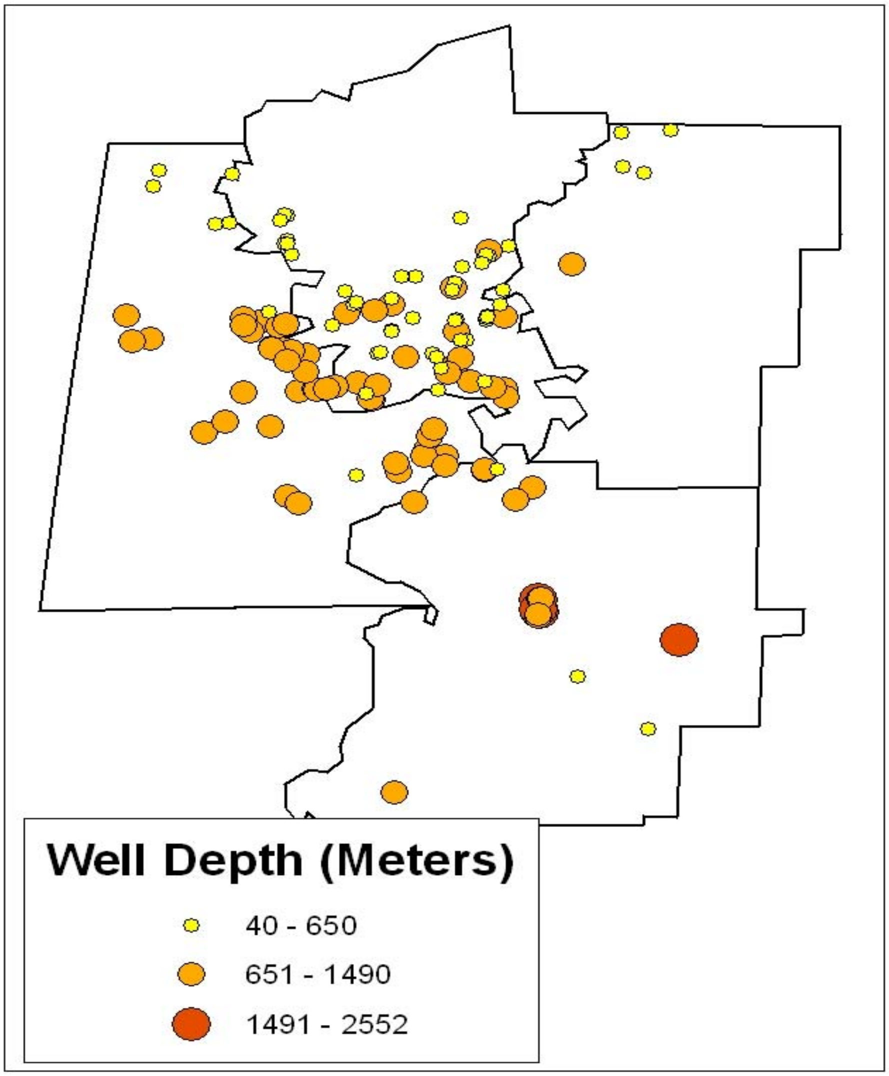


Figure 6. Well depth map for saline-water wells in Greene, Hale, Marengo, and Sumter Counties in west-central Alabama.

IV. POTASSIUM BUDGET FOR INLAND, SALINE-WATER SHRIMP PONDS IN ALABAMA

Abstract

Potassium budgets were prepared for inland shrimp ponds in Alabama in which saline water was supplemented with potassium ion by additions of two fertilizers, potassium chloride and potassium magnesium chloride. The study was conducted during the first shrimp crop in newly-constructed ponds. A total of 1,021.2 kg/ha of potassium were applied to the ponds, and the main input was the fertilizers. The total loss of potassium from ponds was 456.5 kg/ha, and of this, harvest effluent and seepage accounted for 347.9 and 101.2 kg/ha, respectively. Based on the potassium budgets, bottom soil apparently adsorbed 564.7 kg/ha of potassium. However, the potassium increase in the upper 15-cm layer of bottom soil during the first crop was only 374 kg/ha. Potassium likely was adsorbed to a greater depth, but some of the discrepancy resulted from sampling and analytical errors. Soil uptake was an important sink for added potassium in the new ponds, so further studies should be conducted to determine the rate at which the potassium binding capacity of the bottom soil will be filled. Water reuse is the only practical way of decreasing the loss of potassium from inland shrimp ponds.

Introduction

Marine shrimp are cultured in inland ponds supplied with saline water in several nations including the United States (Smith and Lawrence 1990; Limsuwan et al. 2002; Boyd and Thunjai 2003). Well water from saline aquifers often is the source of water. Although this water has adequate salinity for shrimp culture, there may be imbalances of major ions that negatively effect survival and growth of shrimp (Boyd et al. 2002; Samocha et al. 2002; McGraw and Scarpa 2003; Davis et al. 2005). Potassium, magnesium, and sulfate concentrations in saline ground water commonly are relatively low when compared to seawater of the same salinity. In Alabama ponds, the fertilizers muriate of potash (potassium chloride) and Kmag® (potassium magnesium sulfate) typically are added to increase potassium above 40 mg/L, magnesium above 20 mg/L, and sulfate above 50 mg/L in waters with salinities of 2 to 8 ppt (McNevin et al. 2004). Additions of these fertilizers greatly increased survival and production of shrimp, and potassium apparently provided most of the benefit (McNevin et al. 2004).

Typical applications of potassium fertilizers are 250 to 500 kg/ha of muriate of potash and 1,000 to 2,000 kg/ha of Kmag (McNevin et al. 2004). Increased concentrations of ions resulting from fertilizer additions gradually decline because of losses from ponds in seepage, overflow, and harvest effluent, removal in shrimp at harvest, and possibly by adsorption by bottom soil. The purpose of this study was to prepare a potassium budget for inland shrimp ponds in Alabama to assess the relative importance of the different inputs and loses of potassium.

Materials and methods

Ponds and management

Ponds for this study were located on a shrimp farm adjacent to Alabama Highway 43 about 5 km north of Forkland, Alabama in Greene County. The farm is situated in the gently rolling terrain of the Blackland Prairie (Hajek et al. 1975) where the soil is clayey and contains carbonate deposits. The three study ponds were newly-constructed, embankment ponds (Yoo and Boyd 1994) that had not contained water previously. Pond water surface areas were as follows: S-6, 1.42 ha; S-7, 1.90 ha; S-8, 1.94 ha. All three ponds had an average depth of 1.25 m established by a standing overflow pipe. Watersheds of ponds were restricted to the area around each pond extending from the centers of the embankment tops to the water levels. When ponds were filled to 10 cm below the tops of the standing drainpipes, watershed areas were 3,282 m^2 for S-6, 3,802 m^2 for S-7, and 3,841 m^2 for S-8.

Filling of ponds with saline well water was initiated during the last week of April 2003 and continued into May. In early June, ponds were treated with Kmag® and muriate of potash (Table 1) to increase potassium, magnesium, and sulfate concentrations. In mid May, ponds were stocked with post larval shrimp at $30/m^2$. Ponds were not treated with nitrogen and phosphorus fertilizers, but a pelleted feed containing 35% crude protein was applied daily. Feeding rate decreased from 5% to 2% per day of estimated shrimp biomass as the growing season progressed. Mechanical aeration was applied with electrical and tractor-powered paddlewheel aerators as necessary to avoid low dissolved oxygen concentration. The water level in the ponds initially was established at 115 cm leaving 10 cm storage depth for rainfall and runoff. After filling, well water was not added until the water level in ponds dropped below 85 cm. When well water was introduced to replace seepage and evaporation loses, the water level was not increased above 95 cm. Pond draining for harvest was initiated on 25 September and the weight of shrimp in each pond was recorded.

Water budget

A standard rain gauge and class A evaporation pan were installed near the ponds and data were collected from 2 May until 25 September. A staff gauge was installed in each pond and water levels were measured periodically. There was no way to directly measure discharge of the well, and the amount of well water added to ponds was calculated (Boyd 1982) by the following equation:

$$W = (E + S + O + H) - (P + R) \tag{1}$$

where W = water from well, E = evaporation, S = seepage, O = overflow, H = water depth, P = precipitation, R = runoff on 25 September 2003 before pond draining was initiated. Values for Eq. 1 were in centimeters of water depth. Rainfall estimates for Eq. 1 were obtained from the rain gauge at the farm. The watershed surface was well compacted and had scant grass cover. Based on the curve number method (Yoo and Boyd 1994), about 67% of rain falling on the watershed entered the ponds in runoff. The equation for determining runoff for a pond was:

$$R = 0.67\,(a/A)P \tag{2}$$

where a = watershed area (m^2) and A = pond surface area (m^2).

Boyd (1985) found that the pan coefficient for evaporation from aquaculture ponds in Alabama averaged 0.81. Thus, the equation for pond evaporation was:

$$E = E_{pan} (0.81) \tag{3}$$

where E_{pan} = class A pan evaporation (cm). Seepage was estimated during dry periods when there were no inflows to ponds (Boyd 1982). The difference in the decline in water level and evaporation is seepage:

$$S = \Delta H - E \tag{4}$$

Ponds were operated to avoid overflow, but water levels were checked within a few hours after each major rainfall event. If the water level was above the standpipe, overflow was estimated as:

$$O = H - 125 \tag{5}$$

Data on inflows and outflows and well water additions calculated with Eq. 1 were used to prepare water budgets for ponds.

Potassium determinations

Feed samples were collected monthly from the feed storage bin and shrimp samples were obtained during harvest. The samples were dried at 60°C in a mechanical convection oven and pulverized with a mortar and pestle to pass a 40-mesh screen. Portions of 0.50 g each were dry ashed at 450°C in a muffle furnace for 8 h (Jackson 1958). The ash was dissolved in 1.0 N nitric acid, the solution was filtered and made to 100-mL volume, and potassium concentration was measured by flame emission spectrophotometry using a Cole-Parmer Model 2655-00 Digital Flame Analyzer (Cole-Parmer Instrument Company, Chicago, Illinois, USA).

A rain water collector was made by placing a 30-cm diameter plastic funnel in a 2-liter plastic bottle. A spiked ring was placed around the top of the funnel to prevent birds from landing on the edge of the funnel and defecating into it. Water samples were dipped from pond surfaces at monthly intervals and on the day of harvest. Samples of well water also were obtained monthly. On sampling days when the well was not discharging, the pump was started and operated for 10 min before collecting the sample from the discharge pipe. Water samples were analyzed for potassium by flame emission spectrophotometry.

Nine, 5-cm diameter core samples were taken to a depth of 15 cm at random locations in pond bottoms before ponds were filled in April and again in October 2003 after shrimp harvest. The samples were dried at 60°C in a mechanical convection oven and pulverized with a mechanical soil crusher (Custom Laboratory Equipment, Orange City, Florida, USA) to pass a 40-mesh screen. Soil samples were extracted by transferring 5.0-g soil and 25-mL of neutral, 1.0 N ammonium acetate to 50-mL centrifuge tubes, shaking the tubes on a rotating table shaker for 5 min at 180 rpm, and centrifuging the tubes for 5 min at 2,500 rpm. Supernatants were transferred to funnels fitted with Whatman Number 40 filter paper, and the filtrates were collected in a 100-mL volumetric flask. Extractions were repeated twice, and filtrates made to volume with extracting solution. Filtrates were analyzed for potassium by flame emission spectrophotometry, and soil potassium concentrations were calculated.

In April when the initial samples were collected, three core samples from each pond were analyzed for dry bulk density (Blake and Hartge 1986).

Potassium budget

Quantities of muriate of potash, Kmag, and feed and harvest weight of shrimp were obtained from farm records supplied by the owner. Volumes of well water, rainfall, runoff, seepage, overflow, and harvest effluent were obtained by multiplying depths of water in the water budgets by pond areas. Quantities of inputs and outputs were multiplied by their potassium concentrations to obtain amounts of potassium for use in preparing the potassium budgets.

Results and discussion

Rainfall and class A pan evaporation data are given in Table 2. Normal values for a National Weather Service gauging station 30 km southeast at Demopolis, Alabama were 50.2 cm of precipitation and 79.8 cm for class A pan evaporation for the period 2 May to 25 September. Topography is similar between the two locations, and little or no variation in rainfall and pan evaporation between the two stations is expected. Thus, the study was conducted during a period with considerably more precipitation and slightly less evaporation than normal.

Seepage was measured several times, and the average values and standard deviations were similar among the ponds as follows: S-6, 0.163 ± 0.05 cm/day; S-7, 0.190 ± 0.07 cm/day; S-8, 0.152 ± 0.08 cm/day. Seepage could only be determined for periods with no inflow, so average values were used to estimate water loss through seepage.

Water budgets for the ponds (Table 3) revealed that the well was the main source of water, and precipitation and runoff were about 20 cm less than evaporation and seepage. Overflow occurred only from pond S-6, and it was a minor water loss from that pond. Effluent discharged during harvest was the main loss of water containing potassium. Evaporation was a major loss of water, but potassium was not lost through this process. Seepage was a much smaller water outflow than draining of ponds for harvest.

Potassium is lost with both seepage and draining.

The amounts and potassium concentrations of fertilizers, feed, and shrimp are provided in Table 1. Rainfall was low in potassium, and well water contained only 11.4 mg/L potassium even though its salinity was 3.66 ppt (Table 4). Additions of potassium fertilizer increased the potassium concentration of pond water to an average of about 40 mg/L (Table 4). The average concentration of potassium in pond water was used for estimating losses of this ion in seepage and overflow. Potassium was measured in the effluent when ponds were drained for harvest (Table 4).

The major input of potassium to the ponds was muriate of potash and Kmag (Table 5). The input of potassium in well water was only 15.9% of the amount added in fertilizer, and even less potassium entered ponds in feed, rainfall, and runoff (Table 5). The total potassium input averaged 1,021.2 kg/ha for the three ponds. The loss of potassium from ponds was 347.9 kg/ha in harvest effluent and 101.2 kg/ha in seepage. The combined loss in overflow and harvested shrimp was only 7.4 kg/ha as compared to a total loss of 456.5 kg/ha. The differences in inputs and outputs of potassium averaged 564.7 kg/ha (Table 5). The discrepancy is thought to have resulted primarily from the adsorption of potassium by bottom soils.

The potassium concentration in the upper, 15-cm layer of bottom soil in the three ponds increased by an average of 192 mg/kg during the first shrimp crop (Table 6) and corresponded to adsorption of 374 kg/ha of potassium by this layer of soil. This is less than the difference in potassium inputs and outputs of 564.7 kg/ha in the budget (Table 5). The difference is 190.7 kg/ha, or 18.7% of the potassium input, and we do not believe that errors in measurements were the sole reason for this difference. The measured soil uptake of potassium (Table 6) was less than the uptake estimated by difference in the potassium budget (Table 5) because potassium adsorption by soil probably occurred at depths greater than 15 cm or was adsorbed by the nonexchangable fixation mechanism.

The cation exchange capacity of pond soils in the Black Belt Prairie region of Alabama usually has a cation exchange capacity (CEC) of 15 to 30 meq/100 g (Dixon and Nash 1968). Assuming a CEC of 20 meq/100 g, 15,249 kg/ha of potassium would be needed to saturate the cation exchange sites in a 15-cm layer of pond bottom soil. The potassium concentration in pond waters is only 30 to 50 mg/L, and this concentration would not be strong enough to effect potassium saturation. Thus, studies are needed to determine how much potassium the pond bottoms can absorb from the water. It also would be useful to estimate approximately how long the soils will continue to remove potassium from the water.

In preparing the potassium budgets for ponds, only inputs and losses for the individual ponds were considered. However, about two-thirds of the water drained from ponds during harvest was pumped into ponds that had already been harvested and conserved for reuse. Thus, the potassium loss from the farm during harvest is only one-third of the loss reported from individual ponds in Table 5. Even more potassium could be saved if a reservoir pond was constructed so that all water could be saved during harvest (Boyd et al. 2004).

Seepage from ponds cannot be avoided unless ponds are lined with an impermeable membrane, and this practice is thought to be excessively expensive for the culture system presently employed in Alabama. Much higher stocking and feeding rates must be used to justify lining shrimp ponds (McIntosh 1999). However, seepage for inland shrimp ponds in Alabama can be lessened by avoiding sites with highly-permeable soils and using good construction techniques (Boyd et al. 2004). Ponds also should be operated to minimize overflow during rainy periods, and all draining effluent should be stored for reuse. Although it is unlikely that potassium salt applications can be discontinued, it should be possible to lower application rates considerably as the percentage saturation of the soil with potassium increases and water conservation practices are implemented.

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Table 1. Amounts and potassium concentrations of potassium fertilizers and feed added and of shrimp harvested for three ponds (S-6, S-7, and S-8) at an inland shrimp farm in Alabama.

Variable	Potassium (%)	S-6 (kg	S-7 (kg)	S-8 (kg)	Mean ± SD (kg/ha)
Kmag	17.8	1,912	2,242	2,276	1,233 ± 98
Muriate of potash	49.8	1,838	2,119	2,300	1,198 ± 90
Feed	0.96	9,331	11,608	8,772	5,734 ± 1,075
Shrimp	0.23	3,449	6,010	3,256	2,423 ± 742

SD = standard deviation.

Table 2. Precipitation and class A pan evaporation data for the period 2 May to 25 September 2003 at an inland shrimp farm in Alabama.

Month	Precipitation (cm)	Class A pan evaporation (cm)
2-31 May	16.2	14.2
June	13.3	15.6
July	16.4	17.8
August	8.1	15.1
1-25 September	14.1	10.6
Total	68.1	73.3

Table 3. Water budgets for ponds S-6, S-7, and S-8 at an inland shrimp farm in Alabama.

Variable	S-6		S-7		S-8		Mean volume ± SD (m^3/ha)
	Depth (cm)	Volume (m^3)	Depth (cm)	Volume (m^3)	Depth (cm)	Volume (m^3)	
<u>Inflows</u>							
Well	116.1	16,486	115.0	21,850	111.5	21,631	11,420 ± 240
Precipitation	68.1	9,670	68.1	12,939	68.1	13,211	6,810 ± 0
Runoff	10.5	1,491	9.1	1,729	9.0	1,746	953 ± 84
<u>Outflows</u>							
Harvest effluent	96.0	13,632	91.0	17,290	93.0	18,042	9,333 ± 252
Evaporation	73.3	10,409	73.3	13,927	73.3	14,220	7,330 ± 0
Seepage	24.0	3,408	27.9	5,301	22.3	4,326	2,473 ± 287
Overflow	1.4	199	0.0	0.0	0.0	0.0	47 ± 81

SD = standard deviation.

Table 4. Average concentrations and standard deviations for potassium in rainfall, well water, and pond water in ponds S-6, S-7, and S-8 at an inland shrimp farm in Alabama.

Variable	S-6 (mg/L)	S-7 (mg/L)	S-8 (mg/L)
Rainfall	2.4 ± 1.9	2.4 ± 1.9	2.4 ± 1.9
Well water	11.4 ± 1.8	11.4 ± 1.8	11.4 ± 1.8
Pond water:			
Average for crop	42.0 ± 0.7	42.2 ± 16.3	38.2 ± 5.7
At harvest	42.1	34.5	35.0

Table 5. Potassium budgets for ponds S-6, S-7, and S-8 at an inland shrimp farm in Alabama.

Variable	S-6 (kg)	S-7 (kg)	S-8 (kg)	Mean ± SD (kg/ha)
<u>Inputs</u>				
Muriate of potash	915.4	1,055.2	1,145.5	596.8 ± 45.0
Kmag	340.3	405.2	405.2	220.6 ± 16.6
Well water	187.9	249.1	246.6	130.2 ± 2.7
Feed	89.5	111.3	84.1	55.0 ± 10.3
Rainfall and runoff	26.8	35.2	35.9	18.6 ± 0.23
Sum	1,559.9	1,856.0	1,917.3	1,021.2 ± 65.2
<u>Outputs</u>				
Harvest effluent	573.9	596.5	631.5	347.9 ± 49.1
Seepage	143.1	223.7	165.3	101.2 ± 16.2
Shrimp	7.8	13.0	7.4	5.4 ± 1.5
Overflow	8.4	0.0	0.0	2.0 ± 3.4
Sum	733.2	833.2	804.2	456.5 ± 53.2
Soil adsorption	826.7	1,022.8	1,113.1	564.7 ± 22.1

SD = standard deviation.

Table 6. Averages and standard deviations for bulk density, soil potassium concentrations in April and October 2003, and potassium uptake by upper 15-cm layer of bottom soil of ponds S-6. S-7, and S-8 at an inland shrimp farm in Alabama.

Variable	S-6	S-7	S-8	Mean
Bulk density (kg/m^3)	1,260 ± 100	1,320 ± 160	1,330 ± 150	1,303 ± 38
Soil potassium (mg/kg):				
April 2003	162 ± 46	194 ± 24	223 ± 43	193 ± 31
October 2003	377 ± 137	390 ± 111	387 ± 43	385 ± 7
Potassium uptake by soil:				
(mg/kg)	215	196	164	192 ± 26
(kg/pond)	577	737	635	650 ± 81
(kg/ha)	406	388	327	374 ± 41

V. POTASSIUM ADSORTPION BY BOTTOM SOILS IN PONDS FOR INLAND CULTURE OF MARINE SHRIMP IN ALABAMA

Abstract

Adsorption by bottom soils of potassium added in fertilizers to inland ponds for culture of marine shrimp in Alabama continued over a four-year period. The exchangeable potassium concentration in bottom soils did not increase after the first year. In laboratory soil-water systems in which bottom soil was in contrast with potassium-enriched pond water for about 8 months, non-exchangeable potassium fixation accounted for about 75% of potassium adsorption. Total potassium adsorption by soils averaged 518 mg/kg. In an experiment in which bottom soil samples were exposed to consecutive 50-mg/L potassium solutions (potassium chloride in distilled water) and agitated on a shaker, potassium adsorption by soil declined from 406 mg/kg during the first exposure to 70 mg/kg during the sixth exposure. During the next six exposures, potassium adsorption was similar and between 61 and 95 mg/kg during each exposure. Samples adsorbed an average of 1,804 mg/kg of potassium. The pond soils contain 2:1 expandable clay and have a large capacity to adsorb potassium by non-exchange processes. They will remove added potassium from the waters for several years. The only reliable way to determine when potassium fertilizer should be added to inland shrimp ponds in Alabama is to monitor potassium concentration in the water.

Introduction

Inland culture of marine shrimp in Alabama is conducted in ponds filled with saline groundwater from wells (Davis et al. 2005). Well waters usually have a different proportion of major ions than seawater (Boyd and Thunjai 2003). Thus, even though salinity may be adequate for shrimp, ionic imbalances may negatively impact survival and growth (Atwood et al. 2003; Saoud et al. 2003). In particular, potassium concentrations in well water often are too low for good survival and growth of shrimp (Boyd and Thunjai 2003; McGraw and Scarpa 2003; Saoud et al. 2003). Potassium concentrations decline further when the water is held in ponds (McNevin et al. 2004). Thus, ponds in Alabama are treated with potassium fertilizers, Kmag® (potassium magnesium sulfate) and muriate of potash (potassium chloride) to increase potassium concentration to about 40 mg/L (McNevin et al. 2004). Potassium budgets for three, new ponds on an inland shrimp farm near Forkland, Alabama, revealed that uptake of potassium by bottom soil was equivalent to 69% of the potassium applied in fertilizers during the first crop (see Chapter IV).

Soils have a finite capacity to adsorb potassium, and as this capacity is filled, loss of fertilizer potassium to bottom soil should decline allowing fertilizer additions to be reduced. Potassium fertilization is an added management cost, and producers need verification that this expense will be less in the future. Therefore, potassium adsorption by bottom soils of an inland shrimp farm was investigated.

Materials and Methods

The shrimp farm is located beside Alabama Highway 47 near Forkland, Alabama. In 2001 and 2002, there were ten ponds with a total water surface area of 10.24 ha, and six ponds with an additional 9.91 ha of surface area were added in 2003. The ponds had an average depth of 1.25 m, but the water level was maintained 10 cm below the top of the standing drain pipes to avoid overflow. Shrimp were stocked at about $30/m^2$ in May each year. A commercial feed was applied daily and mechanical aeration was provided as necessary to avoid low dissolved oxygen concentrations. When ponds were drained for harvest in September and October, about two-thirds of the water was pumped to empty ponds and conserved for reuse.

Surface water samples for potassium analyses were taken from all ponds on the farm at about monthly intervals between March or April and October during four years (2002 to 2005). Samples were analyzed for potassium concentration by flame emission spectrophotometry using a Model 2655-00 flame photometer (Cole Parmer Instrument Company, Chicago, Illinois). Data on potassium fertilizer inputs were supplied by the farm owner.

Pond bottom samples were collected from three ponds (S-6, S-7, and S-8) in May 2003, October 2003, March 2004, October 2004, and October 2005. Samples were taken to a depth of 15 cm from nine, random locations in the bottom of each pond using a 5-cm diameter core sampler (Wildlife Supply Company, Buffalo, New York). The samples were dried at 60 C in a mechanical convection oven and pulverized with a soil crusher (Custom Laboratory Equipment, Orange City, Florida) to pass a 40-mesh screen.

Samples were extracted with neutral, 1 N ammonium acetate (Knudsen et al. 1982), and potassium concentrations in extracts were determined by flame emission spectrophotometry. Separate cores were collected for determination of dry bulk density (Blake and Hartge 1986).

Samples of about 70 kg representing the original bottom soil of the ponds at completion of construction were collected from a depth of 60 cm at three locations on the farm in the vicinity of the ponds. These samples were analyzed for cation exchange capacity (CEC) by the ammonium acetate method (Jackson 1958; Rhoades 1982), total carbon (Model EC12 carbon analyzer, Leco Corporation, St. Joseph, Michigan), organic carbon (Nelson and Sommers 1982), and pH (Thunjai et al. 2001). Major cations were extracted with neutral, 1 N ammonium acetate and determined by atomic absorption spectrophotometry.

Four portions of each soil were placed into individual, plastic containers (61 cm × 40 cm × 42 cm) to provide a layer about 5 cm deep. The containers and soil were weighed and the tare weight of the containers subtracted to give moist weights of soil in each container. The moisture content of samples from containers was determined (Gardner 1986), and the dry weight of soil in each container calculated. Water was obtained from the supply well at the shrimp farm, and 56 L were transferred to each container. The chemical composition of this water was determined by standard methods outlined by Clesceri et al. (1998). An aquarium air stone in each container provided gentle but continuous mixing. On 1 August 2005, the potassium concentration was measured in each container, and enough potassium chloride was applied to three containers of each soil to increase potassium concentration to about 50 mg/L. One container of each soil was maintained as the control. Potassium concentrations were measured periodically by flame emission spectrophotometry. Re-treatment with potassium chloride to increase potassium concentration to 50 mg/L was made on 11 October 2005 and again on 6 March 2006. The last samples were taken on 20 April 2006. Soil samples were removed from the bottom of each container on 20 April. Samples were dried at 60 C, pulverized, and analyzed for exchangeable potassium as described above.

Another experiment was conducted in which three, 2-g pulverized samples of each of the three soils were placed in 50-mL centrifuge tubes with 50 mg/L potassium solution (potassium chloride in distilled water). Tubes were shaken for 1 h at 180 rpm and then centrifuged for 10 min at 2,500 rpm. After centrifugation, solutions were decanted and potassium concentrations measured by flame emission spectrophotometry. The soil was retained in the tubes and another 50-mL aliquot of potassium solution was added to each tube and the procedure repeated. A total of twelve consecutive extractions were made. The uptake of potassium by the soil during each exposure was estimated by subtracting the remaining potassium concentration from 50 mg/L.

Results and Discussion

Soon after shrimp were stocked in 2001, unusually high mortality and slow growth was noted. Water analysis revealed that salinity was about 3.5 ppt, but potassium concentration was only 7.5 mg/L. Seawater diluted to 3.5 ppt salinity should have about 38 ppt potassium. Ponds were treated with muriate of potash in early July (Table 1), and mortalities ceased and shrimp grew better. However, heavy mortality had already occurred, and it was too late in the season to stock more postlarvae. Potassium concentrations in pond water were not routinely monitored in 2001.

Potassium monitoring was initiated in spring 2002, and large amounts of potassium fertilizers were applied in 2002, 2003, and 2004 than in 2005 (Table 1). Average potassium concentrations increased quickly following addition of soluble, potassium fertilizers (Fig. 1). During the 2002 to 2004 growing seasons, potassium concentration averaged above 30 mg/L, and the concentration of this ion tended to increase from year to year. In 2004, average concentrations of potassium were between 50 and 60 mg/L. Potassium concentrations declined when water was discharged to harvest shrimp and in response to winter and spring rainfall (Fig. 1). However, the concentration of potassium remaining at the beginning of the crop tended to increase from 2003 to 2005 (Fig. 1).

Potassium was lost from ponds by both seepage and soil adsorption. The potassium budget study conducted in 2003 (see Chapter IV) revealed that potassium loss to seepage was only 22.1% of soil adsorption. Thus, most of the decline in potassium concentration following fertilization resulted from soil uptake. The increase in potassium concentration as a percentage of the potassium added in fertilizers was 71.7% in 2002, 69.8% in 2003, and 85.6% in 2004. These observations suggested that the capacity of the soil to adsorb potassium was declining, and the fertilization rate was reduced to about half of the 2004 rate in 2005. There was a much lower concentration of potassium following fertilization in 2005, and the percentage increase in concentration in pond water was only 60.9% of the treatment concentration. Thus, the assumption that the soils were becoming saturated with potassium was erroneous.

Average harvest weight of shrimp (Fig. 2) suggested that the reduction in potassium fertilization in 2005 had a negative effect on shrimp. However, there is no clear trend in shrimp production relative to the potassium concentrations in water from 2002 to 2004. This observation suggests that a minimum potassium concentration, possibly about 40 mg/L, is necessary, but concentrations greater than the minimum provide little or no benefit. Of course, in 2005, the Kmag input was particularly small, and it also is possible that a shortage of magnesium also may have influenced production. Benefits of magnesium additions have been observed in growth of post larval shrimp in laboratory cultures (Davis et al. 2005; Saoud et al. 2003). However, an evaluation of concentrations of ions and shrimp production in 2002 (McNevin et al. 2004) suggested that increased potassium provided the major benefit in ponds.

Concentrations of exchangeable potassium in soils of ponds S-7, S-8, and S-9 averaged 193 mg/kg before the first crop in 2003 (Table 2). The concentration of this variable was higher ($P < 0.05$) at the end of the first crop. However, because of the large variation in potassium concentration, differences were not observed ($P > 0.05$) within ponds for the following years. This suggests that the capacity of the soils to exchange ions for potassium in the water had been largely filled during the first crop. Nevertheless, the observation that potassium fertilizer applications did not give the expected concentrations in the water (Fig. 1) suggest that soils continued to adsorb potassium.

Soils representative of the new pond bottoms for use in laboratory studies of potassium adsorption varied in initial chemical characteristics (Table 3). The soils were alkaline in reaction and high in total carbon concentration. However, much of the carbon was present in carbonate. A particle size analysis was not conducted, but the soils were high in clay content. 2:1 expandable clays are common in Blackland Prairie soils (Dixon and Nash 1968). Cation exchange capacity (CEC) was high, verifying that the soils contained 2:1 expandable clays. For the three samples, CEC declined in relation to increasing carbonate. The major exchangeable cation in the soils was calcium because the soils contained calcium carbonate. Exchangeable potassium concentration averaged 154 mg/kg, and exchangeable magnesium was particularly low. Because the soils were about equally present within the pond area, it was assumed that their average composition was an appropriate representation of average pond bottom soil of the farm.

Composition of the well water used in the laboratory study (Table 4) revealed that it was slightly basic and had a salinity of 3.70 ppt. There were high concentrations of bicarbonate, chloride, calcium, and sodium. Potassium, magnesium, and sulfate concentrations were low.

Graphical depiction of the loss of potassium from the water of laboratory soil-water systems was averaged across the three soils for simplicity (Fig. 3). The potassium loss from water was slower following the second addition of potassium than after the first addition. Nevertheless, potassium concentrations fell to a low level both times. The loss following the third addition was even slower, but the study was terminated a few weeks after the third addition because it was obvious that a prohibitively long time would be required for the soil to become saturated with potassium by the method of exposure. In the controls, the potassium concentration in water gradually declined from 7.4 mg/L to 2.0 mg/L during exposure of the soil for more than 8 months.

The total potassium loss from the water in the containers (Table 5) did not differ greatly among soils (4,357 to 5,432 mg), and the average for the three soils was 4,982 mg. The potassium loss from the water was the result of adsorption by soil. The exchangeable potassium concentration increased much more in soils 1 and 3 than in soil 2 because soil 2 had a much lower CEC (Table 3). Soil 1 increased more in exchangeable potassium concentration than soil 3 in spite of its lower CEC. This probably occurred because soil 3 had a greater initial potassium concentration than soil 1. The total soil uptake of potassium was much greater than the uptake of exchangeable potassium (Table 5). In fact, soil 2 had a comparatively low CEC, but adsorbed about 80% as much potassium as the other two soils.

Soils can hold fixed or non-exchangeable potassium between adjacent tetrahedral layers of clay minerals (Sparks 2000). The amount of fixed potassium often exceeds the amount of exchangeable potassium in soils (Yuan et al. 1976), and 2:1 expandable clays have a particularly great capacity to fix potassium (Brady 1990). Thus, much of the loss of fertilizer potassium from the shrimp ponds was a result of non-exchangeable potassium fixation by bottom soils. This explains why the increase in exchangeable potassium of bottom soils during the first shrimp crop was less than the difference in inputs and outputs of potassium in potassium budgets for ponds S-6, S-7, and S-8 (see Chapter IV). Potassium fixation also is the reason that these pond soils continued to adsorb potassium although exchangeable potassium concentrations were not increasing (Table 2).

When the three soil samples were exposed for twelve consecutive times to a 50-mg/L potassium solution (Fig. 4), there was a rapid decline in potassium adsorption for six exposures, after which adsorption tended to reach an equilibrium. However, the soils adsorbed an average of 50 mg/kg potassium during the twelfth exposure. The total potassium adsorption averaged 1,804 mg/kg for the three soils.

Based upon CEC, complete potassium saturation of the cation exchange sites of the three soils would result in exchangeable potassium concentrations of 5,435 to 17,751 mg/kg (average = 11,183 mg/kg). However, the soils had a high concentration of exchangeable calcium, which is held more tightly than exchangeable potassium (Brady 1990). Moreover, the potassium concentration in the water was increased to only 50 mg/L, and the water contained 1,402 mg/L of sodium (Table 4) which competes with potassium for cation exchange sites. Thus, only a small percentage of the CEC could be satisfied with potassium. The non-exchangeable potassium fixation capacity of the soils was not determined because results of the shaker trial (Fig. 4) suggest that it would take many additional exposures to satisfy this capacity.

Findings of this study revealed that the potassium adsorption rate by pond bottom soil decreases over time with continuous exposure to water of high potassium concentration. Adsorption results from both cation exchange processes and fixation processes. It is likely that potassium uptake by cation exchange is completed rather quickly and that potassium fixation continues. Pond soils finally will become saturated with potassium, but the results of this study suggest that the process will take several years at potassium concentrations applied to inland shrimp ponds. The only reliable way to maintain adequate potassium concentrations in waters of inland shrimp ponds is to monitor soluble potassium concentrations and re-treat with fertilizers as necessary.

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Table 1. Dates and average treatment rates for application of potassium fertilizers to ponds of an inland shrimp farm.

Date	Fertilizer	Amount (kg/ha)
1 May 02	Kmag[1]	1,760
	Muriate of potash[2]	398
2 June 03	Kmag	999
	Muriate of potash	917
8 July 03	Muriate of potash	141
1 June 04	Kmag	784
	Muriate of potash	744
14 April 05	Kmag	52
	Muriate of potash	432
4 June 05	Muriate of potash	22

[1] Potassium magnesium sulfate, 17.4% potassium.

[2] Potassium chloride, 49.8% potassium.

Table 2. Concentrations of exchangeable potassium in bottom soils by three ponds treated with potassium fertilizers at an inland shrimp farm in Alabama. Mean indicated by the same letter did not differ ($P > 0.05$) and determined by the Kruskal-Wallis one way analysis of variance on ranks – horizontal comparison only.

Pond	May 03[1]	October 03	March 04	November 04	October 05
S-6	162 ± 46 a	377 ± 137 b	329 ± 112 b	440 ± 142 b	---
S-7	194 ± 24 a	390 ± 111 b	360 ± 111 b	451 ± 127 b	400 ± 150 b
S-8	223 ± 43 a	387 ± 43 b	446 ± 100 b	509 ± 165 b	427 ± 165 b
Average	193 ± 30 a	385 ± 98 b	378 ± 61 b	467 ± 105 b	414 ± 128 b

[1] Ponds were newly constructed and water had not been added.

Table 3. Composition of samples of original soil from three places within the pond area of an inland shrimp farm in Alabama.

Variable	Soil 1	Soil 2	Soil 3	Average ± SD
pH (standard units)	7.58	7.59	7.27	7.48 ± 0.18
Total carbon (%)	4.84	6.48	2.39	4.57 ± 2.06
Organic carbon (%)	1.7	0.2	1.5	1.13 ± 0.80
Carbonate (% $CaCO_3$)[1]	26.2	52.3	7.4	28.6 ± 22.5
Cation exchange capacity (meq/100 g)	33.1	13.9	45.4	30.8 ± 15.9
Exchangeable calcium (mg/kg)[2]	6,152	2,327	8,551	5,677 ± 3,139
Exchangeable magnesium (mg/kg)	29	16	23	23 ± 7
Exchangeable sodium (mg/kg)	426	426	432	428 ± 4
Exchangeable potassium (mg/kg)	113	106	242	154 ± 77

[1] Estimated from difference in total carbon and inorganic carbon.

[2] Determined by difference from exchangeable magnesium, sodium, and potassium.

Table 4. Chemical composition of saline well water used in laboratory soil-water systems.

pH (standard units)	8.34
Salinity (ppt)	3.80
Bicarbonate (mg/L)	300
Chloride (mg/L)	2,187
Sulfate (mg/L)	0.46
Calcium (mg/L)	65.2
Magnesium (mg/L)	6.4
Potassium (mg/L)	7.4
Sodium (mg/L)	1,402

Table 5. Potassium loss from water and adsorption by soil over 8 months in laboratory soil-water systems containing 56 L of water.

	Soil			
Variable	1	2	3	Average ± SD
Potassium loss from water				
(mg/L)	97.0	77.8	92.1	89.0 ± 10.0
(mg/tank)	5,432	4,357	5,158	4,982 ± 559
Soil weight (kg/tank)	10.70	9.98	8.13	9.60 ± 1.32
Exchangeable potassium adsorption by soil				
(mg/kg)	180	40	188	136 ± 83
Fixed Potassium adsorption by Soil				
(mg/kg)	328	397	446	390±59
(mg/tank)	3,506	3,958	3,630	3,698±234

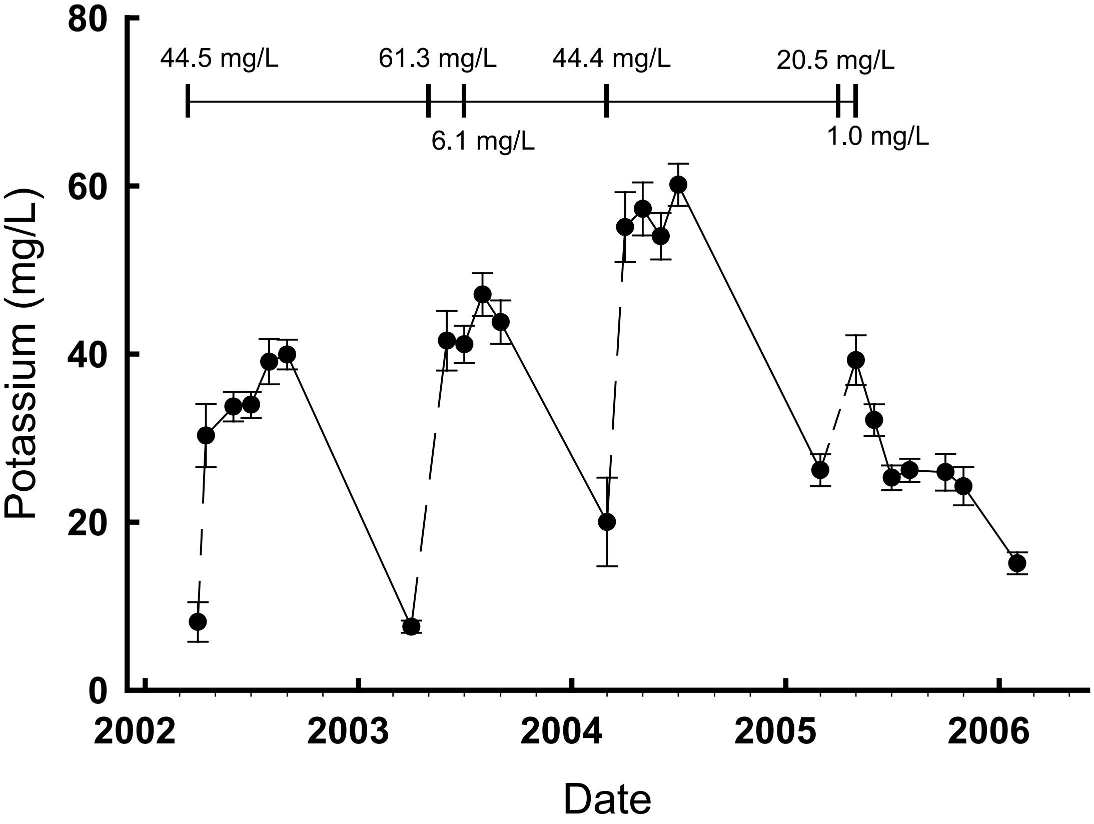

Fig. 1. Averages and standard deviations for potassium concentrations in ponds at an inland farm for producing marine shrimp in Alabama. The small vertical marks and potassium concentrations on the horizontal line across the top of the graph indicates dates and treatment rates for potassium fertilization.

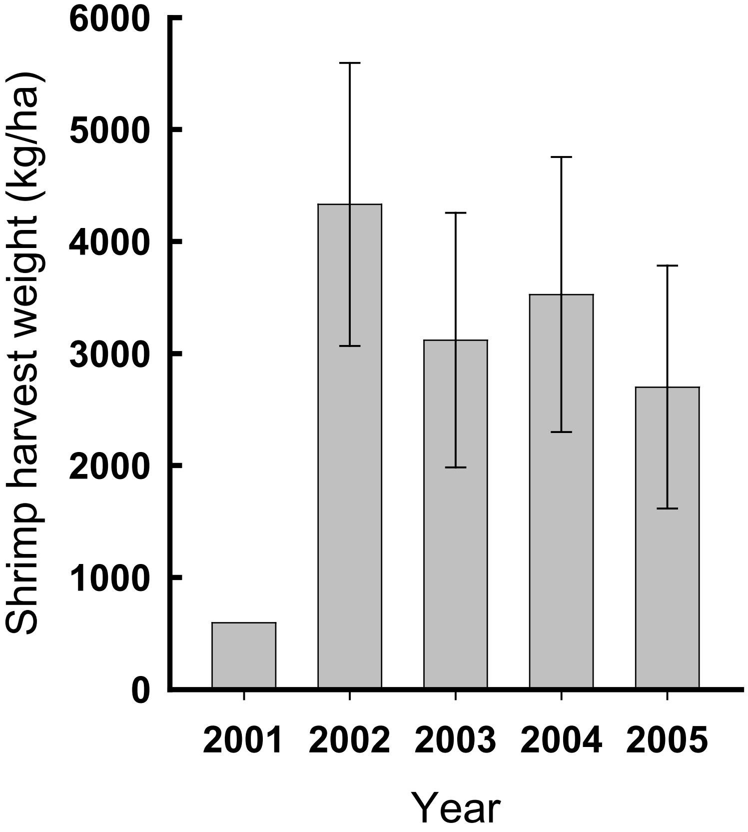

Fig. 2. Averages and standard deviations for shrimp production at an inland shrimp farm in Alabama over a 5-year period.

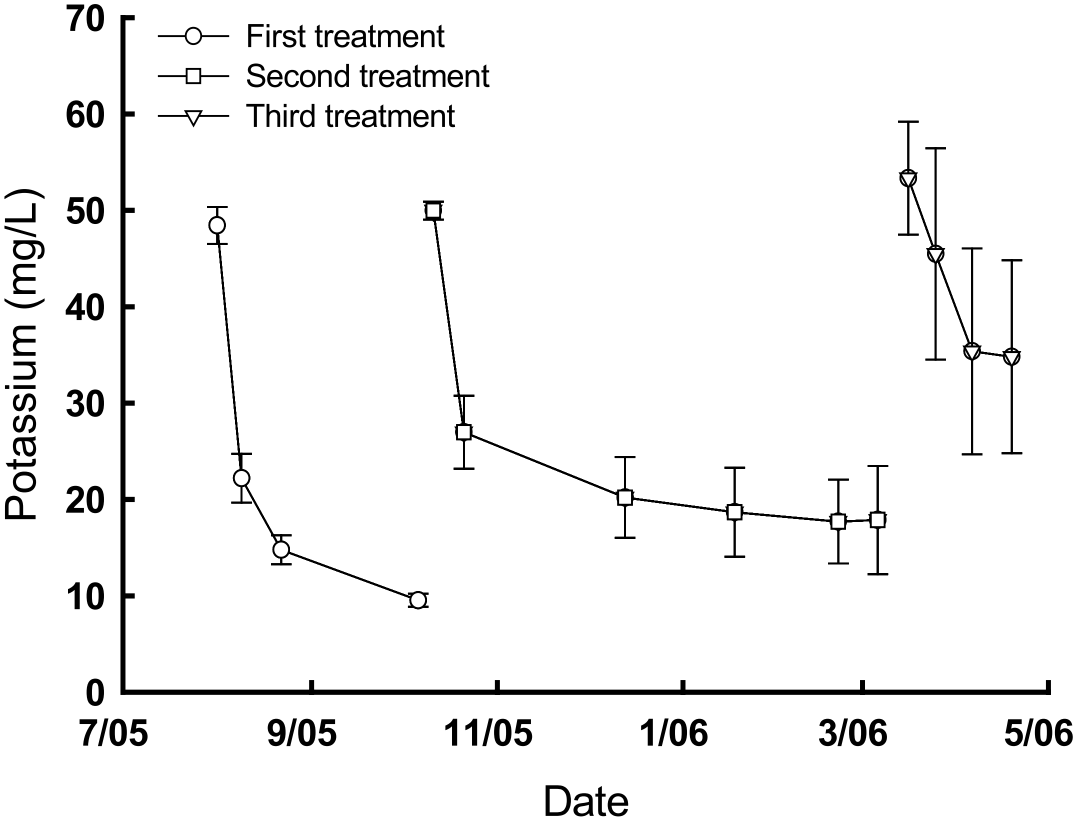

Fig. 3. Averages and standard deviation for declines in potassium concentration following three potassium additions of 50 mg/L each in laboratory systems containing 5-cm layers of original pond soil and filled with water from the source well of an inland shrimp farm in Alabama. Three replicates each of three soils were included in the trial.

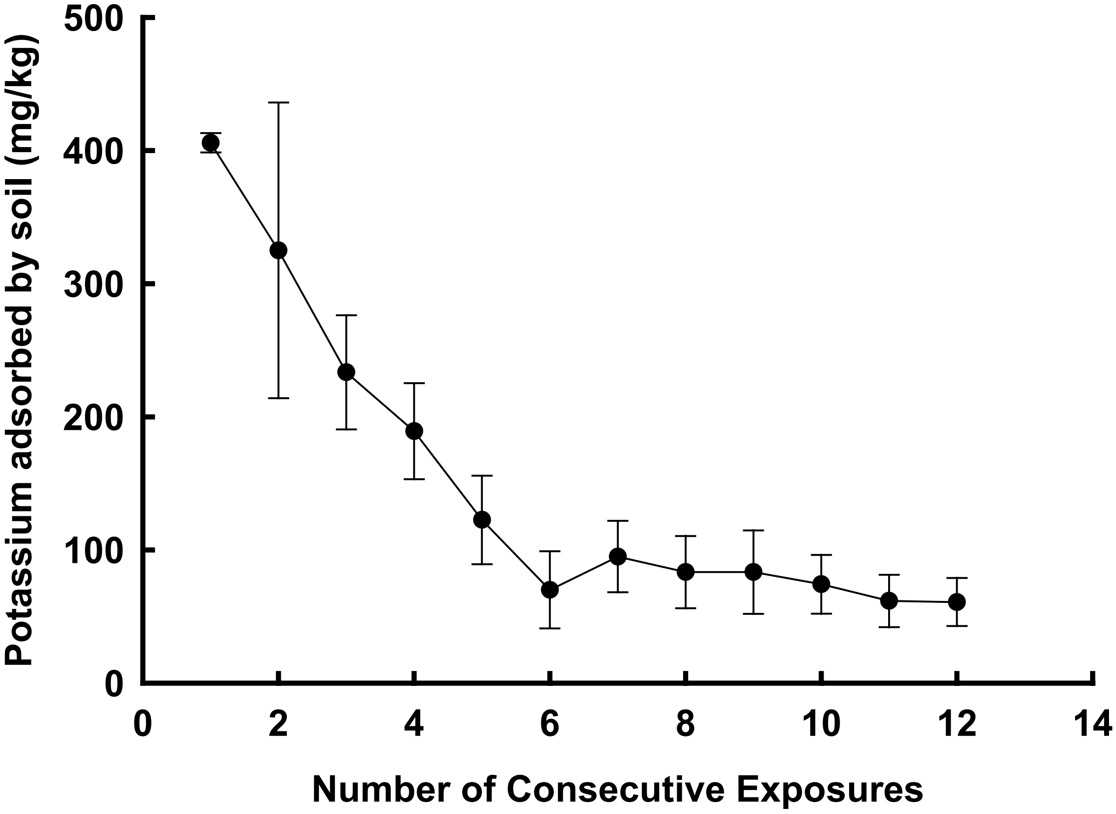

Fig. 4. Averages and standard deviations for potassium adsorption by samples of original pond soil from an inland shrimp farm in Alabama. Samples were exposed twelve consecutive times to 50 mg/L potassium (potassium chloride in distilled water) in a shaker trial. Three replicates of three soils were included.

VI. SALT DISCHARGE FROM AN INLAND FARM FOR MARINE SHRIMP IN ALABAMA

Abstract

The salt balance was estimated for an inland shrimp farm in Alabama supplied with saline well water. Over a 5-yr period, 1,980.8 tonnes of salt were applied to ponds with saline well water, mineral amendments to increase potassium and magnesium concentrations, feed, rainfall, and runoff. Of this salt, 270.4 tonnes remained in pond water and 38.3 tonnes were contained in bottom soil after 5 yr. Only 8.0 tonnes of salt were removed in shrimp harvested from the farm. A total of 1,588.0 tonnes of salt or 80.2% of the input were lost to the environment with about equal amounts exiting ponds in seepage and in overflow and harvest effluent. About 4.2% of the salt input (84.1 tonnes) could not be accounted for because of errors in assumptions and measurements. Salt concentration was elevated in a small stream passing through the pond area and in the shallow aquifer beneath it. Needham Creek, the receiving water body for surface runoff and base flow from the farm watershed, had elevated salt concentrations only when the ponds were partially drained for harvest in the fall. At this time, chloride concentration in Needham Creek exceeded 230 mg/L, the maximum concentration allowed by Alabama Department of Environment Management regulations. Greater water reuse or more gradual release of pond effluent during harvest would reduce the

peak in stream chloride concentration during shrimp harvest and avoid non-compliance with the in-stream chloride criterion.

Introduction

Culture of marine shrimp in inland areas using low salinity water is an expanding endeavor. In Thailand, shrimp are reared in ponds using brine solution from seawater evaporation ponds mixed with freshwater to increase salinity (Boyd et al. 2002). In several other countries, including the United States, saline groundwater from wells is the primary source of water for inland culture of marine shrimp (Boyd and Thunjai 2003). Although inland shrimp farming is hailed as a possible new source of income for rural areas, it presents a risk of soil and water salinization. For example, Braaten and Flaherty (2001) reported an average salt loss per crop to the environment from 0.26-ha inland shrimp ponds in Thailand of 11.5 tonnes in seepage, 9.7 tonnes in harvest effluent, and 1.8 tonnes in sediment removed from ponds. Effluents from inland shrimp culture caused salinity in irrigation canals to increase above safe concentrations for the main crops of the region – irrigated rice and fruit trees.

A few inland shrimp farms have been established in Alabama. These farms typically have several ponds filled with well water of 2 to 8 ppt salinity. Saline well waters in Alabama are naturally low in potassium and magnesium, and the fertilizers muriate of potash (potassium chloride) and Kmag® (potassium magnesium sulfate) are applied to ponds in May or June to provide about 40 mg/L potassium and 20 mg/L magnesium (McNevin et al. 2004). Shrimp are stocked in May, feed is applied, mechanical aeration is used to avoid low dissolved oxygen concentration, and shrimp are harvested during September and October. Water exchange is not used, but some water may overflow after storms. Ponds are partially or completely drained for harvest, but producers can pump harvest effluent to other ponds for reuse. Nevertheless, a portion of the harvest effluent escapes into the environment and enters streams (Boyd et al. 2004). Saline water also seeps from ponds.

The present study was conducted to determine the fate of salt applied to an inland shrimp farm in Greene County, Alabama, and to measure concentrations of salinity in nearby streams and in the shallow, freshwater aquifer.

Materials and Methods

The Farm

The inland shrimp farm is located about 6 km north of Forkland, Alabama, on Alabama Highway 43. The ponds are built in calcareous, clayey soils of the Blackland Prairie (Hajek et al. 1975). The farm has 16 ponds with an average depth of 1.25 m and ranging from 0.49 to 2.02 ha in water surface area for a total water surface of 20.15 ha (Fig. 1). The farm produces Pacific white shrimp (Litopenaeus vannamei) at high density through the use of feed and mechanical aeration. A small, un-named stream originates beyond the west side of the farm, passes through the pond area, and enters Needham Creek (Fig. 1). A ditch runs along the east ends of ponds N-5 to N-8 and enters the farm creek. The drain pipes of the ponds discharge into the ditch or directly into the farm creek.

Water and Soil Analyses

Water samples were dipped from the surface of ponds, farm stream, and Needham Creek at 1- to 2-month intervals during the period May 2001 to December 2005 (Fig. 1). A water sample was collected from the well on each sampling date. If the well was not discharging, the pump was run for 10 min before taking a sample from the discharge pipe. Sampling was not initiated at all stations at the same time, and samples were not taken from the downstream station on Needham Creek until 2003. Three, 15-m deep piezometer tubes were installed in boreholes drilled into the shallow aquifer; one upslope of the ponds and two within the pond area (Fig. 1). Groundwater samples were removed from the piezometer tubes with a bailer.

Salinity and specific conductance of water samples were determined with a YSI Model 30 Salinity Conductivity Temperature meter (Yellow Springs Instrument Company, Yellow Springs, Ohio). Chloride concentration was measured by titration with standard mercuric nitrate to the diphenylcarbazone endpoint (Clesceri et al. 1998).

Salt concentration was measured in bottom soil of pond N-5 before initial filling and following the first harvest. A soil core sampler with hammer attachment was used to collect 5-cm core segments to a depth of 50 cm from six places in the pond. Dry bulk density was determined for one set of samples (Blake and Hartge 1986). The other samples were dried at 60 C in a mechanical convection oven and pulverized to pass a 40-mesh screen with a soil pulverizer (Custom Laboratory Equipment, Inc., Orange City, Florida USA). A 20-g portion of each sample was placed in a 250-mL Erlenmeyer flask with 20 mL of distilled water and mixed for 2 h on an oscillating platform shaker at 180 rpm. The mixtures were filtered by vacuum through a Whatman Number 41 paper in a

Buchner funnel. Salinity of filtrates measured with the YSI Salinity Conductivity Temperature meter was directly equal to soil salinity (Jackson 1958).

Water and Salt Budgets

A simulated water budget was prepared for the shrimp farm for the period 1 April 2001 to 31 December 2005. The following equation (Boyd 1982) was used to estimate the water level at the end of each month:

$$H = (P + R + W) - (S + E + D) \tag{1}$$

where H = water level (cm) and symbols for monthly inflows and outflows in centimeters of water depth were: P = precipitation; R = runoff; W = addition of saline well water; S = seepage; E = pond evaporation; D = harvest effluent. The average depth of ponds was 125 cm, and when H exceeded this depth, overflow occurred through the standing drainpipes. On months when H was more than 125 cm, overflow was calculated as follows:

$$O = H - 125 \tag{2}$$

where O = overflow (cm).

Well water was applied to 10.24 ha of new ponds during April 2001, and to an additional 9.91 ha of new ponds during May 2003. Initial filling was to an average depth of 115 cm, and 10 cm storage depth was retained to lessen or avoid overflow during spring rains (Boyd 1982). Simulation began on 1 April 2001 for the first group of ponds and on 1 May 2003 for the second group by substituting W = 115 cm into Eq. 1 to represent the initial filling of ponds. Monthly precipitation data were obtained from a weather station at Demopolis, Alabama, about 30 km southeast of the farm. Topography and vegetation do not change between the farm and the weather station, and rainfall should not differ greatly. Monthly rainfall estimates were used for P in Eq. 1. The watershed of the ponds extended from centers of embankment tops to the water's edge (6.1 m) around all ponds (4,500 m) and 5.0-ha of land west of ponds N-4, N-6, N-7, and N-8 (Fig. 1). All other runoff was diverted from ponds by earthen berms. Total watershed area was 77,450 m^2 or 3,844 m^2 per hectare of pond water surface area. The watershed surface was well compacted with little grass cover. Based on the curve number method (Yoo and Boyd 1994), about 67% of rain falling on the watershed would enter ponds in runoff. Thus, R was related to P by the multipliers 0.67 and 0.38, the respective ratios of runoff to rainfall and watershed area to water surface area. The runoff equation was:

$$(3) \qquad R = 0.25\ P$$

During the grow-out period (May to October), additional well water was added when the pond water level fell below 85 cm. However, to lessen the possibility of overflow after rains, the water level was not increased above 95 cm by well water addition. In the simulation, the depth of water necessary to restore the level to 85 cm was estimated for the months in which deficiencies occurred by the expression:

(4) $$W = 95 - H$$

and the water level for the beginning of the next month was 95 cm.

Seepage from ponds constructed on clayey soils of the Blackland Prairie region of Alabama averaged 0.15 cm/d (Parsons 1949). Thus, the expression for estimating seepage was:

(5) $$S = 0.15\ (n)$$

where n = number of days in the month. Boyd (1985) found that the pan coefficient for evaporation from aquaculture ponds in Alabama averaged 0.81. Thus, the equation for pond evaporation was:

(6) $$E = E_{pan}\ (0.81)$$

where E_{pan} = monthly Class A pan evaporation (cm).

Shrimp were harvested in late September and October by aid of a fish pump. Approximately one-third of the water in a pond was discharged into the farm ditch or farm creek, and the remainder was pumped back into ponds and conserved for reuse. The equation for estimating harvest effluent was:

(7) $$D = 0.33\ (H_{1Oct.})$$

In the simulation, the value of D was recorded for October, and the water level for 1 November reflected the draining loss. Following harvest, well water was not applied to ponds until the end of January, and then, H was increased only to 95 cm to maintain storage volume for rainfall and runoff. The value of W for refilling ponds in January also was estimated with Eq. 4.

Data from the water budget, farm water surface area, bulk density of bottom soil, feed and potassium fertilizer additions, shrimp harvested from ponds, and concentrations of salt in water, soil, fertilizers, and shrimp were used to estimate a salt balance for the farm.

Results and Discussion

The farm water budget (Table 1) revealed that following initial filling, well water additions averaged 26.6 cm/yr. The total volume of well water used during the period 1 April 2001 to 31 December 2005 was estimated from the water budget and pond area to be 500,599 m^3. Ponds were operated to retain as much rainfall and runoff as possible, and overflow was relatively minor accounting for an average of 12.1 cm/yr for a total volume of 94,903 m^3 during the study. Seepage was a major variable averaging 52 cm/yr for a total volume of 415,881 m^3. Harvest effluent averaged 34.5 cm/yr or 274,997 m^3 during the study. The simulated water budget is thought to provide realistic estimates, because water depth in ponds on 31 December 2005 averaged 66 cm and agreed well with the simulated depth of 61 cm (Table 1). The farm owner reported that water overflowed from ponds for only 1 or 2 days once or twice per year and this confirms the small, simulated overflow volume. Moreover, the simulated timing of water additions during summer agreed well with the actual schedule of water additions.

Salinity and chloride concentrations in the source water averaged 3.66 g/m^3 (ppt) and 2,023 mg/L, respectively (Table 2). Both variables were correlated with specific conductance ($P < 0.01$), and specific conductance did not vary greatly over time (Fig. 2).

Salinity and chloride concentration in pond water averaged 1.79 g/m^3 and 1,059 mg/L, respectively (Table 2). The values were slightly higher at harvest time in October when salinity averaged 2.23 g/m^3 and average chloride concentration was 1,868 mg/L. There also was close correlation between specific conductance and both salinity and chloride concentration (Fig. 3).

The average salinity of the bottom soil in pond N-5 increased from 96 to 388 mg/kg during the first shrimp crop (Table 3). The bulk density of this layer was 1,300 kg/m^3. The salt content of the bottom soil increased by 0.19 kg/m^2 [(338 – 96) mg/kg × 1 m^2 × 0.5 m deep × 1,300 kg/m^3 × 10^{-6}] or by 38.3 tonnes for the entire farm. It was not possible to sample deeper in the heavy clay soil with available equipment, and this equipment was not available after the first harvest. Bottom soils apparently became saturated with salt after one crop. Evidence for this assumption is the observation that the salt concentration was 527 ± 155 mg/kg in October 2001 (Table 4), and after five crops, it was only 580 ± 96 mg/kg in fall 2005.

The salt input to ponds in well water during the study was 1,832.1 tonnes. Potassium fertilizers were applied to ponds in April each year, and if potassium concentration declined below 30 mg/L, an additional application was made later. Farm records revealed that 53.8 tonnes of Kmag and 50.3 tonnes of muriate of potash were applied. The amendments contained approximately 95% dry matter. They were highly soluble and represented a salt input of 98.9 tonnes. Shrimp feed also contained salt in the form of various mineral nutrients. A total of 511.3 tonnes of feed with an average ash content of 11.3% was applied to the ponds. It is assumed that the 57.8 tonnes of mineral matter added in feed and not recovered in shrimp became dissolved salts. A total of 238.7 tonnes of shrimp were harvested. On a fresh weight basis, L. vannamei contains about 3.37% ash (Boyd and Teichert-Coddington 1995), and 8.0 tonnes of mineral matter were removed from ponds in shrimp.

Mineral substances exchange between bottom soil and water, and bottom soils can be a source of dissolved ions in pond water (Boyd 1995). Three soil samples representative of the initial pond bottoms before exposure to saline water were obtained from the vicinity of the ponds. Three, 5-g samples of each soil were put into flasks containing 100 mL saline well water (7.17 mS/cm). The flasks were agitated on a platform shaker at 180 rpm for 2 hr. The resulting specific conductance values of the water were 6.9 to 7.0 mS/cm. Thus, there probably was no net salt transfer from soil to water in the ponds.

The total salt input to the ponds in water, mineral amendments, and feed was 1,980.8 tonnes. Over 5 yr, there was a total of 80.93 crop·hectares [(10.24 ha × 5 crops) + (9.91 ha × 3 crops)], so the salt input averaged 24.5 tonnes/ha per crop.

A total of 1,588.0 tonnes or 80.2% of the salt input entered the environment in seepage, harvest effluent, and overflow. The average annual losses to the environment were 9.20 tonnes/ha in seepage, 8.32 tonnes/ha in harvest effluent, and 2.10 tonnes/ha in overflow. Of the 308.7 tonnes retained in the ponds, 270.4 tonnes were in the water and

38.3 tonnes in the soil (Table 4). The difference in inputs and outputs of salt was 392.8 tonnes of which 308.7 tonnes remained in the ponds. The unaccounted 84.1 tonnes of salt resulted from errors in assumptions and measurements. However, the discrepancy is only 4.2% of the input, and the budget provides a close approximation of the fate of salt applied to the ponds.

Slightly more salt was released to the environment via overflow and harvest effluent than in seepage. However, a portion of the seepage passed through the pond embankments or infiltrated down slope as subsurface drainage to enter the farm creek. Seepage from ponds could be seen entering the farm creek at several locations, and in dry weather, the flow of the creek increased considerably while passing through the ponds.

Results of this study agree with findings of Braaten and Flaherty (2001) in that more than three-fourths of the salt added to inland shrimp ponds is lost to the environment. However, on an areal basis, salt loss from inland shrimp ponds in Alabama was about one-fourth of that reported for inland shrimp culture in Thailand (Braaten and Flaherty 2001). This resulted because the salinity of water at the beginning of crops in Thailand was much higher than for the farm in Alabama, and in Thailand none of the water was conserved during harvest for reuse.

Effect of Salt Losses on Surface and Groundwater

There was a close relationship between specific conductance and salinity and chloride concentration in samples from the streams and piezometer tubes (Fig. 4). Therefore, specific conductance was used to demonstrate changes in salt concentration of the streams and groundwater over time. Averages for specific conductance, salinity, and chloride are presented (Table 5).

The specific conductance of the farm creek upstream of the ponds ranged from 0.15 to 0.76 mS/cm with an average of 0.491 mS/cm (Table 5). There was no clear trend in specific conductance with season, but the two lowest values were recorded following heavy rainfalls (Fig. 5). The midstream samples had an average of 2.43 mS/cm with a range of 0.15 to 6.73 mS/cm. The downstream samples were similar in specific conductance to the midstream samples. Variation between sampling dates in specific conductance was much less at the upstream station than at the two lower stations on the creek. At the lower stations, specific conductance tended to increase during the shrimp crop and to decrease in winter. Ponds seeped in the farm stream and harvest effluent was discharged into it, but the permanent source of water to the stream is runoff from its watershed. Thus, during winter, the increases in rainfall and runoff diluted seepage entering the stream from ponds causing the specific conductance of water in the farm stream to decline.

The specific conductance of groundwater was greater for samples from the middle and lower piezometer tubes within the pond area than for samples from the upper tube at higher elevation west of the ponds. Mean specific conductance values were 2.21 and 2.62 mS/cm as compared to 0.49 mS/cm, respectively. Piezometer tubes were not installed until several weeks after ponds had been filled with saline water. Although specific conductance data were not taken before ponds were filled, it is reasonable to assume that specific conductance of groundwater beneath the pond area was originally similar to that of groundwater further upslope. The shallow aquifer provided base flow to the farm stream, and the stream entered Needham Creek.

Specific conductance for upstream Needham Creek averaged 0.52 mS/cm (Table 5). The maximum value recorded during dry weather in the fall was 0.91 mS/cm (Fig. 6). Specific conductance decreased in winter and early spring, and the lowest value was 0.28 mS/cm. Specific conductance at the downstream Needham Creek station reached a peak of 3.42 mS/cm. The high values were recorded during shrimp harvest, but during the rest of the year, specific conductance was below 1.0 mS/cm (Fig. 6). Although the farm stream often had high specific conductance, Needham Creek had high specific conductance only when ponds were drained for shrimp harvest.

The Alabama Department of Environmental Management (ADEM) does not regulate specific conductance or salinity of effluents entering freshwater streams of the state. However, ADEM regulations specify that “in-stream” chloride concentration must not exceed 230 mg/L (Benoit 1988; Boyd et al. 2004). The farm stream was an intermittent one before the ponds were built and is not subject to the ADEM chloride regulation. However, the shrimp farm should not cause chloride concentrations in Needham Creek to exceed 230 mg/L. Upstream of the shrimp farm, Needham Creek had a maximum chloride concentration of 92 mg/L during dry weather in fall 2005 (Fig. 6). Downstream of the shrimp farm, the chloride concentration exceeded the ADEM limit of 230 mg/L during shrimp harvest, and peak concentrations observed in October of 2003 to 2005 were between 800 and 918 mg/L. The problem with high chloride concentration in Needham Creek was exacerbated by the fact that stream flow in Alabama typically is lowest in September, October, and November (Yoo and Boyd 1994).

Best management practices (BMPs) for inland shrimp farming in Alabama suggest that ponds should be designed, constructed, and operated in a way to minimize seepage, overflow, and harvest effluent (Boyd et al. 2004). Findings of the present study reveal that the main off-site impact of saline ponds was increased salinity in the receiving stream during harvest operations. Producers should strive to conserve water through water reuse as illustrated in Fig. 7 to reduce effluent volume and salt loss. If water must be discharged, it should be discharged slowly from the reservoir (Fig. 7) so that a spike in stream salinity and chloride concentration such as observed in this study can be avoided.

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Table 1. Simulated water budgets in centimeters of water depth for ponds initially filled in April 2001 or April 2002 and operated through 31 December 2005. Water level was 61 cm in ponds on 31 December 2005.

	Filled April 2001		Filled April 2003	
Variable	Inflow	Outflow	Inflow	Outflow
Well water	304	---	191	---
Precipitation	646	---	403	---
Runoff	161	---	101	---
Seepage	---	260	---	151
Evaporation	---	572	---	335
Overflow	---	53	---	41
Harvest effluent	---	165	---	107
Total	1,111	1,050	695	634

Table 2. Average specific conductance, salinity, and chloride concentration in samples from the source well, ponds, and harvest effluent at an inland shrimp farm in Alabama.

Water	Specific conductance (mS/cm)	Salinity (kg/m^3 or ppt)	Chloride (mg/L)
Source well	6.32 ± 0.12	3.66 ± 0.05	2,023 ±45
Pond	3.38 ± 0.17	1.79 ± 0.10	1,059 ± 54
Harvest effluent	5.26 ± 0.88	2.20 ± 0.51	1,868 ± 354

Table 3. Salinity (g/kg) of bottom soil in pond N-4 immediately after construction and before adding saline water (initial) and following the first shrimp crop (final).

Depth (cm)	Initial	Final
0-5	120 ± 20	700 ± 60
5-10	80 ± 20	480 ± 65
10-15	140 ± 15	440 ± 30
15-20	60 ± 25	400 ± 50
20-25	100 ± 30	300 ± 40
25-30	80 ± 40	220 ± 20
30-35	60 ± 20	240 ± 30
35-40	80 ± 25	340 ± 40
40-45	100 ± 30	320 ± 40
45-50	140 ± 50	440 ± 50
Average	96 ± 30	388 ± 140

Table 4. Salt balance for inland shrimp farm in Alabama.

Variable	Volume (m^3)	Salinity (kg/m^3)	Salt (tonnes) Inputs	Salt (tonnes) Losses	Salt (tonnes) Remaining
Well water	500,577	3.66	1,832.1	---	---
Amendments	---	---	98.9	---	---
Feed[a]	---	---	57.8	---	---
Seepage	415,881	1.79	---	744.4	---
Overflow	94,903	1.79	---	169.9	---
Harvest effluent	274,997	2.45	---	673.7	---
Shrimp	---	---	---	8.0	---
Water in ponds	122,915	2.20	---	---	270.4
Bottom soil	---	---	---	---	38.3
Total	---	---	1,980.8	1,596.0	308.7

[a] Difference in salt contained in bottom soil at beginning and end of crop.

Table 5. Averages ± standard deviations and ranges (in parentheses) for specific conductance, salinity, and chloride concentration in water samples from streams and piezometer tubes in the vicinity of a farm for inland production of marine shrimp.

	Specific conductance (mS/cm)	Salinity (ppt)	Chloride (mg/L)
	Piezometer tubes		
Upper	0.49 ± 0.02 (0.30-0.81)	0.20 ± 0.09 (0.1-0.4)	9.6 ± 6.8 (0.39-34)
Middle	2.21 ± 0.79 (0.75-3.3)	1.23 ± 0.49 (0.4-2.0)	570 ± 327 (3.5-1,020)
Lower	2.62 ± 0.81 (0.37-4.1)	1.52 ± 0.41 (0.9-2.2)	728 ± 232 (286-1,072)
	Farm stream		
Upstream	0.49 ± 0.12 (0.15-0.76)	0.19 ± 0.08 (0.1-0.4)	15.6 ± 23.8 (2.1-124)
Midstream	2.43 ± 1.91 (0.15-6.73)	1.38 ± 1.17 (0.1-4.0)	669 ± 631 (45-2,303)
Downstream	2.30 ± 1.50 (0.37-6.7)	1.24 ± 0.91 (0.1-4.0)	626 ± 457 (42-2,216)
	Needham Creek		
Upstream	0.52 ± 0.16 (0.28-0.91)	0.26 ± 0.15 (0.09-0.7)	27.8 ± 21.6 (4.4-92.0)
Downstream	1.26 ± 0.93 (0.29-3.42)	0.62 ± 0.50 (0.1-1.8)	256 ± 309 (17.8-918)

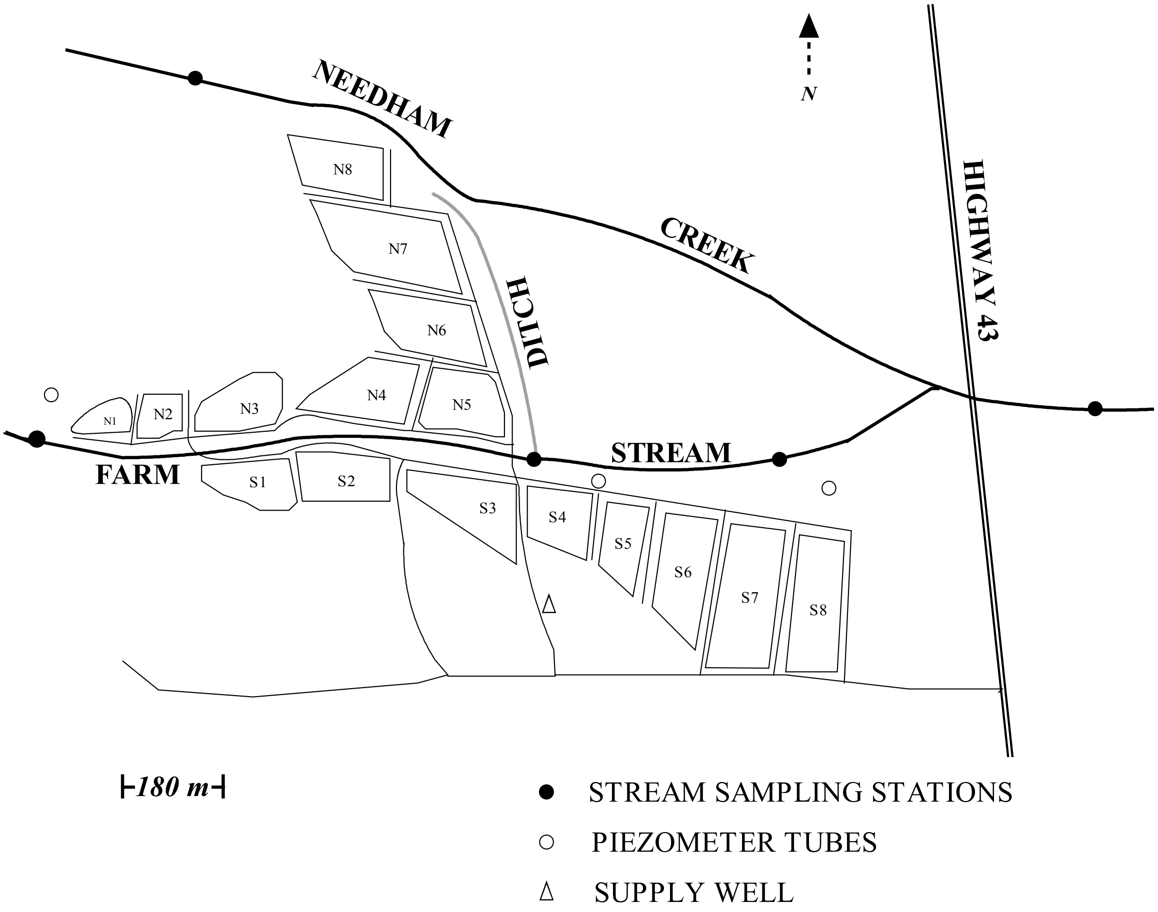

Figure 1. Map of the inland shrimp farm showing stream and groundwater sampling stations.

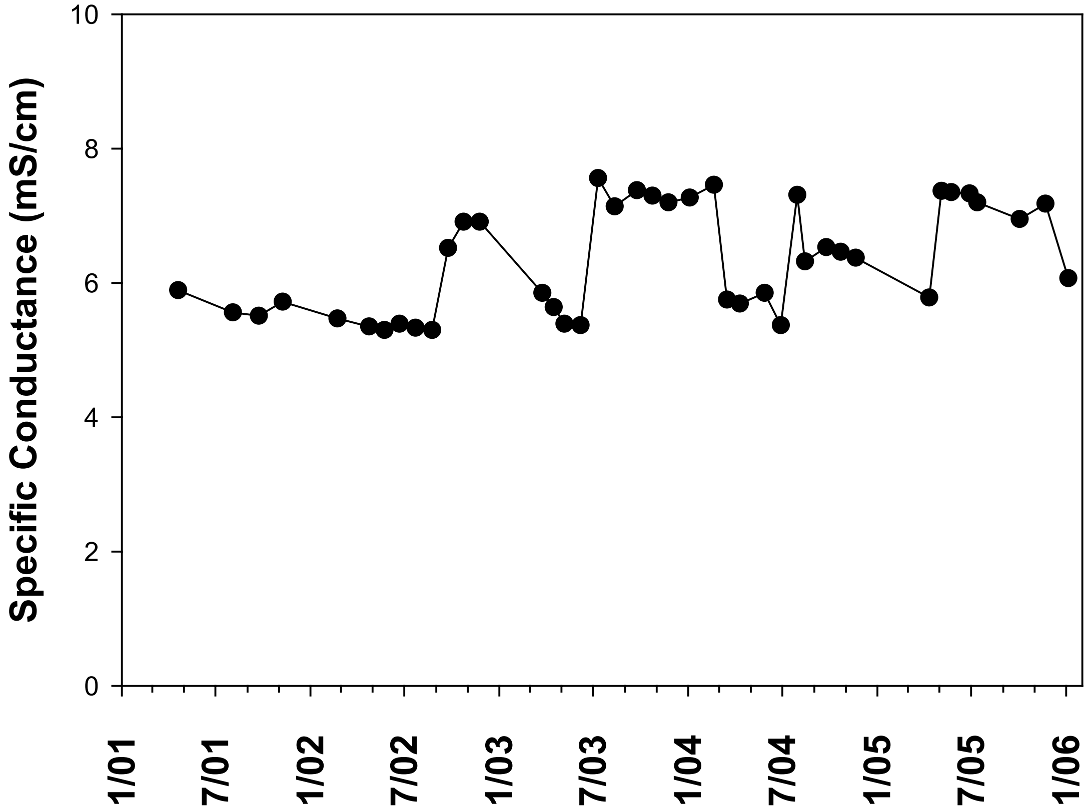

Figure 2. Specific conductance of water from supply well for inland shrimp farm in Alabama.

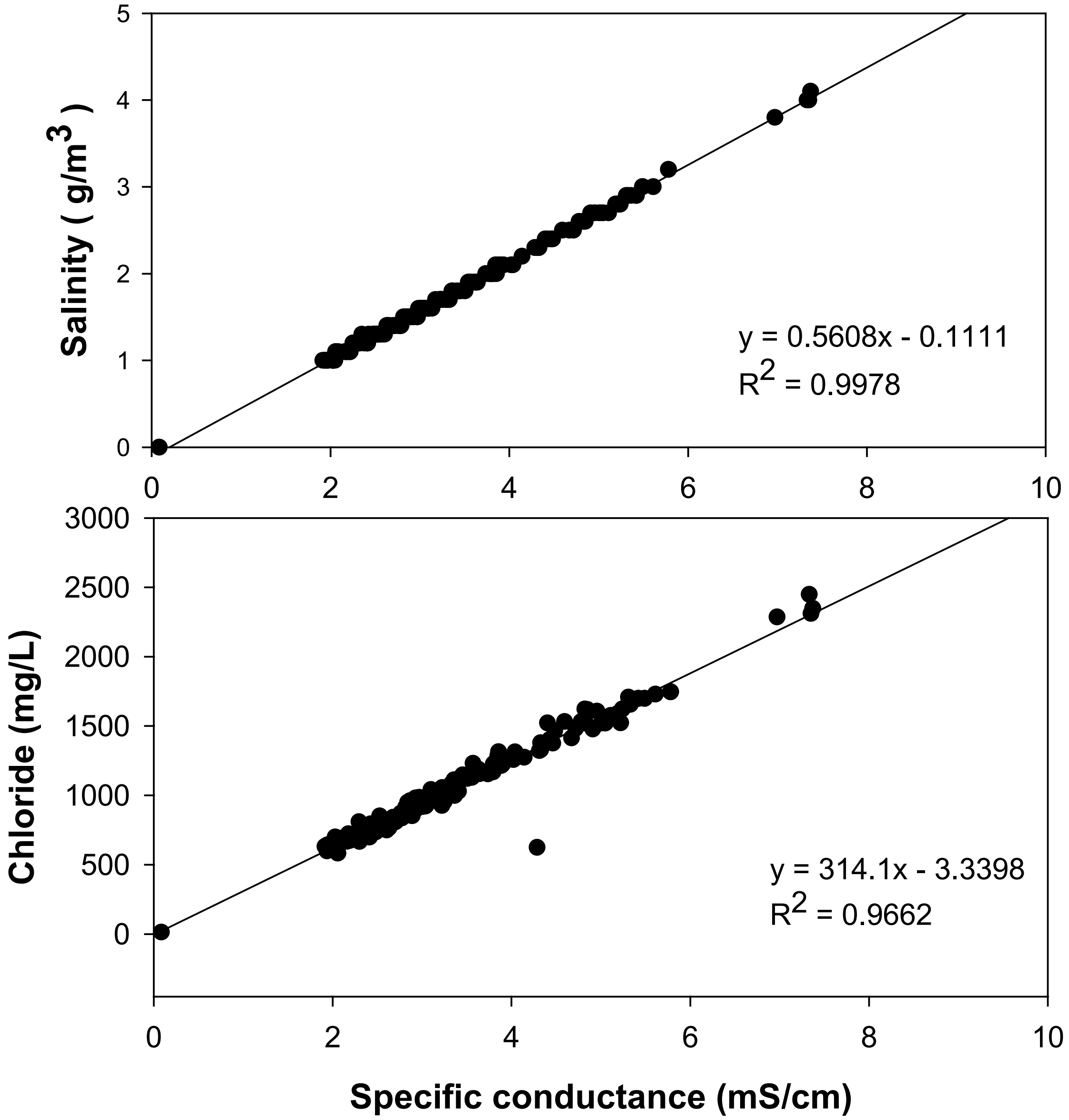

Figure 3. Regressions between specific conductance and salinity and chloride concentration in pond waters of an inland shrimp farm in Alabama.

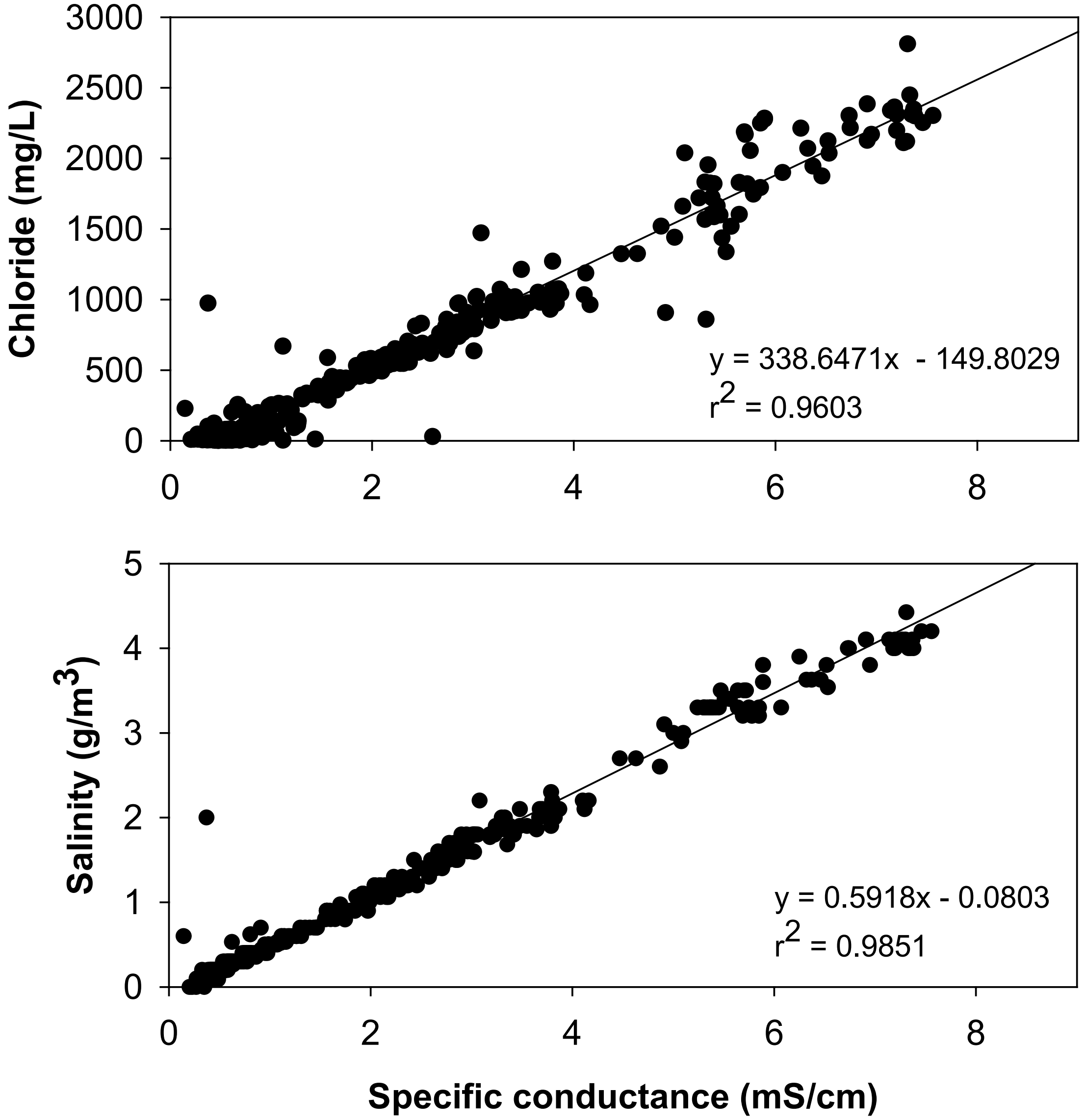

Figure 4. Regressions between specific conductance and salinity and chloride concentration in stream waters and groundwater in the vicinity of an inland shrimp farm in Alabama.

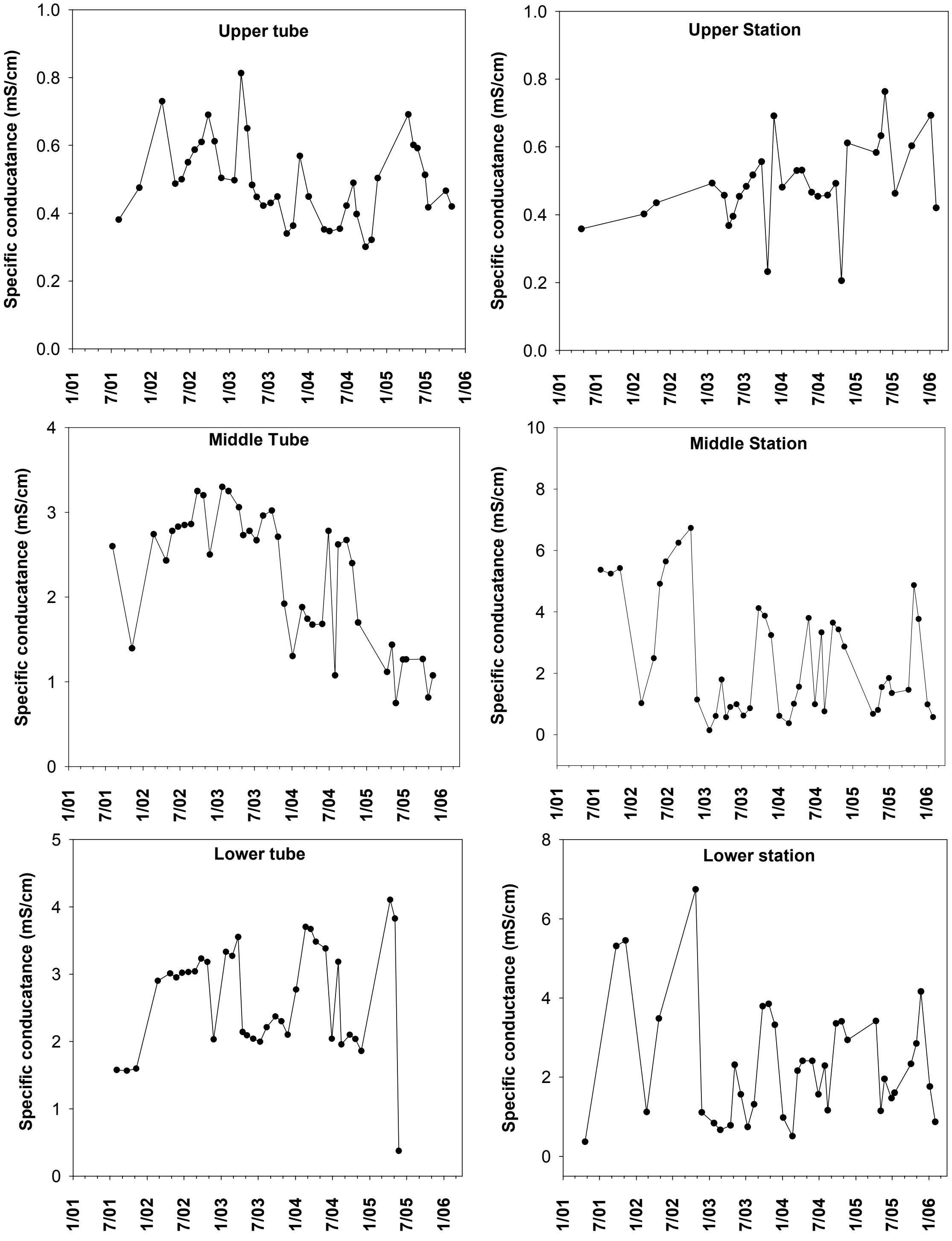

Figure 5. Specific conductance of water from piezometer tubes and small stream upstream (upper) of and within the pond area (middle and lower) of an inland shrimp farm in Alabama.

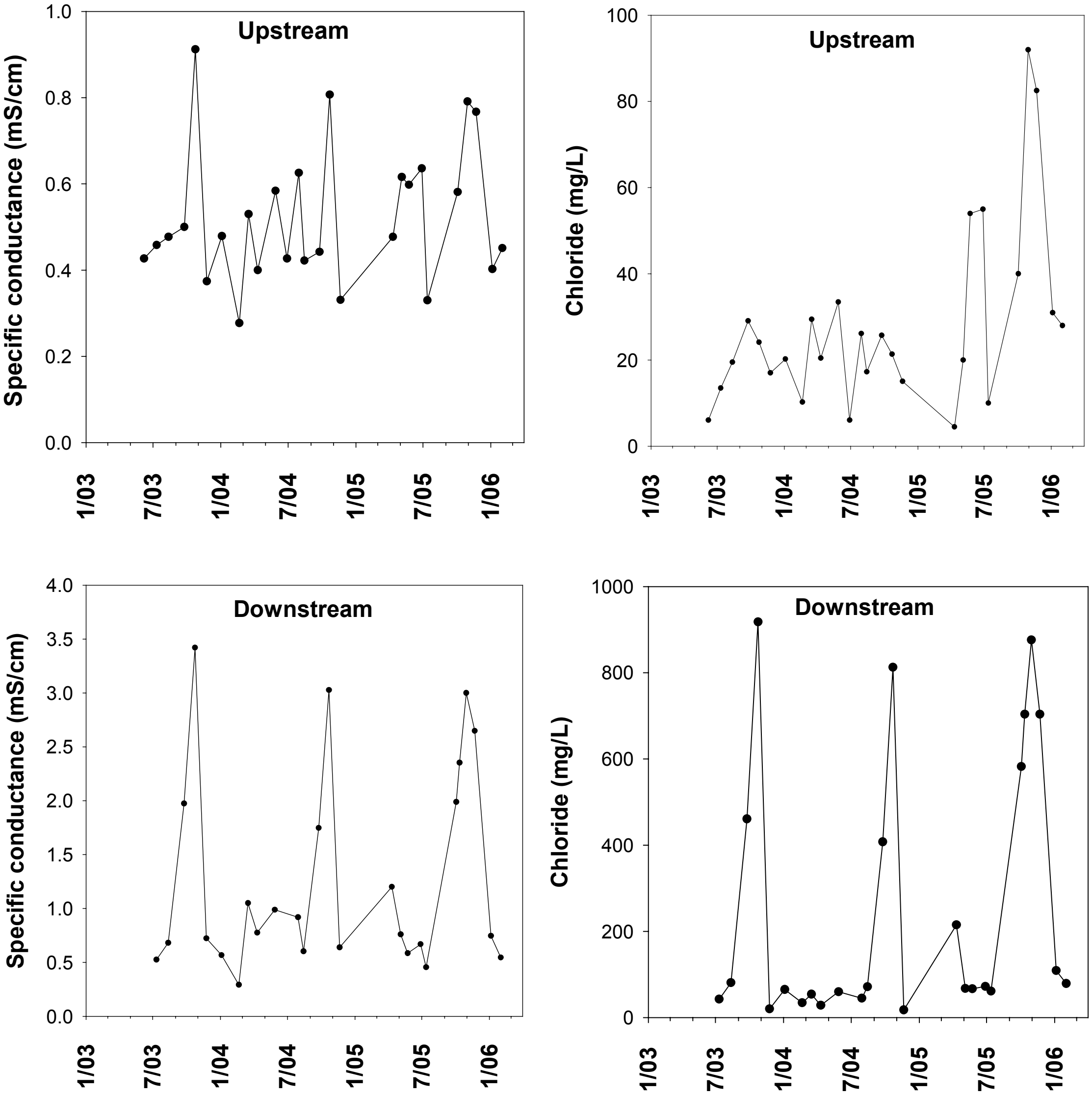

Figure 6. Specific conductance and chloride concentration in Needham Creek upstream and downstream of an inland shrimp farm in Alabama.

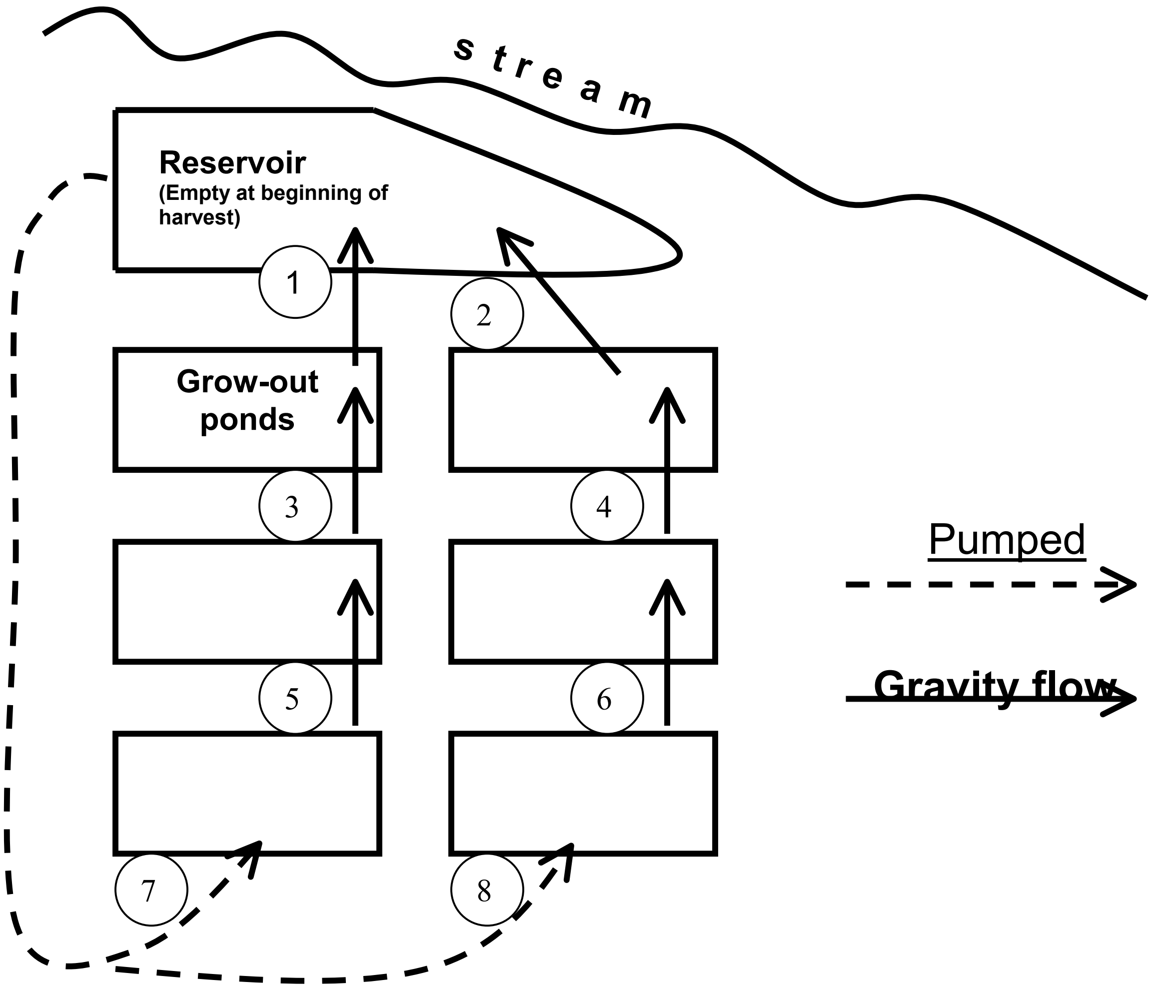

Figure 7. Illustration of method for conserving pond water for reuse during drain harvest of inland shrimp farms.