Water Quality Assessments in the Mississippi Delta

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Water Quality Assessments in the Mississippi Delta

Regional Solutions, National Scope

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Foreword

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Before agreeing to publish a book, the proposed table of contents is reviewed for appropriate and comprehensive coverage and for interest to the audience. Some papers may be excluded to better focus the book; others may be added to provide comprehensiveness. When appropriate, overview or introductory chapters are added. Drafts of chapters are peer-reviewed prior to final acceptance or rejection, and manuscripts are prepared in camera-ready format.

As a rule, only original research papers and original review papers are included in the volumes. Verbatim reproductions of previously published papers are not accepted.

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Preface

The Mississippi Delta is rich in culture and history with a strong agricultural base underpinned historically by the cotton industry. This region was formed and continues to be sustained by the meanderings of the Mississippi River and its tributaries. The low-lying topography and intricate system of rivers, oxbow lakes, and canals throughout the Delta are constant reminders that water is an important resource that must be managed carefully and never taken for granted. As the point of confluence for water flow from central continental North America, the Mississippi Delta provides the crucial and final link in the drainage system feeding into the Gulf of Mexico. This emphasizes the delicate balance of the Mississippi Basin with each component of the system affecting the one that follows. In 1995, scientists and others interested in balancing agricultural viability in the region with environmental integrity formed a coalition known as the Mississippi Delta Management Systems Evaluation Area (MDMSEA) Project to assess the influence of well-chosen agricultural "best management" practices on water quality and ecological stability. The inclusion of the Mississippi Delta within the national context of the U.S. Department of Agriculture MSEA projects added an important component in the effort to conserve and improve water and soil resources across the entire United States.

The first portion of the book (Chapters 1–5) provides the background on the National MSEA Program and describes the agricultural and water quality issues in the Mississippi Delta. These chapters set the stage in turn for the presentation of individual research results (Chapters 6–15) from the project. The final chapters (Chapters 16–18) address watershed management and applications to the overall national water quality goals and relationships to the efforts in other regions.

Given the importance of the Mississippi Delta to U.S. agriculture and the need for environmental stewardship, this book should serve as a valuable resource for an audience far exceeding the boundaries of the Mississippi Delta region. We acknowledge the hard work and dedication of the many individuals who supported the Mississippi Delta MSEA

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project through to this stage of its existence and who made contributions toward completing this book.

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Chapter 1

Mississippi Delta Management Systems Evaluation Area: Overview of Water Quality Issues on a Watershed Scale

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The Mississippi Delta Management Systems Evaluation Area (MDMSEA) Project was initiated as a regional effort to evaluate best management practices that might minimize non-point source pollution of water in the lower Mississippi Delta. The context of Mid-South agriculture was a unique setting to expand on environmental issues previously addressed by the Midwestern MSEA projects. The MDMSEA project is comprised of a consortium of nearly twenty private, state and federal organizations. Evaluating the combined effects of management practices on lake water quality was the primary focus of the first five years. Three oxbow lakes and their respective surrounding watersheds provided systems that were compact and manageable, and essentially hydrologically isolated with regard to extraneous surface water. Thighman Lake watershed was originally protocolled as a control watershed with conventional farm practices; at Beasley Lake watershed, edge-of-field practices (e.g., vegetative strips, slotted board risers) were implemented with conventional practices; and Deep Hollow Lake watershed was established with a combination of agronomic conservation practices such as winter cover crops and conservation tillage, as well as edge-of-field structural mitigations. Sediment, nutrients and

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pesticides were identified as the primary lake pollutants of concern, and lakes were monitored for changes in water quality, microbial communities, and fish populations. Other aspects under investigation included: runoff from fields, soil resource management, ground water quality, insect and weed control, agricultural production, and socioeconomics. Results from the first five years of research have demonstrated the capability of these management practices to reduce the transport of nonpoint source pollutants to the oxbow lakes monitored.

Centuries of meandering by the Mississippi River carved out the region of the United States known today as the Mississippi Delta, an area that includes sections of present day states of Mississippi, Louisiana, Arkansas, Missouri, and Tennessee (Figure 1). Untold quantities of sediment eroded from the center of what would later be named the North American Continent and were redeposited during annual spring floods. Sediment loss from the more northern uplands was gain for the Mississippi Delta as rich alluvial soils formed underneath vast areas of cypress swamps and white pine forests. Native Americans established small settlements that developed into the Mound Culture along the many tributaries, streams, and rivers throughout the region. They were the ones who gave the rivers along the Mississippi Basin names such as "Mississippi" or "Great Water" and "Yazoo" that we still use and recognize today. The first European explorers such as DeSoto arrived in the Mississippi Delta region in the 1500s, and it was not long before others followed and began to settle the land. The great cypress and bottomland hardwood forests were cleared, giving way to livestock and row crops. An intricate system of levees and ditches was built during the first part of the 20th Century, diverting excess water from farms and residential areas to natural streams and bayous.

With the discovery that climate and growth conditions were favorable, cotton was introduced as a key economic crop in the Delta. Great demand for cloth fabric by the textile mills of Europe and the Eastern United States fueled the economy of the Mississippi Delta Region for decades, and "King Cotton" flourished. During the 100 years that followed the U.S. Civil War, farm practices gradually changed from labor intensive, largely African American, to highly mechanized operations. Mechanization enabled farmers to work more land area in a given day. Tilling the earth with heavy equipment, however, took its toll, leaving the soil more vulnerable to the erosive forces of nature which sometimes resulted in annual sediment losses of up to 16 tons ha^{-1} (*1, 2*).

As in the Mississippi Delta, other regions of the United States have experienced large quantities of soil loss as sediment runoff. The US Environmental Protection Agency (USEPA) reported in 1986 that nonpoint pollution was the major cause of the Nation's water quality problems, and that agriculture was a major nonpoint source, primarily pinpointing sediment, nutrient, and pesticide losses resulting from soil erosion (*3*). Efforts on a national scale have been made to address issues of nonpoint pollution from agriculture, but often, progress has been impeded by agricultural and environmental policies that moved in opposite directions (*4*).

Management Systems Evaluation Areas – A National Initiative

Establishment of MDMSEA

The need to improve and conserve America's water resources was recognized at the highest level with the Presidential Initiative on Water Quality in 1989. The Presidential Initiative established the objectives of (i) protecting ground water resources from contamination; (ii) developing water quality programs to address contamination; and (iii) providing the basis to alter practices contributing to contamination (*5*). One underlying premise of this initiative was the notion of "volunteerism": that it was the ultimate responsibility of America's farmers to change practices to avoid contaminating water resources. The US Department of Agriculture (USDA) responded to the Presidential Initiative by establishing a Water Quality Program. A national research and assessment effort called the Management Systems Evaluation Areas (MSEA) emerged from the USDA Water Quality Program (*6*). The National MSEA project was to be a multi-agency effort involving the USDA Agricultural Research Service (USDA-ARS) and the USDA Cooperative State Research, Education, and Extension Service (USDA-CSREES) in cooperation with state agricultural experiment stations; the USDA Natural Resources Conservation Service (USDA-NRCS); the USDA Economic Research Service (USDA-ERS), the US Geological Survey (USGS), and the USEPA. For a more comprehensive review of the history and establishment of the National MSEA program, other sources are available (e.g., *7*, Romkens chapter, this volume).

The original objectives of the MSEA Program were to evaluate the effects of agrichemicals on ground water in the Midwest in various "at-risk" geographic areas and to develop protocols of best management practices (BMPs) to safeguard ground water resources, while satisfying the economic, environmental, and social needs of the region. Initial research efforts focused on five states:

Iowa, Minnesota, Missouri, Nebraska, and Ohio (the Midwest Initiative), beginning in 1990 (*8*). After the Midwest Initiative was well underway, additional regions were explored to expand the national MSEA Program. One of the areas considered for expansion of MSEA was the Mississippi Delta Region.

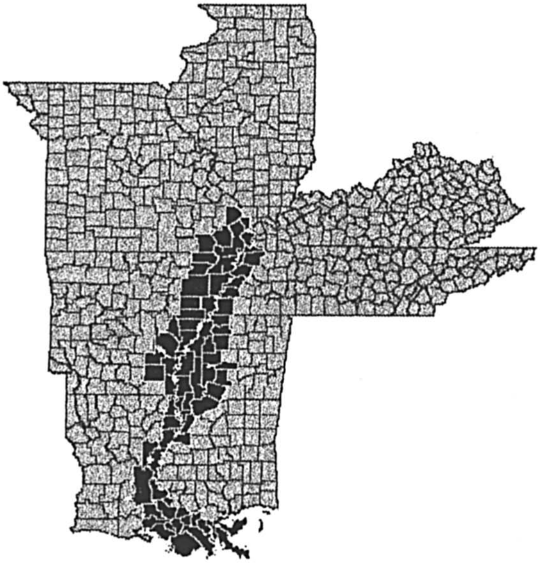

Figure 1. Map of the Mississippi Delta Region.

Several key factors came together in the decision to expand the National MSEA to include the Mississippi Delta Region. The Mississippi Delta is a distinct region that comprises the southern portion of the Mississippi River Alluvial Plain, approximately 11 million hectares (Figure 1). The region extends over 1100 kilometers from southeastern Missouri to the Gulf of Mexico and widens to over 160 kilometers in some places. The Mississippi Delta is an intensively agricultural, rural region. Row crops, rice fields, and catfish farms stretch for miles across the fertile alluvial plain, yielding bountiful agricultural produce. During the last two decades, however, several issues related to agricultural management have raised some environmental concerns.

The humid subtropical climate (average annual rainfall 114 to 152 cm, average temperature 18°C) typically produces periods of heavy rainfall, especially in the spring and fall months. Although the topography averages less than 1% slope, significant quantities of sediment are removed during intense rain events.

Traditional row crop management in the Mississippi Delta involves multiple cultivations during a growing season. Tillage prior to heavy precipitation results in high sediment loss, and findings from earlier research efforts underscored the need to address this issue in the central Delta region. Insect and weed pressures in the humid climate of the south central United States necessitate the use of agrichemicals for effective control. Intense row cropping requires the use of fertilizer, especially nitrogen in non-legume crops such as corn and cotton. Both fertilizers and pesticides are considered as potential contaminants of Mississippi Delta surface and ground water resources (*9*; *10*). Irrigation is a major use of water in the Mississippi Delta, totalling 184,500 ha m per year. The quality and quantity of water used for irrigation is a major factor in assessing the environmental issues in this region.

The Mississippi Delta possessed other distinctions that strengthened its position as a candidate for inclusion within the national MSEA Program. Most of the research in the Midwest Initiative involved cropping systems of corn and soybeans. Corn and soybeans were grown in the Mississippi Delta, but cotton, rice, and catfish were also important components of the agricultural landscape. Agricultural systems that included these latter commodities were not part of the environmental assessments in the Midwest. Additionally, region-specific Delta characteristics, such as being "downriver" on the Mississippi implied that all of the sediment and other pollutants from the Midwest flowed through this region en route to the Gulf of Mexico. Adding the lower portion of the Mississippi alluvial basin to the national MSEA program would complement the Midwest Initiative research in the upper Mississippi basin.

At the same time that national attention was focusing on the need to evaluate nonpoint source pollution in the Mid-South region, the Beaver Creek Watershed Project, a USGS regional effort in water quality assessment in West Tennessee, was nearing completion. In 1993, USGS representatives met with members of several other Delta-based state and federal agencies to evaluate the feasibility of a new environmental project in the Mississippi Delta region to be modeled after the Beaver Creek Watershed Project. It was suggested that USGS coordinate efforts in this regard with other groups, particularly USDA-ARS and Mississippi State University (MSU). Late in 1993, representatives from USGS, USDA-ARS, and MSU determined that the national MSEA was the best vehicle for this regional project, thus the Mississippi Delta MSEA (MDMSEA) was born.

Mississippi Delta MSEA Project: Purpose and Organization

Scope and Purpose

The MDMSEA program was established as a watershed-based project to assess the effects of best management agronomic or conservation practices on water and soil quality within the Mississippi Delta. Specific objectives were to:

1. Increase the knowledge base needed to design and evaluate BMPs that address specific Delta water quality issues
2. Assess how agricultural activities affect surface and ground water quality
3. Quantify and evaluate improvements in soil and water resources resulting from use of combinations of BMPs

Organization

The MDMSEA project is comprised of a consortium of public and private agencies and institutions, with the USDA-ARS, MSU, and USGS taking the lead in funding and scientific staffing for the research efforts. Other state and Federal organizations include the Mississippi Department of Environmental Quality, the USDA-NRCS, the Mississippi Soil and Water Conservation Commission, and the USDA-Farm Service Agency. Participants from the private sector include the Delta Council, the Mississippi Farm Bureau, the Yazoo Mississippi Delta Joint Water Management District (YMD), the Delta Wildlife Foundation, and the Pyrethroid Working Group, a crop protection industry task force.

Early in 1994, the MDMSEA Technical Steering Committee was formed with representatives from USGS, USDA-ARS, and MSU serving as co-chairs. A draft copy of MDMSEA project framework was developed and presented to scientists from the various agencies. Proposals were solicited from the USDA-ARS, USGS, and MSU scientists on potential research projects, and these were used as the basis for finalizing the project framework. A site selection committee was formed to identify and select oxbow lake sites, and the USDA-NRCS was enlisted to advise on lake selection and to serve as a liaison with farmers. An Advisory Committee was established in May, 1994, consisting of farmers and interest groups. Three oxbow lake sites were selected in August, 1994, in Mississippi's LeFlore and Sunflower counties (Figure 2). The following month, a BMP Selection Committee began to evaluate which BMPs to focus on in the project. Core funding was secured for USDA-ARS ($450,000) and USGS ($400,000, half of which was matched funds through the Mississippi

DEQ). Funds and support also came from the Delta Wildlife Foundation, the Department of Interior, the U.S. Fish and Wildlife Service, the Mississippi Department of Wildlife Fisheries and Parks, and a Section 319 (1987 Water Quality Act) grant through the Mississippi Soil Water Conservation Commission Model Farm Program.

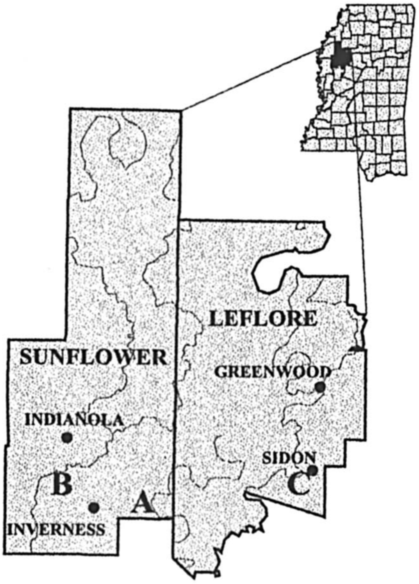

Figure 2. Map showing the locations of MDMSEA watershed sites in Sunflower and LeFlore Counties. The watershed locations are designated as (A) Thighman;(B) Beasley; and (C) Deep Hollow.

Basic Premise for Study

A watershed-based, systems approach was used to assess the effects of best management practices on water and soil quality in three oxbow lake watersheds in the Mississippi Delta. This approach allowed researchers to evaluate a number of factors within the context of a single system and an overall objective. It also allowed the use of a variety of scientific disciplines, each addressing various aspects of the whole, rather than limiting the multi-year program to individual projects without a common endpoint or focus. The experimental approach used real farming systems, which made it easier to translate into practical recommendations for addressing soil and water conservation issues. A primary disadvantage in using a systems approach was that it was difficult to assess the role that individual BMPs played in improving water and soil resources. Within the umbrella of the MDMSEA project, however, there was latitude to evaluate individual BMPs both within and outside of the selected watershed sites.

The MDMSEA Project derived an initial benefit from the planning and organizational experiences of the Midwest Initiative. In the Midwest MSEA, the research watersheds were large and involved many farming operations and management practices. Determining the effects of individual management practices or combinations of practices on water quality was complicated. It was recognized that a simpler, more manageable system was needed.

Meandering rivers and streams in the Mississippi Delta generated numerous oxbow lakes. Many of them represent unique and relatively compact watershed systems. Since oxbow lakes are commonly found adjacent to areas of intense agricultural activity, the decision was made to take advantage of this feature in the landscape. The oxbow lake watersheds are essentially closed systems, with all surface water draining to the lake. Changes in lake water quality therefore became one of the major focal points of MDMSEA evaluations. As well, it was recognized that associated riparian areas were integral components of the oxbow lake systems, and management of these areas was deemed critical to watershed ecology and lake health.

Budget constraints limited the project to three oxbow lake watersheds. In order to maintain the watershed system framework and still address different kinds of practices, the project was designed so that each oxbow lake watershed was cropped and managed using a different set of BMPs, in a hierarchy ranging from no BMPs to a combination of edge-of-field and agronomic measures for conserving and improving soil and water resources (Table 1).

Table I. Installation of BMPs in the MSEA Oxbow Lake Watersheds

BMP	*Thighman*	*Beasley*	*Deep Hollow*
Edge-of-Field			
Grass Filter Strip		X	X
Grass Turn Row		X	X
Slotted Board Riser		X	X
Slotted Inlet Pipe		X	X
Agronomic			
Reduced Tillage			X
Wheat Cover			X
Precision Application			X

Thighman Lake watershed (Figure 3) was designated as the program control, with all management decisions made by the farmers and no improvements implemented by the MDMSEA researchers.

Only edge-of-field practices (Table I) were installed in the Beasley Lake watershed (Figure 4). Edge-of-field measures included structural and vegetative practices. Examples of structural practices included slotted board risers and slotted inlet pipes. Drainage pipes were positioned at low points in the field where surface runoff converges. During periods of high rainfall, wooden boards were placed in slots at the pipe inlet to impede the flow of water through the pipe. Sediment settled out at the pipe entrance as the runoff water slowly drained through the pipe.

One vegetative practice used in the Beasley Lake watershed was the establishment of grass filter strips to serve as a buffer between the field and drainage ditches or the lake itself. Grassed turn rows were another vegetative practice employed at Beasley Lake. Turn rows were areas at the end of a crop row where farm machinery maneuvered into position for a pass down another row. Vegetation in the filter strips and turn rows slowed the rate of runoff and helped trap chemicals and sediment as the water flowed through.

Deep Hollow Lake watershed (Figure 5) received a combination of agronomic and edge-of-field practices (Table I). Agronomic practices at Deep Hollow included cover crops, reduced tillage, and precision application of herbicides. The same edge-of-field practices used in the Beasley Lake watershed were also used at Deep Hollow.

Although each watershed was managed differently, several common parameters were established so that comparisons could be made among the watersheds. Unlike the Midwest region, cotton was a major crop in the Mississippi Delta region. Maintaining cotton as a component of the management system in all watersheds was therefore desirable. Sediment, nutrients, and pesticides were the primary pollutants of concern, and efforts were made to ensure that certain pesticides were used in all three watersheds. One of those pesticides, fluometuron, is a major herbicide applied to the soil in cotton management and was chosen as a key analyte in lake water samples. In areas of the watersheds where cotton or corn was grown, nitrogen fertilizer was applied and evaluated in surface- and ground water samples.

Implementation of MDMSEA Research

Instrumentation for focal sampling points in MDMSEA watersheds was installed during the period from 1994 to 1995, and watershed BMPs were established from 1994 to 1996. A mix of bluegill (*Lepomis macrochirus*),

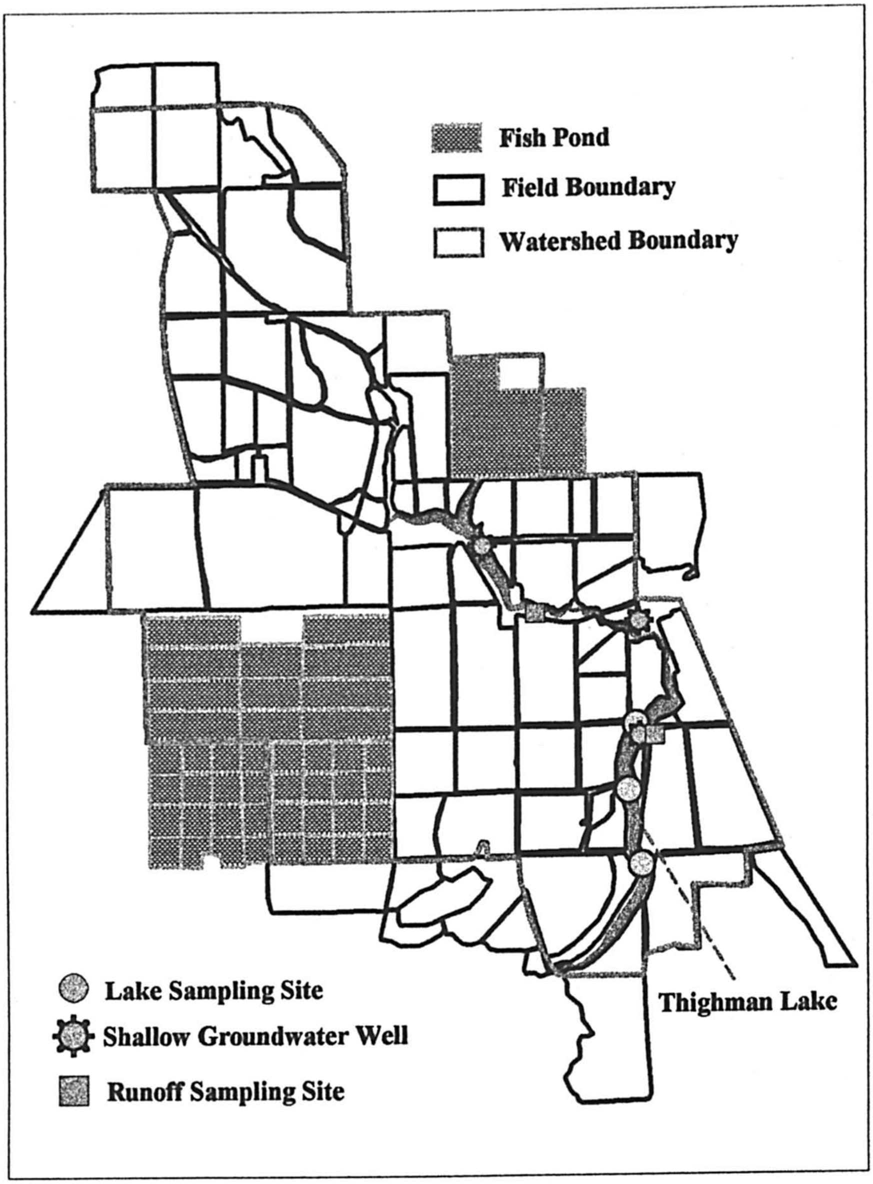

Figure 3. Map of the Thighman Lake watershed.

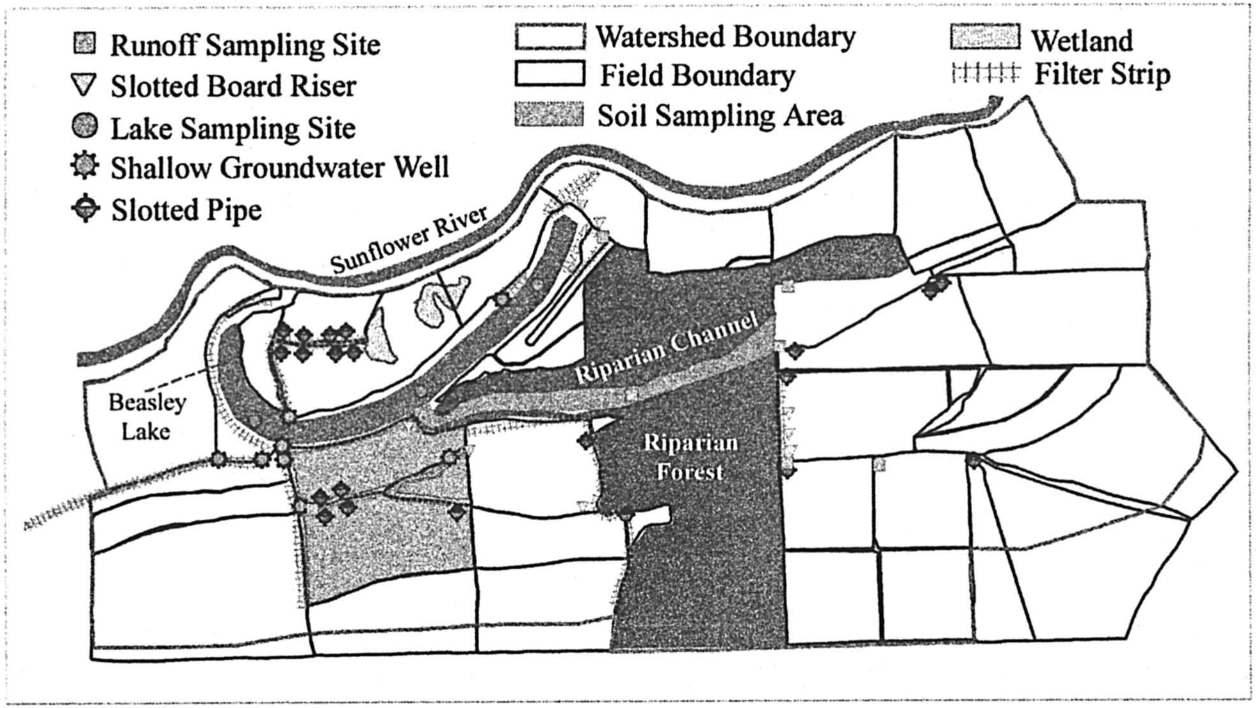

Figure 4. Map of the Beasley Lake watershed.

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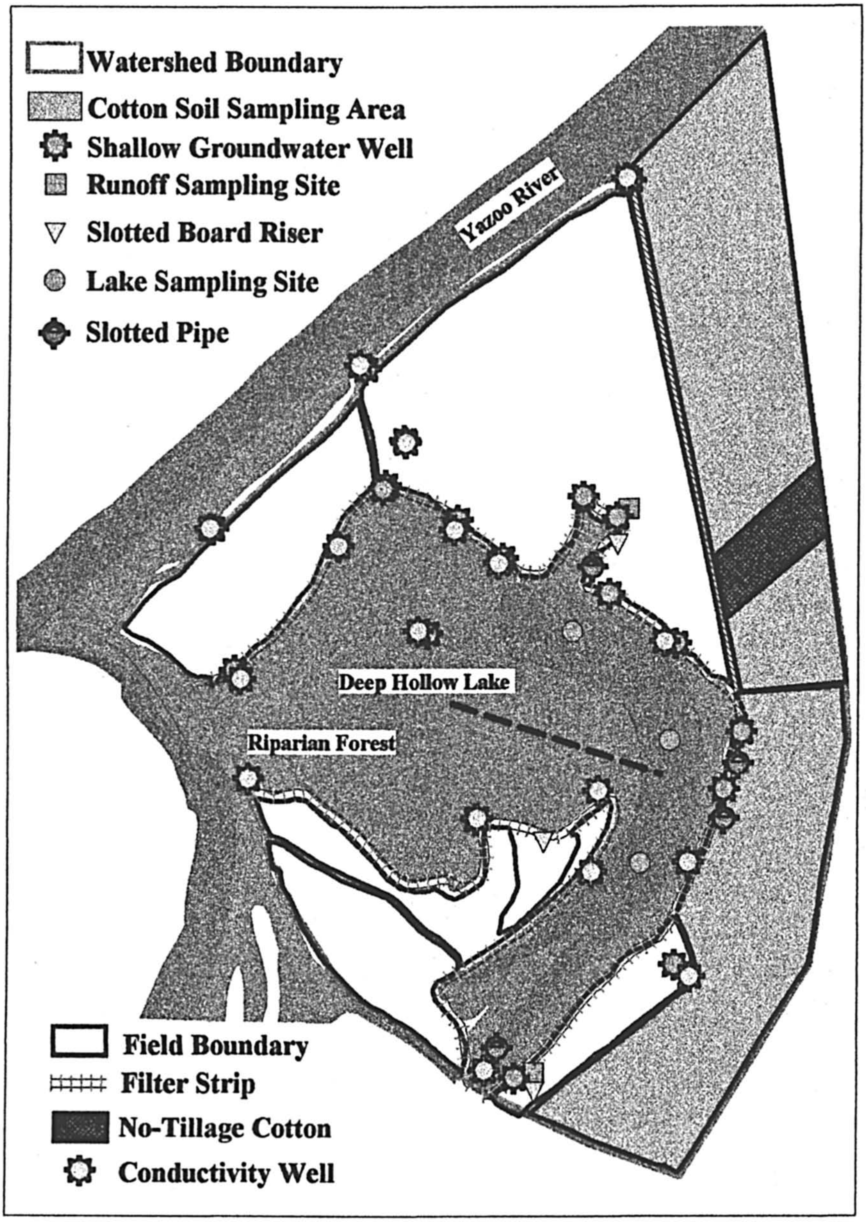

Figure 5. Map of the Deep Hollow Lake watershed.

redear sunfish (*Lepomis microlophus*) and channel catfish (*Ictalurus punctatus*) were introduced in the fall of 1996 followed by largemouth bass (*Micropterus salmoides*) in the spring of 1997. Lake water quality sampling began in the spring of 1995 and has continued through the present.

Thighman Lake watershed (Figure 3), the largest study area, was located in Sunflower County, Mississippi. The lake was 8.9-ha, and total watershed area was 1497 ha. Crops grown in Thighman watershed were soybean, corn, rice, catfish, and cotton. As the control watershed, the approach taken for Thighman Lake was for farmers to manage their land in the way that was most appropriate for them, with no input from the project. However, in some portions of the watershed, farmers voluntarily implemented conservation practices.

Beasley Lake watershed, Sunflower County, Mississippi, was 850 hectares with a 25-ha lake (Figure 4). Cotton, soybean, and corn were major crops in the Beasley watershed. As with Thighman Lake watershed, farmers made the decisions in the way that their crops were managed. Farmer practices in this watershed generally included disking the soil in the fall and preparing seedbeds just prior to planting. Only edge-of-field improvements were made in Beasley watershed. Grass filter strips were established along the edges of the lake at key locations, and grass was planted in some of the turn rows. Slotted board risers also were installed throughout the watershed as needed.

Deep Hollow Lake watershed in Leflore County, Mississippi, was comprised of 202 ha total area and an 8.1-ha lake (Figure 5). Crops grown in the Deep Hollow watershed included cotton and soybean. MDMSEA-introduced management practices for Deep Hollow included both edge-of-field and agronomic measures. A wheat cover crop was planted in the fall and desiccated in the spring prior to planting soybean or cotton. Cotton acreage was managed as reduced tillage, with a fall subsoiling as the only soil tillage operation. Soybeans were managed with no soil tillage. Sensor sprayer technology was used to spot-apply glyphosate for weed control, thereby reducing the amount of herbicides used in the watershed. As with Beasley Lake, grass filter strips, grassed turn rows, and slotted board risers were installed where necessary.

USDA-ARS, USGS, and MSU provided the primary pool of approximately 25 participating scientists and funding for MDMSEA research activities. USGS had the responsibility for instrumentation to evaluate storm events and stream flow rate. Samples were collected to assess quality of surface water runoff and sediment. MSU scientists from Starkville, MS evaluated socio-economic impacts of BMP systems, assessed herbicide dissipation in riparian soils and in vegetative filter strips, and provided support through Mississippi State Extension. National Science Foundation funding was obtained by MSU for a program called Student and Teacher Research Institute – Delta Experience (STRIDE). The goal of STRIDE was to foster interest in middle school students and teachers in environmental issues. USDA-ARS scientists were located at

Oxford and Stoneville, MS, and Baton Rouge, LA. Research activities by USDA-ARS scientists included:

- Shallow ground water quality assessment (pesticides, nutrients)
- Lake water quality assessment (sediment, pesticides, nutrients)
- Assessment of fishery ecology in study lakes
- Evaluation of changes in lake ecology due to BMP implementation
- Assessment of microbial ecology in lakes
- Wetlands assessments
- Pesticide, nutrient, and sediment analyses of runoff water
- Precision application of herbicides
- Characterization of the spatial variability of soil properties
- Evaluation of weed population shifts due to management
- Assessment of agronomic management practices
- Assessment of edge-of-field practices buffer strips, drainage ditches
- Modeling on a watershed scale

Several groups provided support in ways other than research. YMD provided GIS and mapping support. USDA-NRCS provided guidance on BMP establishment, particularly with respect to edge-of-field management practices.

Future Direction of MDMSEA

The MDMSEA project completed its first five years and research results are presented in this book and other publications (*11*). Now that the first phase is completed, the Technical Steering Committee has addressed the questions of future direction. Several issues will determine that direction, and funding is anticipated at least through 2006.

The three oxbow lake watersheds will continue to be at the core of the MDMSEA project. Expansion to other locations will be considered, especially for studies addressing individual BMPs. Changes in research emphasis have occurred since project inception. Because no major problems were found in ground water, it may receive less attention. Surface water quality issues remain as a high priority. Research into and demonstration of individual BMPs were recognized as information gaps, and a matrix of management inputs and outcomes is seen as a potential product of the next phase. Comprehensive economic analyses need to be completed; not only of production management, but also of impacts and benefits to the environment. Section 303(d) of the 1972 Clean Water Act authorizes USEPA or individual states to develop lists of waters impaired by pollutants based on water quality standards. For a water body to be removed from the list, it must not exceed a total maximum daily load of specified pollutant (TMDL). Currently, many surface waters of the Mississippi Delta Region are listed as impaired by pollutants such as sediments, nutrients, and pesticides (*12*). The relatively recent implementation of TMDL policy is a significant concern for farmers and the regulatory community and will continue to serve as a catalyst for future research. A major point for the Technical Steering Committee is to ensure synchronization of national and regional environmental issues with MDMSEA objectives.

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Chapter 2

Watershed Research of the U.S. Department of Agriculture: An Evolution in Mission

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United States Department of Agriculture (USDA) watershed research has been of major interest to the agricultural and rural community of this nation since establishment in the mid 1930's of the Soil Erosion Service, later called Soil Conservation Service (SCS) and in 1994 renamed Natural Resources Conservation Service (NRCS). While early motivation and impetus for this research was driven by a need to evaluate effectiveness of soil conservation practices at the watershed scale, today's focus seems primarily directed to environmental concerns. This chapter describes the evolutionary changes that have taken place over the years from soil conservation concerns in the 1930s, 1940s, and early 1950s; to concerns about hydrologic issues in the 1950s, 1960s, and early 1970s; followed by water quality concerns (primarily surface water) in the 1970s, 1980s, and 1990s; and now about to be driven by ecological issues. This paper gives a brief description of principal locations where USDA-ARS (Agricultural Research Service) is conducting watershed research, the reason for their existence or mission, chronological information and physical details, as well as their main accomplishments. This chapter was written to provide background and better understanding of the many issues of current MSEA (Management System Evaluation Area) research within the watershed context in the Mississippi Delta and elsewhere.

MSEA studies were initiated to address ever-increasing environmental concerns of ground and surface water quality deterioration in important agricultural regions, in part due to farming practices. In identifying the nature and the severity of these problems, different physiographic regions of the country were selected to determine and to assess the conditions that lead to deteriorated environmental situations and to develop management systems that could alleviate existing problems. Within a physiographic region, agricultural watersheds are conventionally viewed as land areas with similar topographic, geomorphic, stratigraphic, and hydrologic conditions and processes that drain to an outlet. Watershed research in these areas is usually concerned with the complex interrelationships between surface and subsurface water bodies, their impact on the water balance and movement of dissolved and suspended contaminants, and their relationships to the physical characteristics of the watershed itself. Because watershed stream systems serve as conduits for watershed discharge, the relationship between the upland cultivated land, pastures, and forested land and the drainage system or water conveyance system is of utmost interest. The main interest of watershed research once focused on the water component and on the load and type of contaminant the water carried. Today, the watershed is more often viewed as a processing area in which erosion is to be controlled, eroded soil and sediment to be retained, and agrichemicals and fertilizer are to be used efficiently by crops and pasture in order to promote a viable and dynamic terrestrial and aqua watershed ecosystem. These different, and to some extent, divergent and often conflicting goals in watershed management must be reconciled. A balance must be struck between the competing interests of agriculture in search of an economically feasible and viable food and fiber production system and the need to minimize impacts of agricultural activities on the quality of the drainage ecosystem, the transition or riparian zones, lakes, and ponds of the watershed. This chapter is written to describe briefly the overall changes in the focus of agricultural watershed research within USDA that have taken place in the last 65 years and to provide a background against which current MSEA research is being conducted. Details about background, mission, objectives and long-term goals, selected accomplishments, and cooperators of research at the various USDA-ARS watershed locations must be sought elsewhere.

Watershed Soil Erosion Research

USDA watershed research started in earnest in 1935 with the establishment of experimental watersheds in Coshocton OH, Riesel TX, and Hastings NE. These watersheds were established to quantify effects of soil and water conservation measures following the calamitous events of the dustbowl. Soil erosion by water had also progressed for many years and had devastated large areas, especially in the southeastern US. Public awareness and the political will to take corrective measures demanded that land use and management practices prevalent since settlement days be changed. The watersheds in Coshocton, OH, and Riesel, TX, are still operational. Figure 1 shows the locations of most larger ARS watersheds that are currently still in operation.

The North Appalachian Experimental watershed at Coshocton (NAEW) was established in 1935 to study and develop methods for soil erosion control and conservation. Site selection involved 419 ha of federally purchased land with conditions representative of those in surrounding States. A unique feature of this watershed was the 1.8 m x 4.2 m x 2.4 m weighing lysimeters with concrete walls and steel bottoms to measure surface runoff and percolating water.

Since the late 1960's, these watersheds have been used in water quality studies to determine the transport mechanisms of persistent pesticides from cropland to surface water bodies and the movement of plant nutrients in subsurface and surface water for different crop rotations, tillage implements, fertilization levels, and pasture grazing schemes. The most significant research accomplishment at this watershed is the pioneering work on the effectiveness of no-till and other conservation practices in reducing runoff and soil loss. Also, the Coshocton wheel, a flow-proportional, flow-powered, slotted vaned wheel for sediment sampling, that is used worldwide, was developed at this location.

The Riesel watersheds are currently managed by the ARS Grassland Soil and Water Research Laboratory in Temple, TX. These watersheds were selected because of the unique hydrologic characteristics of the heavy clay soils with swelling/cracking properties. The slightly rolling land area represents a natural prairie, and significant parts have been in cultivation since settlement days. The purpose of these watersheds was to determine the effects of conservation practices on surface runoff and erosion rates, and to develop hydrologic parameters for these watersheds with swelling/cracking soils. The watersheds were established in 1937 on 336 ha of federally owned land and 2000 ha of adjacent privately owned land. The total land area consisted of 40 individual watersheds ranging in size from 0.10 to 2000 ha. Currently, 18 watersheds on federally owned land are still in operation. These have been upgraded to instrumentation that is all-digital and telemetered to the laboratory on a real time basis. Since 1970, water quality studies have been conducted on these watersheds to determine the movement of plant nutrients, agrichemicals, and other contaminants. The data are being used to develop and validate models (SWAT, EPIC) to predict the effects of alternative agricultural management practices on water quality. One of the most significant contributions of this watershed research is the collection of a near-continuous, long-term database (> 60 years) of surface runoff, sediment yield, and weather data. This database offers opportunities to study the impact of long-term weather cycles on soil and groundwater hydrology for this area and a more precise validation of erosion and runoff models.

The Hastings, NE watershed research program was in operation for about 30 years. The Hastings watershed was located on loess soils with slopes ranging from about 1% to 12 %. The basic research approach was very similar to those of the Coshocton and Riesel watersheds consisting of both government owned land (192 ha) and privately owned land (1168 ha). The land in this watershed was

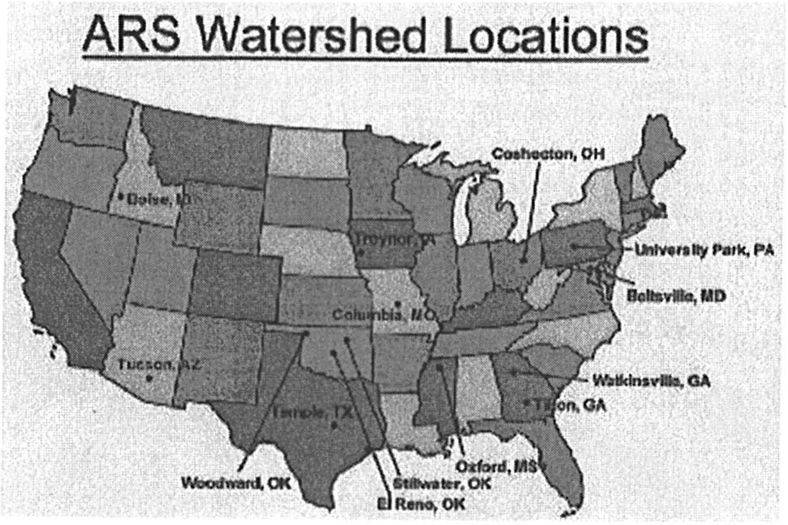

***Figure 1.* USDA-ARS watershed research locations in the continental United States.**

75 % cultivated and planted to corn and wheat, and 25 % was in natural grasses. The last known published data from this watershed dates back to 1967 *(1)*.

The three watersheds were administered by the Research Division of the SCS, which at the time of their establishment was still called the Erosion Service. In 1954, the ARS was established with the responsibility of all Federal agricultural research programs. The SCS watershed research program became part of ARS responsibilities. The watershed program retained its mission to provide research support to the SCS, renamed in 1996 the Natural Resources Conservation Service (NRCS), in guiding its watershed management program. The database collected in these watersheds also served other clientele including Federal and State agencies as well as the private sector.

Hydrology Watershed Research

While in the early stages of the USDA-watershed program the emphasis was soil conservation related, it became apparent due to drought conditions in the 1950's that the quantification of the hydrological component was equally important. Senate Document 59 of 1958 recommended the establishment of six new experimental watersheds. These were:

1. The **Northwest Hydrology Research Watershed** in Boise, ID with research emphasis on the development of fundamental information on erosion and runoff in streamflow from snow melt, rain on snow, and rain on frozen soils. This watershed is representative of the environment of the Pacific Northwest and Great Basin region. The Reynolds Creek Experimental Watershed (RCEW) with subwatersheds, established in 1960, encompasses 234 sq. km, has an elevation range from 1101 to 2241 m, and is the principal outdoor laboratory for this research. Besides a 35-yr hydrologic database for prevalent Northwest conditions and development of specialized sampling equipment and procedures for measuring streamflow and sediment loads under severe winter conditions, this watershed research has developed snow measurement technology that is currently used to forecast water supply in much of the western USA.
2. The research emphasis of the **Southwestern Rangeland Hydrology Research Watershed** in Tucson, AZ, was placed on the evaluation of the effects of upstream conservation programs on downstream water yield. This semi-arid rangeland region is characterized by highly convective storms concentrated on relatively small areas. Rangeland research is conducted in the 150 sq. km semi-arid Walnut Gulch Experimental Watershed, (WGEW). This work started in 1953 but accelerated in 1961 as a result of Senate Document 59. Some of the most significant accomplishments of research in this watershed include: (i) the development of more accurate instrumentation

for measuring primary components of the water cycle in arid and semi-arid regions, such as super critical flumes with traversing slot sediment samplers; (ii) the utilization of collected data sets for the design, development, and validation of hydrologic and soil erosion models; and (iii) the development of a spatially explicit hydro-ecological model (SEHEM) using satellite images to produce daily estimates of regional plant growth, evaporation, and soil water.

3. The mission of the **Southern Great Plains Hydrology Research Watershed** near Chickasaw, OK, was to determine downstream hydrologic impact of NRCS flood water retardation measures. The 610 sq. km Little Washita Experimental Watershed (LWEW) is the largest instrumented ARS watershed. It was started in 1944 under the Congressional Flood Control Act, because thousands of water-retarding structures were built under the 1954 Watershed Protection and Flood Prevention Act. Hydrologic data were collected under Senate Document 59. This watershed is now managed from the Grazinglands Research Laboratory in El Reno, OK. This watershed demonstrated the effectiveness of Best Management Practices (BMPs) in reducing downstream accumulations of agricultural chemicals, plant nutrients, and heavy metals in large watersheds. Data from this watershed played a significant role in testing hydrologic transport and soil erosion models, automated runoff sampling instrumentation (Chickasaw samples), and lately, the effects of climate change on surface water resources, impoundment of water, water quality, and the ecosystem.
4. The research emphasis of the **North Central Hydrology Research Watershed** near Treynor, IA, concerned problems of gully development in cropped fields on the deep loess soils of the North Central Corn Belt. Four watersheds ranging in size from 30 to 60 ha with varying management practices were established in 1961. They are now managed by the ARS National Soil Tilth Laboratory in Ames, IA and are used in water quality studies examining effects of farming management practices of fertilization and agrichemical applications on ground water.
5. The research mission of the **Southeast Hydrology Research Watershed** near Tifton, GA, is focused on the characterization of rainfall-runoff relationships for the Coastal Plain Region in the southeast. Studies began in 1966 with collection of hydrologic data consisting of rainfall (55 locations), stream gages (8 sites), and groundwater observations (3 sites) in the 330 sq. km Little River Watershed in central South Georgia. This long-term (1968-1999) hydrologic database enabled the formulation of water budgets and the partitioning of rainfall into surface and subsurface water for the flatland watersheds of this region. The watershed data collection activities currently emphasize water quality related work including model development and applications.

6. The **Northeast Hydrology Research Center** at Pennsylvania State University, University Park, PA, was established in the mid 1960's to conduct basic research for guiding programs for the control and use of water and stream channel systems in mixed agricultural and urban areas. Facilities include the 7.4 sq. km watershed WE-38 in the Appalachian Valley and Ridge Physiographic Province. The major hydrologic accomplishments of research conducted at this watershed consists of having obtained a better understanding of the interactions between surface and subsurface flow pathways and the groundwater residency time for this physiographic area. The watershed is now used for water quality studies.

In addition to the establishment of these watersheds, a National Center for specialized analysis of hydrologic data was founded in 1961 in Beltsville, MD. It was originally known as the Hydrograph Laboratory but now is the Hydrology Laboratory. Besides the development of technologies for remote sensing of soil water in which the effect of vegetative canopies can be isolated, and the development of a widely used snowmelt-runoff model (SRM), the most significant hydrologic role of this Center is to serve as a depository of precipitation and stream flow data from the agricultural watersheds that ARS maintains. The Center stores data from watersheds ranging from 0.2 ha to 12400 sq. km in size with rain gage networks from 1 to 200 stations, and with periods of record from 1 to 50 years.

Additional watershed facilities were at various times established, usually as part of a Laboratory, to serve a special mission. Those include:

1. The **Woodward Watersheds** were established in 1977, and are part of the Southern Plains Range Research Station. The primary mission of the Woodward watersheds was to develop more resource-efficient grazing systems on rangeland, pastures, and farmed forages for the more than 20 million acres of the southern Plains. The watersheds range in size from 2.7 to 5.7 ha and have an averaged gradient of 7 to 8%. They are equipped with H-flumes and electronic stage recorders. The most significant hydrologic information obtained from these watersheds is the finding that rangelands yield less runoff and soil loss than "graze-out" winter wheat pasture in no-tillage management. The watersheds are currently being used to determine the impact of prescribed burning practices of native and introduced grassland on hydrology and water quality.
2. The **Goodwater Creek Experimental Watershed** near Columbia, MO, was established in 1969 to study hydrology of claypan watersheds that comprise 3.4 million acres in North Central Missouri. The 71.7 sq. km watershed consists of three nested watersheds ranging in size from 12.8 to 71.7 sq. km characterized by gently rolling hills with broad ridges and long slopes of 2 to

5 %. About 85 % of the land area was in crop production in 1990. In 1990, this watershed became part of the Missouri Management System Evaluation Area (MSEA) to study water quality and transport of chemicals for these watershed conditions. Because of funding shortfalls, it had only limited success as a hydrologic resource station.

3. The **Goodwin Creek Experimental Watershed (GCEW)** in northern Mississippi was established in 1982 to evaluate the impact on sediment movement of stream channel stabilization measures (mostly grade control structures) in the highly unstable bluffs along the lower Mississippi River. These measures were part of the DEC-project (Demonstration Erosion Control) to stabilize the rapidly degrading streams draining Bluff Line Watersheds along the lower Mississippi River Valley. The 21.3 sq. km watershed was partitioned into 14 nested subwatersheds with gaging stations equipped with supercritical flumes and supplemented with a network of 35 raingages and 2 hydro-meteorological stations. The main hydrologic contribution from this watershed is the nearly continuous record of land use, precipitation, streamflow, and sediment load over the period 1981-1999. Other accomplishments relative to the research mission of controlling sediment movement in this watershed include the development of design criteria and testing of low-drop grade control structures, streambank stabilization by vegetation, habitat improvement, etc. The database is used extensively by scientists from ARS, other Federal agencies, and national and foreign universities. Current use of GCEW includes a wide range of objectives such as development of Total Maximum Daily Loads (TMDL) guidelines for incised streams in support of the Federal Water Pollution Control Act section, 303.

Besides these larger watersheds, a large number of smaller agricultural watersheds ranging from USLE (Universal Soil Loss Equation) plot size of 0.004 ha to several ha have been in use at several other ARS locations, including Watkinsville, GA, Oxford, MS, Pullman, WA, and El Reno, OK, etc.

Water Quality Related Watershed Research

Water quality research in many of these watersheds began in the early seventies when environmental issues became a major concern to the public. The Clean Water Act was the impetus for research on the fate of agri-chemicals applied to agricultural fields, an issue usually referred to as non-point source water pollution. Early stages of the research concentrated on monitoring that focused on groundwater contamination by leached nutrients. Additional research involved transport of nutrients and agrichemicals in runoff from plots and fields. Modeling these processes at the field scale (CREAMS, GLEAMS, AGNPS) became part of water quality research.

In response to environmental concerns, especially those that impacted large water bodies such as the Gulf of Mexico, the Water Quality Initiative (WQI) research program was formulated with the following goals:

1. Ground and surface water resources should be protected from contamination by fertilizers and pesticides without adversely affecting the economic vitality of U.S. agriculture.
2. Water quality programs should be instituted that address the immediate need to halt contamination, and BMPs should be developed that meet the future need for environmentally sound farming production systems.
3. Farmers should have the ultimate responsibility for changing production practices in a way that avoids the contamination of ground and surface waters.

Management System Evaluation Areas (MSEA) became the research venue for this work *(2)*. A total of eight MSEAs were established across the Nation - each with a specific focus and thrust reflecting local problems and concerns. The Midwest was selected for the pilot research since this region was one of the most intensively farmed areas in the U.S and because high levels of nitrates had been observed in groundwater and drainage water. In addition, many of the watersheds that were established for soil erosion control and hydrologic investigations, were enlisted in water quality research as well.

The first phase of the MSEA projects consisted of a five-year effort funded by ARS and the Cooperative State Research, Extension and Education Service (CSREES). This phase exclusively focused on groundwater problems in the Midwest. These MSEA's were:

1. **Iowa MSEA.** The focus of the research in this State is the evaluation of the effect of agricultural management systems on ground water contamination in three major regions: (i) The western region with deep loess soil over rolling glacial till and a topography with narrow, gently sloping ridges, steep side slopes, and well-defined alluvial valleys. The soils are well drained but the steep slopes are prone to excessive erosion and runoff if cultivated. (ii) The Des Moines Lobe with extensively cultivated soils from the Clarion-Nicollet-Webster association that have a level to gently rolling topography. Depending on soil type and position in the landscape, drainage ranges from well-drained to poorly drained, which in some cases requires tile drainage. (iii) The Nashua region with soils derived from glacial till that are moderately to poorly drained with a level to gently rolling topography. Shallow wells in

all three regions show presence of nitrates and pesticides. Soil water hydrology of the three regions is characteristic of 35% of the State. Corn and corn-soybean rotation are the primary cropping systems. High rates of fertilizer application are common for these production systems with substantial amounts leached into groundwater, drained by tiles or seeped via subsurface lateral flow into surface water.

2. **Minnesota Northern Corn Belt Sand Plain MSEA.** The focus of the MSEA in this Region (Minnesota, North and South Dakota, Wisconsin) is the evaluation of the impact of a ridge-tillage corn-soybean rotation on groundwater quality in representative sand plains of the four geographic regions. Also studied are the nitrogen management, groundwater flow in the aquifers with respect to transport and storage of agri-chemicals, and the relationship between groundwater recharge and agri-chemical loadings of the aquifer. The research sites are: (i) Anoka Sand Plain (Minnesota). This sand plain area has one of the largest aquifers of surficial water (4400 sq. km) and is extremely sensitive to land surface practices. The sand plain has a flat topography and low runoff. The soils have high saturated hydraulic conductivity, shallow depth to the water table, high rates of recharge and ground water seepage, high seepage to surface water bodies, and low organic matter content and sorption characteristics. Soil profiles developed on the undulating uplands and narrow escarpments (Zimmermann association) are excessively drained, but those in the depressions (Isanti and Lino associations) are poorly drained. Significant levels of nitrate-nitrogen (> 8 ppm) occur in the surface and groundwater of these soils. (ii) Wisconsin River Sand Plains (Wisconsin). The soils in these areas are intensively farmed, deep, permeable sands where significant amounts of agri-chemical levels have been detected in the groundwater. (iii) Oakes Site (North Dakota). This site represents an aquifer starting at a depth of 3m consisting of medium sand to gravel. Runoff is less than 2 cm annually. About 50% of the rainwater of 46 cm circulates through the aquifer. (iv) Big Sioux Aquifer (South Dakota). This site, representative of an area of about 3000 sq. km, consists of a shallow aquifer of approximately 3 m thickness with the water table within 4.5 m from the surface. About 15% of the annual precipitation of the 53 cm is runoff and about 19 % circulates through the aquifer.
3. **Missouri MSEA.** The purpose of the Missouri MSEA is to design and evaluate alternative, environmentally sound farming systems for problem prairie claypan soils of the Midwest, especially those in the north central part of Missouri. Claypan soils cover an area of about 4 million ha in Missouri, Illinois, and Kansas, and are hydrologically similar to soils in Oklahoma, Indiana, and Ohio. The topography of the watershed is nearly level but has a well-developed drainage network. The soils (Armstrong-

Leonard- Mexico- Putnam- Adco- Chauncey associations) vary from moderately well drained to poorly drained silt loams with a clay layer beginning at a depth of 15 to 30 cm. This layer restricts air and water movement, and retards root development. The low permeability of these soils leads to significant ponding resulting in lateral flow over the claypan with seepage occurring at the side slopes. During periods of drought, the claypan develops desiccation cracks, which can lead to high infiltration and percolation to deeper strata during periods of subsequent rain. The soils were derived from Wisconsin loess and vary in depth from 0m at the creek bottom to about 3 m at the ridge top. The research site is located in the Goodwater Creek watershed. Nitrate-nitrogen and agri-chemical contaminations of surface and groundwater are of major concern with concentration levels of nitrate having been observed to exceed maximum allowable levels.

4. **Nebraska MSEA.** The goal of this MSEA project is to develop and evaluate profitable cropping practices for irrigated conditions in Nebraska Central Valley that will reduce groundwater contamination. The current farming system is primarily corn with an occasional rotation into soybeans. Runoff is practically non-existent since excess rain and irrigation water is collected at the ends of fields by dikes and in the irrigation furrows. The public water supply companies extract groundwater from the principal aquifers in this region. Nitrate-N levels in 1974 averaged 18 ppm in some places. Some shallow monitoring wells reported nitrate-N concentrations as high as 100 ppm. Based on nitrogen isotope studies, the nitrogen sources were agronomic in origin. A more than 2000 sq km contiguous groundwater area exceeded the EPA's nitrate-nitrogen level in 1994. Also, detectable amounts of agrichemicals have been measured in groundwater. Agri-chemical leaching is highly influenced by irrigation management and soil type.
5. **Ohio MSEA-I.** The principal objective of this MSEA project is to develop improved and profitable agricultural production systems that reduce groundwater pollution of buried valley aquifers. These aquifers are typically shallow, permeable, and unconfined, have high recharge rates, exist along most rivers and streams in the midwestern U.S., and are a major source for drinking water. They are very vulnerable to contamination from leaching surface water. The water source for about one-third of the population in Ohio is drawn from these aquifers. The highly productive soils overlying the aquifers are very permeable with saturated conductivities of 15 m/day. There is high susceptibility to groundwater pollution with increased use of fertilizers and agri-chemicals. The research site is located in the Scioto River Basin in south central Ohio, approximately 3 km south of Piketon.

In the second five-year phase, additional MSEA projects were established in:

1. **Ohio MSEA-II.** This MSEA project was funded in 1996. Besides evaluating the impacts of agricultural management systems on productivity, profitability and groundwater quality, the project also included water table management and development of decision aids and expert systems. Furthermore, it included work involving riparian ecosystems, agricultural water management systems, and integration of wetlands into agricultural production systems.
2. **North Carolina MSEA.** This MSEA was also funded in the second phase of the MSEA projects. The available report indicated the finding of the removal of nitrate from runoff in a 2.8 ha wetland into which 384 ha cultivated watershed drained.
3. **Mississippi Delta MSEA.** In contrast to other MSEA projects, the Mississippi Delta MSEA (MDMSEA) goal is to develop economically feasible BMPs that are effective in reducing suspended sediments and agri-chemicals that would otherwise pollute oxbow lakes in the Mississippi Delta. This MSEA was funded by ARS, United States Geological Survey (USGS), and the State of Mississippi and is focused on surface runoff and its contaminants and to a more limited extent on the agrichemical contamination shallow groundwater aquifer. The Mississippi Delta is a physiographic region with a nearly level topography, highly fertile soils of medium to heavy texture, and high water tables. A large part of the Delta area has the potential to flood during the winter season. Subsurface drainage is non-existent. During the summer season, many of the watersheds drain into oxbow lakes and thus form closed drainage systems. Fields are intensively cropped in row crop cultivation with cotton, soybeans, rice, and in recent years with corn. The high, and usually very intensive, rainstorm regimes with annual amounts of more than 135 cm per year and the high usage of agri-chemicals, especially in cotton production for pest and weed control, create favorable conditions for serious contamination of the surface water system. The MDMSEA research area consists of three watersheds in the Mississippi Delta: (i) 1600 ha Thighman lake watershed; (ii) 400 ha Beasley Lake watershed; and (iii) 160 ha Deep Hollow Lake watershed. These watersheds are farmed with no BMPs, edge-of-field improvements only, and both edge-of-field and agronomic BMPs, respectively.

Ecological Watershed Research

Ecological interest in the watershed context started in the 1980's with concerns of the impact of sediment on the aquatic ecosystems of surface waters. Much of the early experiences were obtained in the Mississippi Delta. It further evolved in the 1990's with issues related to stream corridor restoration and the stabilization of the rapidly degrading streams in the DEC (Demonstration Erosion Control) watersheds of the Bluff-line area along the Mississippi River. The measures taken, involved grade control structures and the associated riprap reinforced plunge pools. These artificially-created and flow energy-dissipating scour holes on the downstream side of these structures offered the opportunity for wildlife to establish itself and to flourish. This positive experience became a powerful asset in the design and development of hydraulic engineering structures that were environmentally and ecologically friendly. Besides the grade control structures, the stabilization of channel systems through stream channel banks with vegetative growth and the drainage of fields through ponds with drop pipes further enhanced vegetative growth and a favorable bufferzone for fish and wildlife habitat. Creating these conditions for healthy aquatic and terrestrial ecosystems in the stream channel system and the adjoining bufferzones has been the subject of study in the research program of the National Sedimentation Laboratory. Added support for ecologically-related research is the recent emphasis of the role of wetlands for habitat improvements, which also would serve as a filter for agricultural runoff in eliminating sediment and agrichemicals including fertilizers. All these measures either singularly or in combination can, depending on the local situation, significantly impact the ecosystem of watersheds.

The above measures have been shown to be very effective in improving the ecosystem. Data and experiences so far are mostly qualitative in nature. Quantitative guidelines need to be formulated as to what practices should be used in a given situation, what the designs should be, and what the expected outcome might be. The scientific dimension needs to be examined in greater detail.

Another issue that currently is the focal point of a lot of discussions and that ostensibly has strong ecological overtones, is the issue of TMDLs (Total Maximum Daily Load). To the extent that rain and seepage water draining fields and watersheds impairs or adversely impacts the habitat of streams and lakes, research emphasis will require an integrated solution approach that is practical and economically feasible, and which do not adversely affect the profitability of farming operations. This requires searching for the proper combination of agronomic, structural, and stream system engineering approaches, including the use of proven buffer and riparian zones that enhances the ecosystem.

Summary

Watershed research in USDA has evolved from on-site soil erosion and conservation research to off-site water quality and ecology concerns. This trend will probably continue for the foreseeable future albeit at a modified pace. The need to develop scientifically-based standards for reasonable and rational TMDLs will be a major issue of today's watershed research. The MSEA projects offer the opportunity to develop practices and production systems that address these issues. It should be apparent that a proper balance must be sought between on-site and off-site concerns and that an integrated solution approach in the watershed context is the venue by which this objective may be accomplished. Important in this matter is that the economic viability of the farming community must be part of this debate.

Acknowledgment

Much of the information concerning individual watersheds was obtained from unpublished information submitted by watershed location personnel to the USDA-ARS National Program Staff. These contributions are gratefully acknowledged.

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Chapter 3

Surface Water Quality in the Delta of Mississippi

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Land use, hydrologic modifications, changes in riparian areas, point, and nonpoint source pollution have influenced water quality in the slow moving, warm-water, streams of the Mississippi Delta. Understanding the extent and character of nonpoint inputs is fundamental to finding solutions. The United States Department of Agriculture Natural Resource Conservation Service conducted monthly surface water quality sampling on the major interior Delta streams from 1993 through 1997 at 22 sites for varying lengths of time. Sediments, nitrogen forms, and total phosphorus were major inputs into all streams. Seasonality of these inputs, relationships between nutrients and sediments, and the potential effectiveness of management practices were key foci. This paper examines implications for water quality improvement and conservation implementation.

A friend of mine, a child of the Delta, tells the story of a first grade art lesson. The teacher told the class to draw a picture of a stream. My friend took crayons in hand and rendered his first grade version of the stream near his home. The water was brown. His teacher scoffed at his effort and holding it up for the class to see said, "everyone knows water is blue". He remembers to this day his frustration, because in all his seven years, he had never seen blue water.

The flatlands of the Mississippi Delta, with slopes of 0.2 meters per kilometer (1 foot per mile), have streams with water that is neither crystal clear nor blue, not

In Water Quality Assessments in the Mississippi Delta; Nett, M., et al.;
ACS Symposium Series; American Chemical Society: Washington, DC, 2004.

cold except in the dead of winter, and often in recent years only flowing in response to a soaking rain. These warm-water, slow-moving streams have not been as extensively studied as other riverine systems. Very little stream restoration work deals with systems where the water does not flow. Biological indices do not fit and patterns of traditional water quality indicators are difficult to explain. The entire concept of what defines a healthy aquatic ecosystem begs to be re-examined.

Seasonality is a major feature of water quality in the Delta. Winter rains fall on bare, tilled ground. The soil moves in rivulets of silty brown mud from the edges of fields to bare dirt ditches picking up more sediment while making its way to the nearest bayou or stream. Winter in the Delta has long been the time of erosion; the loss of the fertile soils makes her waters brown.

Springtime brings warm moist air laden with the heady scents of jasmine, magnolia, honeysuckle, and soil mingling in the mind with images of freshly plowed, planted fields and brown water.

Stained with the tannins of organic matter decay, green with phytoplankton, and with the murky underpinning of colloidal materials that seldom completely settle out, Delta waters are either clear green to black in summer and early fall. The land is covered by vegetation and the rains soak into cropland before moving across fields and into now-grassed ditches, settling much of the sediment load before it reaches a stream.

The Mississippi Delta is not a true delta, but an alluvial floodplain. Geologists propose that the Mississippi River on the west and the Ohio on the east flowed freely flooding this land for perhaps two million years. The rivers cut crescent lakes and bayous and deposited layers of gravel, sands, and fertile soils. Then the Ohio's route changed from south to west leaving the Yazoo River system and the bluff hills as the eastern border of this floodplain. Periodic flooding from the Mississippi and the Yazoo rivers continued to be the main force shaping the Delta landscape until the 1800's. Settlers constructed the first levees in 1803 along the high banks of the Mississippi River *(1)*.

Non-riverine streams flowing through the Delta also deposited heavy loads of soil during the high waters of winter and spring. Larger streams built the high natural levees by flooding and depositing coarser materials along their banks, allowing the fines to settle out more slowly as water spread over the land. The famed Mississippi "Deer Creek soils" or "ice cream lands" are excellent examples of these well drained, coarser soils. No more beautiful cotton ground exists than on the banks of Deer Creek near Hollandale and Onward, Mississippi. Rice fields and catfish ponds are preferentially located on the heavy clay "gumbo" or "buckshot" soils of the land further from the stream edges. Bands of soils seem to run almost parallel to one another following river or stream courses.

The Delta's soil building process no longer follows this pattern. All the major Delta streams and rivers parallel the Mississippi River, confined by 274 miles of man-made Mississippi River main-stem levee on the west and the bluff hills to the east. Internally, man-made channels, cutoffs, straightened sections of streams, and miles of drainage ditches and small levees developed for flood control have changed the natural meandering and seasonal flooding of most Delta streams and rivers. A series of cutoffs, levees, and gates channel them into the Mississippi at a single point, near Vicksburg, MS. Virtually all the waters of the Delta enter the Mississippi commingled. Increased use of the Mississippi River Alluvial Aquifer has also decreased stream baseflows particularly in the Sunflower River and the Bogue Phalia.

Hundreds of millions of dollars, decades of back-breaking labor, countless tons of soil and rock moved, and still the fight continues to preserve an agricultural area that has sparked the imagination of Americans looking for that perfect bit of land. The "best use" of land is historically determined by the needs of the people at the time the decision is made. Land clearing for cities and towns, dam building, forest harvest, agriculture land forming, river manipulation, are all examples of land use that reflect the needs of modern times.

A river isolated from its floodplain can not function as it did in its unrestrained condition. The seasonal cycles of brown water may not be eliminated, but sediment loading can be greatly reduced. Conservation practices can be implemented to keep productive soils in place thus reducing erosion and the subsequent over fertilization of Delta waters. Wetland restoration, stream rehabilitation, and riparian zone enhancements can be done with the cooperation of landowners and funding institutions. These measures would ensure restoration of habitat for wildlife as well as fisheries, improvement in overall water quality, and yet maintain a good quality of life and healthy economy for the people of the Delta.

Current Water Quality

USDA NRCS began a Mississippi Delta-wide study in 1992 (Delta Study), at the request of the Yazoo Mississippi Delta Joint Water Management District (YMD), to find alternative water supplies for irrigation and environmental quality maintenance during low flow periods. Existing Delta surface water quality needed to be monitored in order to determine how best to address supply and quality concerns. NRCS staff conducted monthly surface water quality sampling on the major interior Delta streams starting in 1993 with Deer Creek and expanding by 1994 to the Sunflower River, Bogue Phalia, Coldwater River, and Quiver River. Data were gathered through 1997 at 22 sites for varying lengths of time (Figure1) *(2)*.

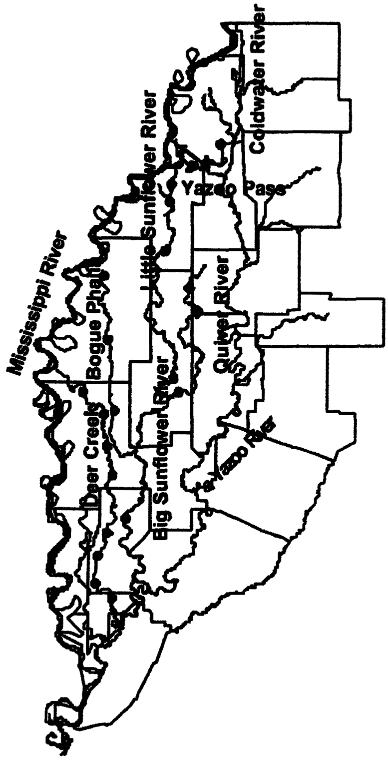

Figure 1. NRCS water quality sampling sites from major Delta streams.

About 1,215,000 of the Mississippi Delta's 1,620,000 hectares are in agricultural production. Agriculture is essential to the economic viability of this area. The opportunities for sediment and nutrient control are plentiful. The NRCS study concluded that the technology is available to address the Delta's environmental concerns. The current challenge is to find the funding and, using watershed planning, implement these practices in sufficient numbers in strategically located areas to achieve the area's water resource goals.

Water Quality Data Discussion

The Delta Study documented sediment and nutrient enrichment of surface waters from nonpoint source runoff (Table I).

Table I: Sunflower River Seasonal Data for Nutrients and Turbidity

Parameter	*Season*	*Avg.*	*Max*	*Min*	*Geo Mean*	*Count*	*Percentile*		
		ppm (mg/L)					25th	50th	75th
Total N	Winter	1.64	3.67	0.36	1.47	30	1.24	1.56	1.93
	Spring	2.23	5.23	0.67	2.02	30	1.39	2.09	2.75
	Summer	1.19	4.14	0.40	1.03	36	0.71	0.96	1.36
	Fall	1.23	2.22	0.36	1.11	36	0.85	1.31	1.60
	Low Flow	1.02	2.22	0.01	0.92	38	0.66	0.96	1.38
		ppm (mg/L)							
Total P	Winter	0.53	1.61	0.08	0.46	30	0.35	0.51	0.61
	Spring	0.71	2.39	0.06	0.53	30	0.29	0.62	0.91
	Summer	0.45	1.75	0.14	0.36	36	0.20	0.37	0.61
	Fall	0.32	1.00	0.01	0.25	36	0.17	0.28	0.42
	Low Flow	0.30	0.69	0.25	0.25	38	0.19	0.25	0.40
		NTU*							
Turbidity	Winter	342	2120	11	203	30	159	219	311
	Spring	535	2318	35	322	30	134	307	740
	Summer	204	2248	25	109	36	60	101	138
	Fall	110	468	5	73	36	47	93	148
	Low Flow	88	275	8	68	38	51	84	105

*NTU nephelometric units

Monthly concentrations of total nitrogen, nitrate plus nitrites, and total phosphorus follow similar patterns at all sample locations and did, at some time during the year, exceed Mississippi Department of Environmental Quality (MDEQ) target levels for waters designated as fish and wildlife streams. Turbidity, total solids, and total phosphorus in the Delta reached maximum levels during winter and early spring runoff. Concentrations of total phosphorus in 131 of 343 samples or 38 percent of the samples *(3)* exceeded the 0.3 ppm target standard suggested by MDEQ for waters designated as fish and wildlife streams *(4)*.

Sampling and testing methodologies have been detailed in the proceedings of the 26th Mississippi Water Resources Conference (Reference 3). This discussion will be limited to data analysis. Data were grouped across all sites by month and averaged. Table I organizes data for the Sunflower River into seasons. Geometric means of total nitrogen data do not fall to below 1 ppm except during the low flow season. Total phosphorus falls to a geometric mean of 0.25 ppm during fall and the low flow season. This illustrates that even when sediments have settled, the water remains very fertile. Levels of nitrogen and phosphorus this high are usually associated with eutrophic or hypereutrophic streams *(5)*. It is probable that stopping the constant influx of new sediments and nutrients into the river will allow its nutrient load to decrease as plants cycle the nitrogen and phosphorus.

Linear regression analyses were run using monthly averages for the dependent variables total phosphorus, total kjeldahl nitrogen, and the independent variables total solids, total suspended solids, and turbidity. The relationship between turbidity and total suspended sediments was also determined (Table II).

Data collected for the Sunflower River at the town of Sunflower were used to estimate parameter loads because long-term stage data were available to calculate flow volumes per month. Water quality and flow data were grouped by month for load calculations. Loads for a range of "acceptable" parameter concentrations, based on available published data for water quality standards, were calculated using the same equations. Linear regression analysis of data averaged by month, as concentrations (1-7) or loads (8-9), for all sites are listed in Table II. Regressions showed a strong correlation between all three indicators of sediment concentration and concentrations of phosphorus and nitrogen in these waters.

Total phosphorus coefficients of determination (r^2) were approximately 0.8. This indicates that all measures of water borne sediment were good predictors of total phosphorus concentration. Interestingly, the r^2 values for total kjeldahl nitrogen were approximately 0.9, suggesting an even better predictive ability. This is probably because soil organic matter makes up part of the total solid load and most nitrogen in the soil is in an organic form. Erosive losses from fields are potentially having a negative impact on soil productivity through the loss of soil, organic matter, and associated nutrients.

Turbidity was strongly correlated to total suspended sediment load, $r^2 = 0.99$. Turbidity is an easy to perform field measurement which, due to its correlation to nutrient and sediment concentrations, could serve as a monitoring tool.

Table II. Regression Analysis for Monthly Average Parameter Concentrations (1-7) and Parameter Loads (8-9)

	Parameters	*Equations*	r^2
1	Total Phosphorus to Total Solids	TP = (0.0014 * TS) - 0.0225	0.78
2	Total Phosphorus to Total Suspended Sediment	TP = (0.001 * TS) + 0.2026	0.80
3	Total Phosphorus to Turbidity	TP = (0.0007 * TS) + 0.2669	0.83
4	Total Kjeldahl Nitrogen to Total Solids	TKN = (0.0048 * TP) - 0.1214	0.89
5	Total Kjeldahl Nitrogen to Total Suspended Sediment	TKN = (0.0036 * TP) + 0.6825	0.90
6	Total Kjeldahl Nitrogen to Turbidity	TKN = (0.0025 * TP) + 0.9298	0.87
7	Turbidity to Total Suspended Sediment	Turbidity = (1.4266 * TSS) - 93.869	0.99
8	T Phosphorus to TSS Sunflower River @ Sunflower	TP = (0.001 * TSS) + 14.5922	0.94
9	T Kjeldahl Nitrogen to TSS Sunflower River @ Sunflower	TKN = (0.003 * TSS) + 31.5782	0.98

Examination of the monthly changes in total phosphorus, total solids, turbidity, total kjeldahl nitrogen, and total suspended solids reaffirmed the seasonal variations in water quality in the Mississippi Delta (Tables I & III). Higher concentrations of all five parameters occurred when the soil was bare and were lowest when there was good canopy cover. There is a clear change in concentration of all parameters between June and July corresponding to the appearance of crop canopy cover, decreased monthly rainfall, and the development of the low flow season. The highest influx of sediments and nutrients occurred during winter and spring, periods of highest monthly rainfall and the largest extent of bare ground (Table III).

Table III. Monthly Average Concentration Values for Selected Water Quality Parameters.

Month	*Total Phosphorus*	*Total Solids*	*Turbidity*	*Total Kjeldahl Nitrogen*	*Total Suspended Sediment*
	ppm	ppm	NTU	ppm	ppm
January	0.56	444	450	1.86	378
February	0.36	353	285	1.85	284
March	0.63	514	542	2.49	453
April	0.76	500	549	2.25	442
May	0.48	329	241	1.40	233
June	0.43	306	235	1.29	211
July	0.36	253	97	1.14	116
August	0.31	277	66	0.94	122
September	0.24	267	60	1.04	114
October	0.34	267	67	1.43	117
November	0.38	286	121	1.27	152
December	0.45	266	135	1.24	163
Avg. Jan.-June	0.53	408	384	1.86	333
Avg. July-Dec.	0.35	269	91	1.18	131

During a "typical" year in the Delta, crops are harvested by mid-September to early November. Weather permitting, this is also a time when soils are prepared for spring planting using several conventional operations from deep tillage to disking. Landforming can be done whenever weather permits, but late fall is often optimal for groundwork. These operations leave soil bare for the winter rains. Data in Table III indicate that by February there may be sufficient winter cover from natural weed growth to provide some protection from erosion. However, field preparation begins in earnest in March with corn planting and rice ground preparation again exposing bare soil to erosive forces. Crop canopies are well developed by July. They continue to grow through harvest in September and early November with dropped leaves providing some ground cover. Dry ground can decrease runoff events in early November and early December, but concentrations of sediment and nutrient parameters begin to increase in December peaking in January, repeating the cycle. One key to improved water quality appears to be implementation of conservation options that address the problems of winter and spring runoff.

An Analysis of Conservation Practices to Control Soil Erosion and Improve Water Quality

Methods to limit sediment and nutrient loss from fields have varied efficiencies (Table IV). Conservation tillage and grass filter strips are two practices used in the Delta that could be expanded to many more acres. They are both effective year round and have sediment control benefits during the critical winter and springtime periods.

Table IV. Conservation Practice Efficiencies* Used for the Following Analysis.

Practice	*Sediment*	*Nitrogen*	*Phosphorus*
		% Controlled	
Conservation Tillage	75	45	55
Grass Filter Strip	85	75	50

NOTE: *Efficiencies are broad averages covering different soil types, plantings, and BMP characteristics. They are based on research and used by NRCS as best professional judgements, not as absolutes for all situations in which the practices might be used.

Applying the conservation practice efficiencies from Table IV to current Sunflower River total phosphorus, total kjeldahl nitrogen, and total suspended sediment loads determined the concentration of these parameters which would remain with either or both of these conservation practices in place. Total phosphorus could be reduced by either practice to a load equivalent to a concentration less than 0.3 ppm, a potential water quality standard, in all months except January, March, and April. Delta soils are high in native phosphorus. This indicates that even without added fertilizers, sediment inputs into streams will be likely to maintain total phosphorus concentrations at higher levels than in some other parts of the country.

Neither conservation practice could, at any time during the year, lower total kjeldahl nitrogen load to a level less than a concentration of 1 ppm, also a possible water quality standard. However, the alternative standard of 2 ppm was met by either practice all year. These numbers emphasize the need to set water quality standards locally to accurately reflect local limitations. Setting an obtainable standard is essential to the success of a program such as the TMDL process.

Determining Costs

The implications of these results for surface water quality are straightforward. Reduce the sediment in the water and the nutrient load will be reduced. Implementation of both practices over the entire Sunflower River watershed, 345,218 hectares (852,390 acres), would control all of these parameters at the indicated levels for an estimated cost of 21 to 33 million dollars (Table V). Costs for the practices are those currently used by NRCS in the Mississippi Delta and reflect current market values.

Table V. Conservation Practice Costs for the Sunflower River Watershed.

Practice	*Hectares*	*Cost per ha $*	*Total Cost*
Conservation Tillage	345,218	42 - 79	$15 to $27 million
Grass Filter Strip	345,218	17	$6 million
Total	345,218	59 - 96	$21 to $33 million

This is a significant investment covering only the Sunflower River Basin. It would be difficult to install conservation tillage or grassed filter strips on every farmed acre in the Sunflower watershed. Watershed planning to place practices on the most susceptible acres could produce significant benefits for the entire area without treating every farmed acre. There are many other conservation practices that should be considered from winter cover to nutrient management to water control structures with slotted board risers to the use of parabolic subsoilers that cause a minimum of surface disturbance. Some of these, such as conservation tillage and water control structures with slotted board risers, complement each other to produce additive benefits. The following is an example of load and cost calculations for one such combination of practices.

The Sunflower River at the town of Sunflower could transport 84,510 tons of sediment annually and still meet a 100 ppm standard (Table VI). The estimated annual sediment transported in 1996 was calculated to be 384,544 tons. Therefore, the Sunflower River contained 300,034 tons (384,544 tons – 84,510 tons) of sediment that would need to be removed for the 100 ppm

Table VI. Monthly Suspended Sediment Load Calculated for the Sunflower River Watershed at the Town of Sunflower.

Month	*1994-1996 Avg. Monthly Flow*	*Monthly Total Suspended Solids*	*Calculated 1996 Sediment Load per Month*	*Sediment Load at a 100 ppm Water Quality Target**
	cubic ft/sec	ppm (mg/L)	tonnes	tonnes
January	1,320	1,050	101,662	9,682
February	1,660	241	29,344	12,176
March	1,800	1,005	132,692	13,203
April	1,300	800	76,283	9,535
May	1,000	310	22,738	7,335
June	820	476	28,630	6,014
July	500	130	4,768	3,668
August	400	98	2,875	2,934
September	110	182	1,468	807
October	90	313	2,066	660
November	350	200	5,134	2,567
December	1,100	200	16,136	8,069
Annual Total Suspended Sediment			423,797	76,651

NOTE: * MS DEQ possible target 100 ppm total suspended solids
tentative Mississippi Department of Environmental Quality standards to be met.

The Sunflower River watershed represents about one third of the total farmed acres in the Delta. Extrapolation, assuming similar landuse across the Delta, results in the determination that about 1.36 million tonnes of sediment would need to be controlled to reach water quality standards for total suspended solids in Delta steams. This extrapolation assumes a similarity of land use and land type that is probably acceptable for this unique area. More detailed calculations can be made as refinements in inputs for various land uses and cultural practices come from the Mississippi Delta Management Systems Evaluation Area (MDMSEA) project.

Field monitoring demonstrated that one of the most effective and cost efficient systems to control sediment in Delta farmland involved a combination of practices. These were permanent pads and levees, water control structures with slotted board risers, a water management plan to pond water in the winter months, and a land management plan, which included minimum tillage *(6)*. This system reduced sediment loss by 5 tonnes/ha/year (2.25 tons/acre/year). The average cost per hectare was approximately $272.00. Treating to remove 1.36 million tonnes of sediment would involve an estimated 272,000-hectare (670,000 acres) (1.36 million tonnes/5 tonnes per hectare), which would require about $73 million. All farmed land would not receive this combination of treatments; however, this calculation does provide an interesting working number for a treatment system to meet target standards used in this example. Determination of sediment standard criteria has not been completed for Mississippi. Selection of a different standard would alter these calculations, as would refinement of inputs from other sediment sources.

The Sunflower River is considered an agrading channel; the Corps of Engineers estimates that the channel has filled in approximately 1 meter since the 1960's. This, along with the fact that there has been no quantification of bank erosion or bedload, led to the assumption that the primary sediment inputs were from nonpoint sources, primarily agricultural lands. This would need to be verified because significant bank caving could occur in the Delta and the additional sediment input would dampen the ability to detect water quality changes due to installation of conservation practices.

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Chapter 4

Agricultural Practices of the Mississippi Delta

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The Mississippi Delta is one of the largest contiguous agricultural areas in the United States with an area over two million hectares. With deep, alluvial soils, 220 to 260 frost-free days per year, average annual soil temperatures greater than 15^0 C at a 51 cm depth, and annual precipitation ranging from about 114 cm in the north to 152 cm in the southern areas of the Delta, this region is agronomically very productive under proper management. In addition, its near level topography is well suited for large-scale mechanized agriculture. Major agricultural enterprises of the Mississippi Delta include soybean, cotton, rice, corn, catfish, small grains, pasture, and vegetables. The following is a general overview of production practices of major crops grown in the Mississippi Delta.

In Water Quality Assessments in the Mississippi Delta; Nett, M., et al.;
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Overview of the Mississippi Delta Ecosystem

The Mississippi Delta has many advantages for commercial crop production. Its topography is well suited for large-scale mechanized agriculture. Typical of large flood plains, the area ranges from nearly flat to undulating, gentle slopes *(1.)* Elevations range from about 15 to 61 m above sea level. There are extensive surface water resources with over 40 thousand hectares of perennial streams and lakes. Oxbow lakes, created from past stream and river meandering, are prevalent throughout the region. These lakes serve as water sources for irrigation and recreation, as well as a natural filtering and flood control system.

Delta soils are largely alluvial and very deep, having developed over many years of deposition from seasonal flooding of the Mississippi River and its tributaries. Delta soils are nutrient rich, but vary widely in texture, structure, depth, and frequency of overflow from rivers and bayous. Coarser, sandier materials tend to be deposited adjacent or in close proximity to rivers and bayous, while finer textured silts and clays are deposited farther away in slack water areas. Many clayey soils contain montmorillonite clay which swells when wet and shrinks when dry. These clayey soils are commonly referred to as "gumbo" or "buckshot". Because these clayey soils have slow permeability, they are difficult to manage when wet and slow to dry in the spring.

Crops requiring good drainage such as cotton (*Gossypium hirstum*), corn (*Zea mays*), and most vegetables are suited for the well-drained soils. These are predominately sandy loam, silt loam, or loamy soils and include Commerce, Dubbs, Dundee, and Robinsville series. They compact easily under equipment traffic, generally respond to subsoiling, and can be planted soon after a rain. Many of these soils are low in organic matter content ranging from 0.5 to 2.0% while 0.9 to 1.2% is most typical. Organic matter is closely related to clay content; as clay content increases, organic matter increases.

Silty clay loams, loamy clays, and clay soils such as Forestdale, Alligator, and Sharkey series typically have high clay content and are mostly found on flats or in depressions. They have poor to very poor internal drainage and require special treatment to improve surface drainage. Many of these soils are well suited to flood culture rice. Forestdale silty clay loams can be utilized for cotton production because they have comparatively better drainage. Fall plowing, subsoiling, and bedding are often necessary for satisfactory production (2).

Yearly rainfall amounts in the Mississippi Delta range from approximately 114 cm year^{-1} in the northern areas of the region to 152 cm year^{-1} in the more southern portions. Although rainfall seems plentiful, much of it occurs during months in which the major crops are not actively growing and production surface areas have their greatest exposure. This leaves the soil surface most vulnerable to erosion during winter and early spring months when crops are not being grown. Data collected at the Delta Research & Extension Center in Stoneville, Mississippi over a 30-year period showed that 72% of the yearly rainfall occurred from September to April, whereas only 28% occurred during May, June, July, and

August *(3)*. Due to the rainfall distribution, irrigation is often necessary to meet crop needs and provide a measure of risk management against crop loss due to drought.

Historic Agronomic Production Practices

For over two centuries, agriculture has been the mainstay of the Mississippi Delta economy. Early agriculture was limited to tobacco production in the Natchez, MS area and indigo in the lower Mississippi Valley Region. Though settlers had crowded into other parts of Mississippi by the early 1800's, the Delta region was avoided due to dense, almost impenetrable cypress swamps *(4)*. By the early 1800s; however, eastern cotton planters whose land was worn out by continuous agriculture production, began to move into the Delta in search of fertile soils. Agriculture quickly developed into a labor-intensive plantation system based on African slave labor. Cotton had become the Delta's major crop and remained so until the Civil War.

Following the Civil War, sharecropping and tenant farming replaced the slave-based plantation system. With the exception of having more workers, labor methods for large farming operations were the same as small ones *(5)*. In the Delta region, the almost annual flooding of the Mississippi River hindered access to its fertile soils. Intensive development of its fertile agricultural lands was not possible until the early nineteenth century, when systems of levees were constructed to control flooding from the Mississippi River.

Throughout the twentieth century, agriculture in much of the Mississippi Delta evolved into large, mechanized, low labor, and capital-intensive farms. The twentieth century also saw an increase in diversification of commodities from cotton to commodities such as catfish (*Ictalurus punctatus*), rice (*Oryza sativa*), corn, and soybean (*Glycine max*).

In 1999, as a percent of total harvested hectares in the state, the Delta accounted for 100% of the rice, 80% of the cotton, 77% of soybean, 45% of the corn, and 92% of hectares of water surface in catfish production (Table I) *(6)*. Though more hectares of soybeans are harvested in the Mississippi Delta, cotton represents the major dollar value to the region, followed by catfish, soybean, rice, and corn.

Agricultural Production Systems

Cotton

In 1999, Mississippi ranked fourth in the nation in cotton production after Texas, California, and Georgia, with 379,320 million tons produced *(7)*.

Mississippi farmers planted 486,000 hectares of cotton with an average yield of 780.5 kg per ha. Of the five top cotton-producing counties, all were located in the Delta *(8)*.

Table I. Major Agricultural Commodities and Their Value-Mississippi Delta - 1999

Crop	*Harvested Area*[a] *(x 1000 ha)*	*Percent of MS Total*	*Value*[b] *(x 1000)*
Cotton	383	80%	$367,315
Catfish[c]	40	92%	$270,575
Soybeans	592	77%	$188,527
Rice	131	100%	$95,813
Corn	56	45%	$40,946
Total			$963,175

[a] SOURCE: USDA - NASS

[b] SOURCE: Dr. John Lee, Agricultural Economics Department, Mississippi State University

[c] Water surface area used for production.

The decade of the 1960's saw the establishment of full mechanization in cotton production. The transition to advanced levels of production technology has had a marked effect on cotton production in the Mississippi Delta, characterized by improved cultivars, high levels of fertilization, chemical weed control, intensive insect control, supplemental irrigation, mechanical harvesting, and careful management.

Cultivars

Development of new cotton cultivars tends to focus on improving lint yield and fiber quality. Other traits include plant maturity, smooth leaves (hairy leaves can be a source of trash in the cotton lint) and pest resistance. The recent introduction of genetically modified cotton cultivars that are insect resistant because they contain the Bt gene has significantly impacted the cotton industry. Adoption of herbicide-tolerant crops has been rapid since their introduction in 1995. In 2000, 78% of MS cotton hectares were planted with a transgenic cultivar containing either the Bt gene, herbicide tolerance genes or both (stacked genes) *(9)*.

Pests

Insects and weeds are the major pests of cotton in the Mississippi Delta. Cotton has a long growing season (April to October) and crop yield is very sensitive to weed and insect pressure. This, combined with the sub-tropical climate of the Mississippi Delta, creates intense pest pressure on the crop, resulting in a high dependency on agricultural pesticides.

The potential for loss to insect pests is greater in cotton than any other field crop *(10)*. More than a dozen different species of insect pests attack cotton, each of which is capable of causing severe economic yield loss. In 2000, the major economic losses occurred due to bollworms (*Helicoverpa zea*), tobacco budworms (*Heliothis virescens*) and plant bugs (*Lygus lesperus*) (1). Cotton growers may invest more than \$1235 hectare^{-1} in producing cotton, \$173 to \$247 hectare^{-1} of which goes to control insects *(11)*. The boll weevil (*Anthonomus grandis grandis*) eradication program, implemented in the Delta counties in 1999, has allowed producers in the boll weevil free area to receive higher profits per hectare *(12)*.

Integrated pest management (IPM) is practiced on all of Mississippi's cotton hectarage to control insects. Non-insecticide management tools include cultivar selection, crop rotation, destruction of over-wintering sites by tillage and other means, careful monitoring of insect pest populations throughout the growing season and timely and judicious use of insecticides.

Cotton does not compete well against weeds, especially during the early stages of growth. If weeds are allowed to emerge and compete for a minimum of five weeks after cotton emergence, yield may be reduced, even if the cotton crop is weed-free the remainder of the season. In 2000, an estimated 9% of the Mississippi cotton crop was lost due to weed competition, predominantly from morningglory (*Ipomoea sp.*), pigweed (*Amaranthus sp.*), common cocklebur (*Xanthium strumarium*), and johnsongrass (*Sorghum halapense (13)*.

Typically, soil residual herbicides, followed by timely applications of various postemergence herbicides, are used to minimize economic loss from weeds. In conventional-tillage systems, cultivation supplements these systems. Predominant soil herbicides include trifluralin, pendimethalin, fluometuron and pyrithiobac. Postemergence materials include glyphosate in glyphosate-tolerant cotton and pyrithiobac in conventionally-bred cotton.

Seedling diseases are the most prevalent pathogens of cotton. Soil-borne fungi are the primary cause of seedling diseases of cotton; it was estimated that in 1995 in Mississippi, 3% of the crop was lost to seedling disease, equaling \$24.3 million *(14)*. Cool wet soils favor seedling disease development. Because conservation tillage leaves crop residues on the soil surface soil warming in the spring is delayed and the incidence of disease increases. To minimize the incidence of seedling diseases, producers plant on raised seedbeds to promote good drainage and warming of soils in the spring. In addition, avoiding fields with a history of severe seedling diseases, and rotating crops with small grains and corn, can reduce the extent of yield loss due to soil-borne pathogens.

Fertility

Nitrogen fertilization of cotton is complicated; either too much or too little, can be detrimental to lint cotton production. Inadequate N limits yield and quality, whereas excessive N delays maturity, increases attractiveness to insects, increases the incidence of boll rot, and makes harvesting more difficult.

Most new cotton cultivars have a greater daily requirement for potassium (K) than other crops. Uptake of K increases during early boll set with some 70% of total uptake occurring after first bloom *(14)*. Supplemental P is rarely needed for cotton due to the naturally high levels of soil test P.

Cotton grows best in soil with a pH between 5.8 and 7.0. When the soil pH falls below 5.2 on clay soils and 5.5 on loam soils, limestone application is recommended *(14)*. The irrigation water from wells in the Mississippi Delta typically contains 2240 to 2800 kg ha^{-1} limestone equivalent per 76 ha cm^{-1} of water; less limestone is usually needed on irrigated fields used for row crops.

Tillage Practices

The majority of cotton grown in the Mississippi Delta is produced on conventionally-tilled fields, largely due to the cotton crop's vulnerability to both wet and cool soils. Plant residues on the soil surface increase soil moisture levels and slow the soil from warming in the spring. If not managed properly, this can cause a number of problems for the cotton plant. Cotton seed will not readily germinate and develop unless soil temperature at a 5-cm depth is at least 18^0 C. Seedling diseases also become a greater problem when soils are cool and wet.

Interest in conservation-tillage practices has increased over the past several years largely due to economics and the development of better herbicides. Stale seedbed is a modified conservation-tillage system used in the Mississippi Delta, practiced primarily to save time during the planting season. In stale-seedbed systems, field preparation operations are limited to stalk shredding and listing, and are performed as soon after cotton harvest in the fall as possible. The next spring, herbicides are applied prior to planting to control winter weeds, and then cotton is planted with minimal tillage. Because stale-seedbed systems are more dependent on pre-plant herbicides, pesticide input costs can increase, but may be offset by a reduction in certain types of tillage. Specialized equipment and a higher level of management are necessary to insure success.

Irrigation

Irrigation water is an important cotton production management practice just like fertilization and tillage. Cotton has the potential to use more water per day in the production of a harvestable product than any other field crop, with the possible exception of alfalfa (*Medicago sativa*) *(15)*. A successful irrigation program is highly dependant on precisely timed irrigations according to when soil moisture is inadequate and seasonal needs of the crop. This requires close monitoring of the cotton crop and timely application of controlled amounts of water.

Crop rotations

Historically in the Delta, cotton has been grown in a monoculture cropping system where cotton is grown year after year on the same land. The prime reason for this system has been economics, as cotton results in high net returns. In addition, cotton production requires higher capital investment in equipment used exclusively to grow and harvest the crop. Alternate field crops such as soybean, corn, grain sorghum, or wheat have not always generated as much income per hectare as cotton.

There are a number of problems associated with cotton monoculture. It is well documented that crop rotations are successful in reducing the incidences of diseases, nematodes, and weeds in cotton *(16, 17, 18)*. Recently, reniform nematodes (*Rotylenchulus reniformis*) have become a serious cotton pest and rotation to corn or grain sorghum are the primary means of reducing nematode populations.

Soybean Production

Mississippi ranks fifteenth in soybean production in the United States with approximately 527 thousand hectares planted in 2001 *(19)*. Soybean yields in Mississippi from 1997 to 2001, however, averaged 1774 kg ha^{-1} *(20)*, which is low compared to the national average. Reflected in this 5-year average are 1998, 1999, and 2000, which were droughty years that negatively impacted soybean yields, especially on non-irrigated hectares.

Despite hectare declines, soybean remains an economically important crop to Mississippi especially in the Delta Region where more than 70% of the state's soybeans are grown *(21)*. Approximately 1 to 1.2 million tons of soybeans from 770 and 648 thousand hectares were harvested in Mississippi in 1999 and 2000, respectively.

Soybean production in the Mississippi Delta emerged in conjunction with cotton production. Initially, traditional soybean production systems used much of the same equipment and cultural practices used in cotton production. Soybeans were grown using wide (96.5 to 102 cm) row spacing.. Weed control programs often included directed-herbicide treatments. More recently, cultivation use has decreased and soybean row spacing has narrowed as adoption of the glyphosate-tolerant soybeans has increased and use of residual herbicides has decreased.

Traditional soybean production systems in the Mississippi Delta involved planting late-maturing cultivars in May and June *(22)*. Unfortunately, this system has resulted in consistently low yields resulting from traditionally low rainfall during July through September. The Early Soybean Production System (ESPS) was developed to remedy this problem for producers in the mid-southern United States and has improved soybean yields in Mississippi *(23)*. This system focuses on planting early- maturing cultivars in April to avoid seasonal drought and maximize yields. Widespread adoption of this system was evident in Mississippi in 2001 with 74% of all soybean acreage in the state planted on or before May 6 *(24)*.

Cultivar Selection

Cultivar selection remains one of the most critical decisions made by Delta soybean producers. Mississippi Delta soybean producers have widely adopted glyphosate-tolerant soybeans. Approximately 65% of producers responding to a recent survey (n=74) reported planting glyphosate-tolerant soybean in 1999 *(25)*. In fact, over one-fourth (27%) of respondents planted all of their hectares in glyphosate-tolerant cultivars. More recent estimates suggest that 63% of all soybean planted in Mississippi in 2001 were glyphosate-tolerant cultivars *(19)*.

Pests

After drought stress, weeds are the most limiting factor in Mississippi Delta soybean production. Losses due to weeds in Mississippi soybean fields have been estimated at more than $68 million annually *(26)*. Herbicides alone represent 16 to 48% of the direct costs of soybean production in Mississippi, depending on the production system utilized *(27)*, and will continue to be the primary means of soybean weed control as fuel and labor costs continue to increase and the price of glyphosate continues to decrease.

Grasshoppers (*Melanoplus* spp.), bean leaf beetles (*Cerotoma trifurcata*), and soybean loopers (*Pseudoplusia includens*) are the most common foliage-feeding insects in Mississippi Delta soybean fields. Greater use of the ESPS has resulted in earlier soybean harvests, which coincides with cotton defoliation and rice harvest. Consequently, stinkbugs (*Nezara viridula*) leave cotton, rice, and early-planted soybean fields and infest late-maturing soybean fields causing significant damage

Most soybean seeds planted in the Delta are treated with materials that control soil-borne diseases. Charcoal rot (*Macrophomina phaseolina*) is considered by some to be the most limiting soybean disease in the Mississippi Delta. Research is ongoing to develop resistant cultivars. Foliar fungicide use has increased slightly in the Mississippi Delta since 1995 when only 3% of the hectares in the state were treated *(28)*.

Nematodes of economic significance to soybean are often problems only on lighter textured soils. Consequently, nematodes are not a major problem in the Delta because most soybean production occurs on heavy clay soils.

Tillage

Conventional tillage remains the most commonly used tillage practice for soybean producers in the Mississippi Delta. However, no-till and reduced-tillage practices are becoming more popular. Approximately 61, 42, 38, and 27% of growers polled in a recent survey reported using conventional tillage, no-till, stale-seedbed tillage, and deep tillage, respectively, on their farms *(25)*. Stale seedbed production often involves one or more tillage events in the fall to incorporate residue and remove ruts left by harvest equipment *(29)*. With this system, no tillage occurs in the spring prior to planting, and winter vegetation is controlled chemically, allowing farmers to plant earlier. The popularity of no-till and reduced-tillage systems is likely to increase in Mississippi as the price of non-selective herbicides for spring weed removal decreases.

Crop Rotation

Most soybean in the Mississippi Delta is grown in rotation with rice or in soybean monoculture. In a recent survey, monoculture soybean and soybean grown in rotation with rice were produced by 72% and 50% of respondents, respectively *(25)*. Soybean rotations with crops other than rice were practiced by less than 30% of the respondents. Interest in double cropping soybean with wheat is limited in the Mississippi Delta with only 13% of the soybean hectares planted following another crop. Soybean may be grown in rotation with wheat, but rarely in a double crop production system unless irrigation is available.

Irrigation

Approximately 30% of Mississippi's soybean crop is irrigated *(30)*. Furrow irrigation is the most common system of irrigating soybeans in the Delta and is 50 to 70% efficient. This system involves pumping water into row middles that have slopes ranging from 0.05 to 0.5%. Border irrigation is increasing in popularity and includes aspects of furrow and flood irrigation. Border irrigation is a flush irrigation system that moves water downhill between small levees or dikes in a 12 to 24 hr period, and is best suited to straight-levee rice fields and fields with no side slope.

Sprinkler irrigation including center pivots, traveling guns, and linear-move systems are less popular in the Delta for soybean production. Disadvantages of sprinkler irrigation in Delta soybean fields include deep rutting in wheel tracks on heavy clay soils and an inability to supply sufficient water to the crop during peak water usage periods.

Rice Production

Mississippi is a major producer of rice in the United States, ranking behind Arkansas, Louisiana, Texas, and California *(31)*. Rice hectares in Mississippi over the ten-year period from 1988 to 1997 have fluctuated between 85,050 and 127,000 hectares *(32)*. Yields have more than doubled since the early 1950's and currently average greater than 5,936 kg ha^{-1} *(33)*.

The Delta is ideal for rice production. High average temperatures during the growing season, a plentiful supply of irrigation water, and a smooth land surface with less than one percent slope to facilitate uniform flooding and drainage are available. Most rice fields have soils with an impervious subsoil layer that inhibits percolation of irrigation water from flooded fields.

Rice in Mississippi is grown in a "continuous flood culture" to provide a favorable environment for rice growth, help control weeds, and stabilize soil ammonium N. Rice seed is generally planted into a dry seedbed. If rain does not occur following planting, growers will flush (wet the soil in each field) one or two times to provide the necessary moisture for seed germination and early-season growth. A shallow (15 cm), permanent flood is established approximately 21 to 28 days after plant emergence coinciding with a plant growth stage of 3- to 4-leaves.

Cultivar

Rice cultivar selection involves consideration of such factors as length of growing season, grain type, availability of weed-free seed, disease susceptibility, processing characteristics, yield potential, and market demand (price). Mississippi produces exclusively long grain cultivars.

Pests

Weeds are the most serious pests affecting rice production in Mississippi. The economic impact of weeds in rice includes losses in yield and quality, added cost of herbicides, extra land preparation and cultivation, and increased cost of harvesting. It was estimated in 1999 that economic loss in rice to weeds in Mississippi was $18.7 million *(34)*.

Since rice is grown in an aquatic system, the humid microclimate favors disease development, which can cause substantial losses in yield and quality. The incidence of soil-borne rice diseases in Mississippi is on the rise *(35*, due to the expanded rice acreage in the state, the prolonged re-cropping of rice in certain fields, and the limited availability of suitable new land for long crop rotations.

Fertility

Delta rice soils are generally slightly to moderately acid and medium to high in P and K *(36)*. Rice tolerates acid soils, and in general, most Delta soils require no supplemental lime, P, or K fertilizers. Rice generally receives between 112 and 202 kg ha^{-1} of N per year, depending on cropping history and the rice cultivar being grown.

Tillage

Conventional tillage is the most common method used in rice production. The land is tilled in the fall or early spring depending on the rotation crop planted prior to the rice. If decomposition of crop residues is not complete by planting, microorganisms that decompose crop residue will compete with rice plants for nutrients, particularly N, resulting in N deficiency in the rice plant.

Conservation tillage is a recent innovation in rice. It has the potential to lower production costs and improve timeliness in planting. Types of conservation-tillage practices used in rice include no-till and stale seedbeds. With no-till, rice is planted directly into the previous crop's residue, typically soybean or wheat. In stale-seedbed systems, tillage operations are performed in the fall, and the seedbeds remain idle while winter vegetation becomes established. Non-selective herbicides are used to control winter vegetation prior to planting. The introduction of improved no-till grain drills has greatly enhanced the capability to produce rice with reduced tillage.

Irrigation

All rice in Mississippi, as well as the United States, is irrigated. In the continuous flood system of irrigation used in the Delta, water depth is regulated in rice fields by construction of levees. After a rice field is flooded, a considerable amount of water is required to maintain optimum water depth in the field. During a four-year survey in Mississippi from 1991 to 1994, the overall water use averaged between 181 to 194 cm ha^{-1} $year^{-1}$ *(37)*.

Crop rotations

In the Mississippi Delta, rice is typically rotated with soybean because both crops are adapted to the clay soils of the Delta. When soybean were grown behind 1 or 2 years of rice, the average soybean yield increased 625 kg ha^{-1} compared to continuous soybeans *(38)*. Clearly, rice makes a valuable rotation crop with soybean and the economic returns exceed those for either crop grown in continuous monoculture.

Corn Production

Corn hectares have declined since the 1930's when there were more than 1.2 million hectares grown in Mississippi. This decrease has been even more striking in the Delta, due in part to lack of need for local feed, competition with cotton for best soils, no development of local cash markets, and the need for irrigation to produce profitable corn yields. Most of the limited hectares for corn in the Delta were produced under high levels of management and for silage for cattle feedlots.

In 1999, 138,000 hectares of corn were grown in Mississippi, 45% of that in the Delta. In recent years, more hectares of corn have been grown because producers are looking for good yielding, profitable alternatives to cotton. This is especially true where irrigation is available to help maintain yield potential. In addition, corn is an excellent crop to rotate with cotton.

Pests

Both seedling diseases, favored by cool, wet weather following planting, and leaf, ear, and stalk diseases, favored by warm, wet mid-season weather, are a problem for corn in Mississippi. Problems with aflatoxin, a toxic chemical by-product from the growth of the fungus, *Aspergillus flavus*, are more likely in Mississippi than the Midwest Corn Belt because of hot, dry weather during the late growth stages that are conducive for fungal growth *(39)*.

The economic threat from insects to corn varies from year to year. Fall armyworms (*Spodoptera frugiperda*), seedcorn maggots (*Delia platura*), cutworms (*Agrotis sp.*), corn earworms (*Helicoverpa zea*), and southern corn rootworm (*Diabrotica undecimpunctata*) are insect pests of corn in Mississippi *(40)*.

Weed control is important to prevent yield and harvest losses. In Mississippi, it was estimated that economic loss due to weeds in 1999 equaled $5.5 million *(34)*. Production practices such as crop rotation, early planting, cultivation and judicious herbicide use are used to control weeds.

Fertility

Nitrogen is typically the most limiting nutrient to high corn yields. It is recommended that growers apply 1/3 to 1/2 of the total N recommendation before corn emergence; with the remainder added as a split N application delayed until 5- to 8- true leaves have emerged. In Mississippi this occurs about 25 to 35 days after emergence *(41)*.

Irrigation

Irrigation can significantly increase corn yields. Typically, corn needs 51 to 61 cm of water during the entire growing season and up to 3.8 cm per week during the peak growing period. Timing is critical with water requirements of corn being greatest from tasseling through kernel filling. An ample moisture supply during pollination is critical for complete ear and kernel formation.

Tillage

Corn producers in the Delta use several types of tillage practices. Conventional tillage is the most common, though some type of conservation tillage is used on 36% of the hectares, typically no-till or mulch till *(34)*.

Grain Sorghum Production

The production of grain sorghum in the Mississippi Delta has increased somewhat during the past decade, largely due to the low commodity prices of the traditional Delta crops and the occurrence of drought. Sorghum is more drought tolerant than corn, has a relatively short growing season, and adapts well to rotations with soybean or cotton. In addition, grain sorghum can be grown on a wide variety of soil types. Though highest yields are obtained on deep, well-drained soil, good yields can occur on heavy clay, clay loam soils, poorly drained soils or soils that are subject to moderate drought stress *(42)*.

Small Grain Production

Small grains are grown throughout Mississippi with soft red winter wheat (*Triticum aestivum*) as the primary crop followed by oats (*Avena sativa*). Wheat continues to be grown on a relatively small number of hectares, mediated by market price and the availability of cultivars resistant to wheat leaf rust.

Forage Crops

In the 1950's, pastures were distributed throughout the Delta, predominantly in low, flat areas. Pasture programs and cow-calf operations were gradually replaced in the Delta by row crops during the 1960's. The shift to row crops, mainly soybeans and rice, resulted in greater net returns per hectare. Today, pastures are mostly limited to areas along the Mississippi River levee system that are not well suited for row crop production.

Fruit, Nut and Vegetable Production

Commercial fruit, nut and vegetable production annually contributes $76 million to Mississippi's economy. This number has gradually increased over the past five years mainly due to the growth in hectares of sweet potatoes (*Ipomoea batatas*) (45% of the total MS vegetable production in 2000). Today few fruit, nuts and vegetables are produced in the Mississippi Delta with pecans (*Carya illinoenisis*) and sweet potatoes comprising the bulk of production.

Catfish Production

By the mid to late 1970's, Mississippi had emerged as the leading producer of farm-raised catfish in the United States with nearly 9,315 hectares of ponds *(43)*. By 1985, production had expanded to more than 30,400 hectares. Today, the area of water surface used for catfish production in Mississippi is estimated at nearly 47,800 hectares with 85% of ponds located in the Delta *(20)*. Mississippi catfish production in 2000 was estimated at 173 million kg (44) generating nearly 300 million dollars in sales. Total economic impact in Mississippi due to catfish production is estimated at nearly $2 billion annually *(45)*.

Water is an essential input for catfish production and the need for water conservation relative to catfish production has increased as the industry has expanded. Most ponds are managed to efficiently capture rainfall, which significantly reduces the need for pumped groundwater and reduces the amount of effluent discharged *(46)*. Catfish ponds in the Mississippi Delta are generally constructed in montmorillonitic clay soils that become nearly impervious to water flow when wet. Consequently, water losses due to seepage are minimal *(47)*.

Several herbicides *(48)* and ferulic acid *(49)* have been evaluated for algae control in commercial ponds. Diuron, a photosynthesis-inhibiting herbicide used primarily in field crops, is now registered in the state of Mississippi for use in commercial catfish ponds via an emergency exemption label (Section 18) *(50)*. At very low use rates, diuron is effective against the species of blue-green algae responsible for most off-flavor in Mississippi farm-raised catfish.

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Chapter 5

Evaluation of Best Management Practices in the Mississippi Delta Management Systems Evaluation Area

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Best Management Practices (BMPs) with potential to cost-effectively reduce sediment yield from agricultural fields were evaluated in a combination of field and computer modeling studies. BMPs included: no-till, reduced-till, cover crops, filter strips, grade-control pipes, and impoundments. A cost/benefit analysis was conducted in which initial and future costs were combined into a single current cost using annuity calculations with a 25-year planning horizon. Benefits were determined as the mean sediment yield reduction predicted in a 50-yr simulation using the model AnnAGNPS, Version 2.0. No-till and a permanent impoundment covering <3% of the watershed were the most effective individual sediment-reduction BMPs; each reduced sediment yield by at least 50%. Volunteer winter weeds and edge-of-field grade control pipes were the most cost-effective BMPs to supplement conservation tillage systems.

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Introduction

The Mississippi Delta has a serious soil erosion problem despite relatively flat topography. Murphree and Mutchler (1) reported a five-year average sediment yield of 17.7 t ha^{-1} from one flat Delta watershed. From 2 to 8 cm y^{-1} of fine sediment accumulated in natural lakes along Bear Creek, a Mississippi Delta drainage system where 75% of the land was in cultivation (2). Accumulated sediment has covered the bottom of many lakes and stream sections with fine silt (3). Sediment has been identified as the pollutant most limiting to fishery health in oxbow lakes in the Mississippi Delta Management System Evaluation Area (MDMSEA); when suspended sediment loads exceeded 80 to 100 parts per million, fish growth rates were reduced (4).

Management options for minimizing sediment yield and nonpoint source pollution from agricultural land areas include conservation tillage (5), grass filter strips (6, 7), and impoundments that retard water flow and allow suspended sediment transported in runoff sufficient time to settle out (8). However, it is a challenging task to estimate the impact of a particular BMP on water quality before it is implemented (9, 10). It is even more difficult to predict the integrated effects of several BMPs. Further, relatively little data on BMP effectiveness has been collected within the Mississippi Delta, which is one of the most intensively farmed agricultural areas of the United States. The MDMSEA was initiated to fill this void by developing and assessing alternative innovative farming systems for improved water quality and ecology in the Mississippi Delta.

Because of cost, MDMSEA field research looked at only a finite number of practice combinations. Yuan et al. (11) showed that the Annualized Agricultural Non-Point Source Pollution model (AnnAGNPS 2.0) could predict monthly and annual sediment yields of a 3-year record from a 12-ha gauged subwatershed. Yuan et al. (12) generalized these findings by applying AnnAGNPS to 50 years of simulated climatic data for a large number of BMP combinations. The objectives of this chapter are to describe the BMPs studied in the MDMSEA, synthesize a cost-benefit analysis of these practices based on the studies cited above, and introduce an innovative practice combination that may offer cost-effective edge-of-field sediment control.

Methods and Procedures

AnnAGNPS 2.0 Model Description

AnnAGNPS 2.0 is a continuous simulation, daily time step, pollutant loading model that can be used to study the effects of alternative cropping and tillage systems on runoff and water quality variables (13, 14, 15). AnnAGNPS is part of a suite of models called AGNPS 2001 that includes additional tools to assist in data preparation and simulation of channel processes, including ecological impacts.

Within AnnAGNPS, spatial variability of soils, land use, and topography are accounted for by dividing a watershed into user-specified homogeneous drainage areas. The AGNPS 2001 data preparation tools TOPAGNPS (16) and AGFLOW (17) can automatically delineate cell boundaries, land slope, slope direction, and channel reach descriptions from user supplied physical information. Climate data can be generated using the climate data generator (GEM) program (18) based on data from climate stations located in the region surrounding the watershed. Sheet and rill soil erosion within each field is predicted based on the Revised Universal Soil Loss Equation (RUSLE) (19, 20).

Site and Practice Characteristics

The effects of various BMP combinations were determined at a gauged site located within the Deep Hollow Lake watershed (-90.22 W, 33.41 N) in Leflore County, Mississippi (11, 12). Detailed records of agricultural operations including tillage, planting, harvesting, fertilization, cover crop planting, and pesticide usage plus measurements of runoff and sediment yield have been maintained since 1996. The main crops grown in the Deep Hollow watershed are cotton (*Gossypium hirsutum* L.) and soybean [*Glycine max* (L.) Merr.]. As is typical for cropland in the vicinity of oxbow lakes, there was about 2 m of elevation difference between the edge of the cropped fields and the base lake level. When lake levels were low and runoff was high, this relatively steep slope created the opportunity for concentrated runoff to create a gully in which a headcut could advance toward or into the field.

BMPs evaluated were based on current Mississippi USDA-NRCS practice standards (http://www.ms.nrcs.usda.gov/fotg.htm) and included both in-field agronomic practices and edge-of-field engineering practices. The agronomic BMPs included: reduced-tillage (NRCS Code 329B) cotton; no-tillage (NRCS Code 329A) soybean; and winter wheat (*Triticum aestivum* L.) cover crops (NRCS Code 340) for cotton and soybean. The engineering practices were grade stabilization pipes (NRCS Code 410) to control edge-of-field gully growth; grass filter strips (NRCS Code 393) to trap eroded sediment; and temporary or permanent impoundments to trap sediment (see below). All of these practices are used in the Mississippi Delta, but the relative contribution of each to water quality improvement is uncertain.

At the downslope edge of the gauged subwatershed, an earthen berm called a "pad" was constructed to direct runoff to an outlet where a grade-stabilization pipe passed under the pad. About 1.5 m of the 2 m of elevation difference between the field and lake levels was dropped within and at the outlet of a 13.7-m long, 0.56-m diameter pipe that discharged into a natural channel about 30 m from the lake. This pipe was the basis for simulations of three kinds of pipe structures. The simplest, called a "slotted-inlet" pipe (P), had a weir welded across the bottom half of the pipe's inlet end and had the top half of the upstream 0.5 m of the pipe removed; this allowed the pipe to be set at a lower elevation, facilitating drainage, and improved its resistance to clogging with debris. A more elaborate pipe inlet, termed a "slotted-board riser" (R), was a box inlet into which boards could be stacked in the winter to impound water on the field. The third type of pipe, termed an impoundment (I), was simulated assuming boards were left in the box inlet for the entire year, creating a 0.37-m deep impoundment whenever runoff occurred. Assuming a semicircular catchment with a gradient of 0.008 in all directions upslope of the pipe invert, the area that would be ponded by a water depth of 0.37 m at the outlet is 0.35 ha.

In our simulations, the effect of a P pipe was determined by comparing sediment yield estimates including a bare earthen channel between the field edge and the lake with simulations that ended at the pipe invert. I was estimated by simulating a permanent 0.37-m deep impoundment at the field outlet. R performance was estimated by combining the December through February sediment yields of I with those from P for the rest of the year. Sediment deposition in temporary ponds when peak runoff exceeded pipe conveyance was not considered in this study; therefore, the benefits of the P and R practices are underestimated in our simulations. As discussed later, placing a vegetative barrier upstream of the pipe inlet to increase hydraulic resistance at flows that would not fill the pipe is an enhancement of this principle that will be the subject of future research.

Simulation Scenarios

The baseline production system simulation against which all BMPs were compared was conventional tillage (CT) production of cotton and soybean with no winter weed growth and no pipe grade control. This was the "base case" to which we compared simulation results reflecting individual and combined impacts of BMPs. We modified the management files to reflect reduced tillage (RT) and no-tillage (NT) and ran simulations in which the following other BMPs were combined with each of the three tillage systems: volunteer winter weeds (W), a winter wheat cover crop (C), a grass filter strip (F), and grade stabilization pipes (P, R, and I, see above).

Starting after harvest, and cotton stalk shredding, CT for both crops consisted of deep tillage (subsoiling) in the fall, disking in February and March, row building (hipping) in April, followed by harrowing, re-hipping again, and re-harrowing before planting. Both soybean and cotton also received two post-emergence cultivations to assist in weed control. NT received no soil or residue disturbance except that associated with the planter. RT involved subsoiling and rebuilding rows in the fall each year followed by no-till planting in the spring. Neither NT nor RT received post-emergence cultivations; weed control was accomplished with herbicides. Wheat cover crops were aerially seeded in October or later after harvesting cotton and soybean and were chemically killed the following spring in all tillage systems. This resulted in 4.5 Mg/ha of surface residue. When simulated, weeds were assumed to begin growth immediately after harvest and to produce 0.78 Mg/ha of residue when killed in the spring. Filter strips were simulated in AnnAGNPS as strip crops with a large roughness factor (cover code 3). To account for sediment settling in backwaters, the filter strip length was simulated as 12% of slope length rather than the actual planted width as suggested by Toy and Foster (21).

BMP Cost Estimation

We estimated BMP costs based on Mississippi average 2001 prices and estimated land rent generously at \$480 ha^{-1} y^{-1} (\$200 ac^{-1} y^{-1}). Costs were divided into one-time initial (establishment or construction) costs and ongoing or annual costs. Initial and annual costs of each BMP combination were combined into a single "total net cost" through an annuity-type calculation. A 5% interest rate, a 25-year BMP lifetime, and equation [1] (22) were used:

$$TotalNetCost = InitialCost + \sum_{n=0}^{24} \frac{AnnualCost}{(1+0.05)^n} \qquad (1)$$

We used the term "distributed cost" to refer to the total cost of a practice divided by the subwatershed area (12 ha).

Initial cost of a P grade stabilization pipe (NRCS Code 410) was estimated at \$1300, including the costs of pipe, earthwork for construction of an embankment to store 0.15 m of runoff, and labor. An extra charge of \$200 was added for the box inlet of the R and I practices. Spreading these initial costs over a 12 ha watershed resulted in a distributed initial cost of \$108 to \$125/ha. A distributed annual cost of \$14 ha^{-1} y^{-1} was assigned to the impoundment for removing 0.35 ha from production.

USDA-NRCS estimates cover crop (NRCS Code 340) costs at \$40 ha^{-1} y^{-1} for cereals and \$96 ha^{-1} y^{-1} for legumes. In this study, the \$40 ha^{-1} y^{-1} figure was utilized. NRCS estimates filter strip (NRCS Code 393) establishment costs at \$380 ha^{-1} (filter strip area). Assuming that a 10 m filter strip is established along 400 m of downslope field edge, the distributed establishment cost would be \$12/ha. An additional recurring land rent cost, at a rental rate of \$480 ha^{-1} y^{-1}, is estimated to be \$16 ha^{-1} y^{-1}.

Reduced tillage and no-tillage costs are difficult to estimate. Parvin and Cooke (23) compared cotton budgets from commercial Mississippi no-till cotton fields with standard budgets. They concluded that costs were lower and profits, at current crop prices, were higher with NT than with CT management. Some farmers, however, experience yield reductions in early years of NT management that may be related to learning how to best manage their planting equipment, weed control, and fertility (24). Thus, producers could experience either a gain or a loss of income from adoption of conservation-tillage BMPs. In some areas, NRCS offers a one-time incentive payment of up to $72/ha to assist producers in adopting NT. In this study, RT was estimated with annual costs of ±$37 ha^{-1} y^{-1} and NT with annual costs of ±$75 ha^{-1} y^{-1}.

Results and Discussion

Fifty-year annual average sediment yields simulated for the alternative BMPs combined with the three tillage systems are shown in Figure 1. Percentage sediment reduction relative to the CT baseline (without winter weeds) was calculated to show what combinations of BMPs could achieve a desired level of control. The simulation in Figure 1 that is closest to the validation case of Yuan

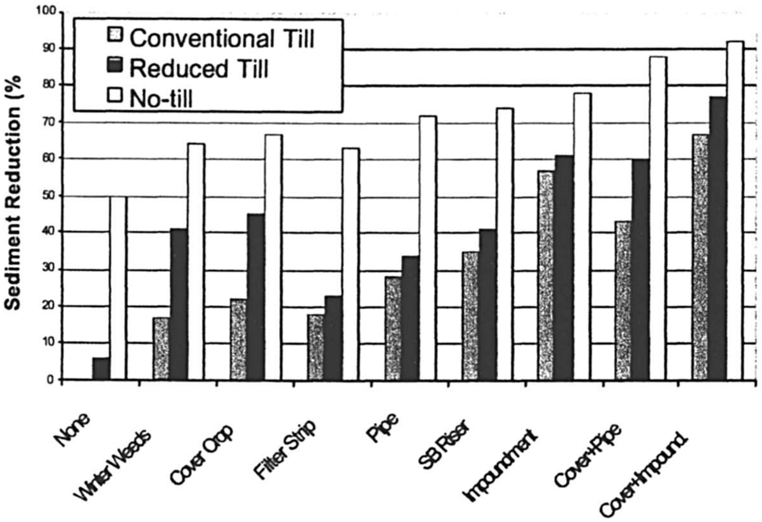


Figure 1. AnnAGNPS-predicted sediment reductions (%) from a Mississippi Delta watershed achieved by BMPs for three tillage systems (Yuan et al., 2002).

et al. (11) is RT with a cover crop and a pipe, which resulted in a 60% reduction in sediment yield compared to no BMPs or winter weeds. The true validation case simulation conducted by Yuan et al. (11) had NT rather than RT soybean and predicted a 3-year average sediment yield of 3.8 t ha^{-1} y^{-1} compared to a 3-year average measured sediment yield of 3.6 t ha^{-1} y^{-1}. This successful application of the uncalibrated AnnAGNPS model to Mississippi Delta conditions lends a degree of credibility to all comparisons presented in Figure 1.

The impact of some BMPs varied with tillage system. For example, cover crops or winter weeds reduced soil loss the most in RT systems. Cover crops reduced sediment yield by 22% in CT, compared to 39% in RT and 17% in NT. Without a cover crop, there was little difference between RT and CT because fall tillage buried fragile crop residue in both systems and the additional spring and summer tillage with CT had relatively little effect on residue cover. In contrast, cover crop growth in NT had less effect because crop residues provided a degree of surface cover.

In these simulations, soil conservation benefits of cover crops may be exaggerated because no winter weed growth was simulated in the baseline scenario. In Mississippi, volunteer winter weeds frequently act as a winter cover crop and can approximately double the amount of soil surface cover in the spring compared to that remaining from crop residues in no-till cotton production systems (25, 26). In the Mississippi Delta, common winter annual weeds include chickweed (*Stellaria media* L.), annual bluegrass (*Poa annua* L.), and henbit (*Lamium amplexicaule* L.). Although simulated weed biomass production was less than one fourth that of the winter wheat cover crop, canopy covers were similar, and winter weed reductions in AnnAGNPS-predicted sediment yield were within 5% of those achieved with wheat. However, weeds were not included in the baseline scenario because late fall tillage reduces winter weed growth in RT and CT systems, making benefits variable and difficult to predict.

Impoundments were particularly effective in CT systems (Figure 1). Because little sediment was generated in NT fields, edge-of-field sediment trapping practices, such as F and I, produced relatively small additional benefits when combined with NT. Gully erosion control by P accounted for a greater reduction in sediment yield for NT than a cover crop or filter strip. Pipes reduced sediment yield by 13 to 28% of the control for all tillage systems.

When initial and ongoing annual BMP costs are combined using Equation [1] over a 25-year lifetime with 5% interest, the total cost is determined principally by the ongoing annual costs. For this reason, supplemental BMPs that included a planted cover crop have the largest 25-year total net cost (Figure 2).

To help visualize the relative cost and benefit interactions between tillage systems and other BMPs, the net present cost of a conservation system was plotted against sediment reduction (Figure 3). Regression lines were fitted separately for each tillage system. The slope of the regression lines represents the total cost per annual ton reduction in sediment yield ($ $(t/y)^{-1}$) within each tillage system. For clarity, lines are shown only for the points reflecting increased profits with RT and NT systems; similar equations fitted through points with decreased profits have identical slopes but different intercepts

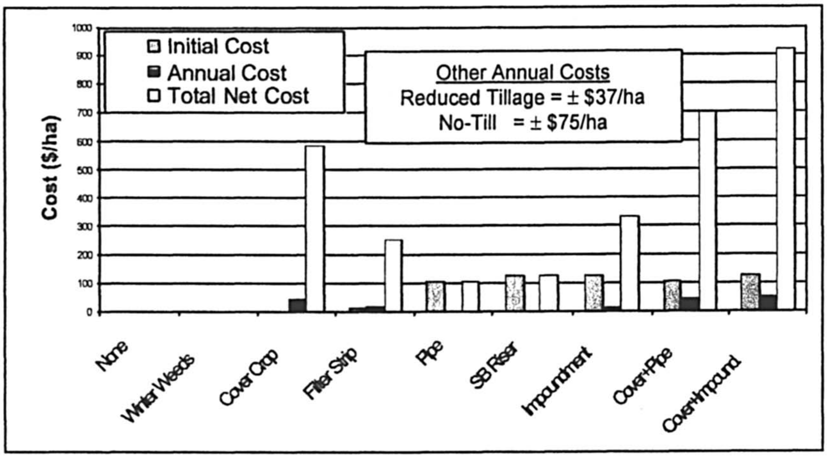


Figure 2. Initial (fixed), annual (direct, ongoing), and total net 25-year cost of implementing selected BMP combinations. Total cost determined using Equation (1) with a 25-year planning horizon and an interest rate of 5%.

determined by the relative profitability of RT and NT relative to CT.

Marginal annual sediment reduction costs were $109 $(t/y)^{-1}$ for CT, $119 $(t/y)^{-1}$ for RT, and $198 $(t/y)^{-1}$ with NT (Figure 3). The greater cost with NT occurs because sediment yield is reduced 50% by NT alone, and further reductions tend to be more difficult and expensive.

Increasing residue cover with W and using P or R pipes to control edge-of-field gullies created the largest positive deviations from the NT trend line (Figure 3). Thus, they are the most cost-effective supplemental BMPs for NT systems in the Mississippi Delta. Adding W to NT reduced sediment yield by 64% compared to the baseline. Combining NT with P achieved 70% sediment yield reduction without W and this improved to 84% with W. Figure 3 demonstrates

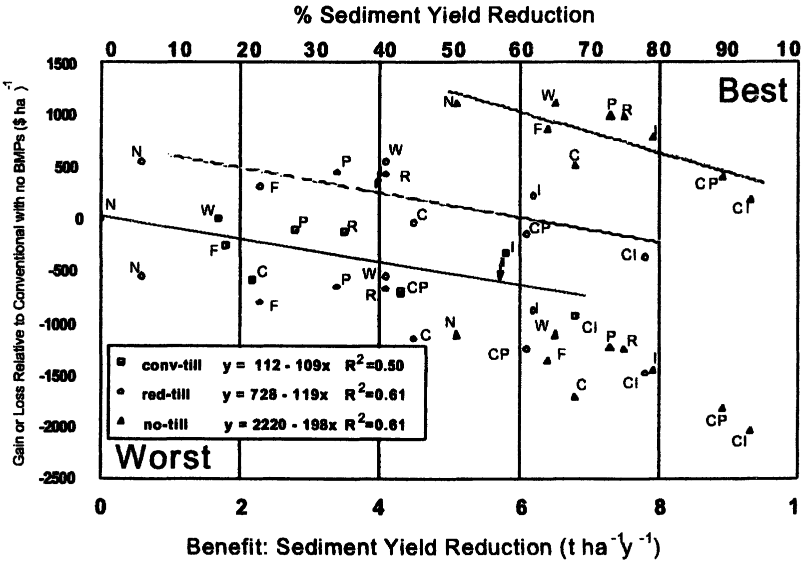


Figure 3. Present value (gain or loss) of BMP adoption (25-year life expectancy) for three tillage systems plotted against annual reduction in sediment yield. Abbreviations: N – none, W – winter weeds, C – wheat cover crop, F – vegetative filter strip, P – slotted inlet pipe, R – slotted board riser pipe, I – 0.37-m deep impoundment. Arrows indicate BMP that creates the most positive deviation from RT and CT trend lines. Reduced-tillage and NT points plotted for both assumed positive and negative economic impacts, but trends are fitted only for the positive points.

that farmers who find NT management more profitable than CT, will achieve a win-win situation of increased soil conservation benefits and increased profits.

The large deviation of the volunteer winter weeds (W, Figure 3) simulation from the RT trend line suggests that winter weed management could provide a particularly cost-effective supplemental BMP for sediment control within RT systems in the Delta. By managing winter weeds so that spring residue cover is increased and volunteer weed seed supply is maintained, farmers can realize the full benefit of this BMP. Late fall surface tillage that disrupts winter annual weed growth and kills vegetation in late winter, before biomass is accumulated or seed is produced, may reduce these soil conservation and water quality benefits.

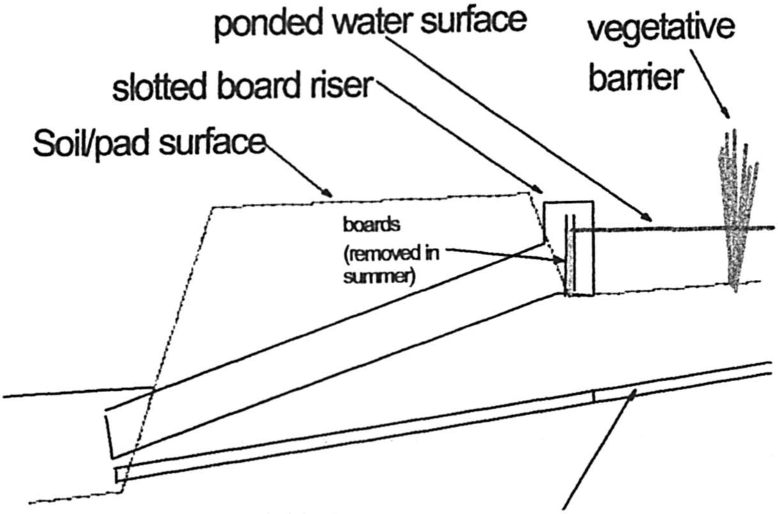
For CT farmers, a permanent impoundment, I, was the most cost-effective way to achieve at least a 50% reduction in sediment yield and produced the largest deviation from the CT trend line (Figure 3). The low cost of I relative to its benefit results from the relatively small amount of land (<3% of the watershed) removed from production with the land slope of 0.8% existing at the study site. Much land in the Mississippi Delta is being precision leveled to land slopes of 0.1 to 0.2%. On leveled land, a 0.37-m deep impoundment would inundate a much larger area and increase the cost of this practice proportionately. A sediment basin (NRCS Code 350) might be an alternative in this situation. Sediment trapped in I would need to be removed periodically to maintain the functionality of this practice; this may increase the total cost of this practice by 20 to 25% (12). Still, for natural Delta landscapes in the vicinity of oxbow lakes, small impoundments or constructed wetlands are one of the most cost-effective BMPs for sediment yield reduction in CT systems.

This analysis did not find 10-m wide filter strips, F, to be a particularly cost-effective BMP for any of the tillage systems (Figure 3). This is because the land removed from production was larger than that for I, but the estimated benefit was smaller (Figure 1). Although F could be installed at lower initial cost than P, their ongoing annual land rent cost and total net present cost were higher (Figure 2). For sediment control, grass strip recurring costs might be decreased by as much as a factor of 10 by employing a 1-m wide Vegetative Barrier (NRCS Code 601) in place of the filter strip. Vegetative barriers, or stiff-grass hedges, function by remaining erect while retarding concentrated runoff (27), allowing sediment to settle out upslope of the grass (28). A potential BMP combination that is being investigated in the MDMSEA is the placement of a vegetative barrier in an 8-m diameter semicircle around the inlet of P and R pipes (29). Figure 4 illustrates a cross section through such an installation that includes a subsurface drainage tile under the water furrow to minimize wet spots. When combined with R, the tile would be plugged when boards were in place, and grass would need to tolerate inundation during the winter. This combination might achieve some of the sediment removal benefits predicted for I, while taking less land out of production and having lower maintenance costs.

Summary

All BMPs studied reduced sediment yield, but there were interactions between tillage systems and other practices so that benefits were not simply additive. The benefits from a cover crop were most pronounced when combined with RT. However, planted cover crops were the most costly BMP evaluated. When able to grow following harvest, weeds provided sediment reduction benefits similar to that of planted cover crops at no cost.

For CT systems, a permanent impoundment was the most cost-effective way to trap sediment. It reduced sediment yield by more than 50%.



4" perforated **drainage tile** set at 0.5 to 2% grade for about 100' long upslope of riser
Use solid pipe under the pad, have plug in end during winter.
Use "socked" (polyester woven cloth) pipe cover to exclude sediment on sandy soil
Cover pipe with at least 30" of soil.

Figure 4. This innovative combination of BMPs is currently being evaluated within MDMSEA with both slotted-inlet and slotted-board riser pipes (29). Placing boards into the riser and a plug in the drain creates an impoundment during the winter. After boards and the plug are removed in the spring, the vegetative barrier traps sediment in a temporary impoundment that forms during storm events. The tile limits development of local wet spots that limit field access and reduce crop growth.

Both P and R pipes had better than average cost-effectiveness for all tillage systems. However, pipes did not achieve a 50% sediment yield reduction from CT or RT systems unless combined with a planted or volunteer cover crop.

Vegetative filter strips, F, were less cost-effective than pipes in reducing sediment yield. Narrower grass strips and strategic placement of vegetative barriers upslope of pipes might be more cost-effective for sediment reduction.

In the Mississippi Delta, the total marginal cost of reducing sediment yield by 1 t ha^{-1} y^{-1} for 25 years with supplemental BMPs was \$109 $(t/y)^{-1}$ for CT, \$119 $(t/y)^{-1}$ for RT, and \$198 $(t/y)^{-1}$ for NT. The higher cost with NT reflects the fact that sediment yield is reduced 50% by NT alone, and further reductions tend to be more difficult and expensive. Using the average marginal cost of \$109/ha for 1 t ha^{-1} y^{-1} sediment reduction with CT, the 50% or 5 t ha^{-1} y^{-1} reduction with NT has a net present value of \$545/ha, equivalent to ongoing annual cost of about \$37 ha^{-1} y^{-1}. If the profitability of NT was lower than that of CT, but within the margin of \$37 ha^{-1} y^{-1} then it would be more cost-effective than the average CT sediment-reduction BMP. On the other hand, if NT was more profitable than CT, its adoption would be a win-win outcome of increased profits and cleaner water.

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Chapter 6

Groundwater Nutrients in the Beasley Lake Watershed of the Mississippi Delta Management Systems Evaluation Area

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Shallow groundwater was monitored in an intensively-farmed area of the Mississippi Delta. Samples were obtained during 1996-2001 from 1.5, 3.0, and 4.5 m deep observation wells in the grassed borders of agricultural fields and from 0.6, 1.5, and 3.0 m wells in an extensive riparian forest between the cropland and an oxbow lake. Samples were analyzed for dissolved organic C (DOC), Cl, NO_3-N, NH_4-N, and PO_4-P. Nitrate-N concentrations in shallow groundwater were very low, usually <1.0 mg L^{-1}, in both the agricultural and riparian areas, and posed no threat to well or surface water quality. When compared to Midwestern MSEA (Management System Evaluation Area) projects or upland agricultural watersheds in northern Mississippi, shallow groundwater in the Delta is relatively high in DOC and PO_4-P and much lower in NO_3-N. Considering warm soil temperatures, abundant rainfall, and a year-round labile carbon supply, high rates of soil denitrification are suspected for the low dissolved NO_3-N concentrations. Since farmers harvest more P in crops than they apply in fertilizer, the relatively high groundwater PO_4-P values may reflect the high native P content of Delta soils.

In Water Quality Assessments in the Mississippi Delta; Nett, M., et al.;
ACS Symposium Series; American Chemical Society: Washington, DC, 2004.

Introduction

Groundwater contamination by fertilizer nutrients has been documented by various federal and state agencies in the United States and Canada (1,2). Nitrogen (N) and phosphorus (P) are the nutrients controlling eutrophication in most fresh water bodies and estuaries (3, 4). Shallow groundwater interacts with and affects surface water quality through tile drainage, return flow, and base flow seepage (5, 6). In Mississippi, groundwater constitutes 54% of all freshwater and is the drinking water supply for ~~of~~ 93% of the population (7). In a national assessment, groundwater under the Mississippi Delta was considered to be at "moderately serious" risk of nitrate contamination (8).

Surface and ground water contamination by nutrients is determined by a complex combination of soil, management, and climatic factors. Nitrate contamination is related to high levels of fertilizer or manure inputs, intensive and continuous cropping, permeable soils and subsoils, subsurface drainage, and a lack of vegetative buffers (6, 9, 10). Although phosphorus generally moves slowly through soils, water quality problems arise when there is a regional imbalance between P inputs and exports (5). Anaerobic and acidic soil conditions generally increase P in soil solution (11, 12). Soils in the Mississippi Delta have high levels of native P (13).

Vegetative buffers and wetlands are best management practices (BMPs) that reduce nitrate concentrations in shallow groundwater through plant uptake, dilution, and denitrification (8). Four conditions are needed for denitrification to take place: a supply of nitrate, a population of appropriate bacteria, a carbon source for energy, and anaerobic conditions (14). Under reduced conditions, the bacteria use the oxygen in NO_3 as an electron acceptor as they feed on the carbon source, converting NO_3 to N_2O and/or N_2. Under well drained soil conditions, dissolved organic carbon (DOC) in the vadose zone is rapidly oxidized to CO_2 so that DOC declines rapidly with depth (14). In most cases where groundwater nitrate concentrations are elevated, denitrification is limited by the supply of labile carbon (14, 15, 16, 17), although exceptions have been reported (18, 19). When soils are saturated, oxidation of labile carbon reduces dissolved oxygen to the point where denitrification can proceed. Denitrification requires approximately 0.35 mg DOC to reduce each mg of dissolved O_2 (20) in addition to from 1.0 to 3.3 mg DOC for each mg of NO_3-N reduced to N_2 (8, 20, 21, 22). Thus, DOC values of 4 mg L^{-1} are not sufficient to cause much denitrification (14, 23, 24, 25), while 10 mg DOC L^{-1} denitrified approximately 6 mg L^{-1} of NO_3-N from an initially aerobic aquifer (25).

The purpose of this research was to quantify the concentration of nutrients found in shallow groundwater within an intensively cropped area of the

Mississippi Delta and an adjacent wetland riparian area and to interpret the results in light of contemporary environmental guidelines.

Materials and Methods

The area of study was the Beasley Lake Watershed (33.4008 N, -90.6729 W), described by Locke (Chapter 1, this volume). The approximately 850 hectare (2100 acre) drainage included a 125-ha wooded riparian area (Figure 1) and 660 ha of cropland, while the oxbow lake had a surface area of 25 hectares. Soil texture varied spatially and with depth, as may be expected adjacent to a meandering river, ranging from sandy loam to silty clay. Cropland management practices, including rates, methods and timing of fertilizer inputs, were recorded based on interviews with the four farmers managing land within the watershed.

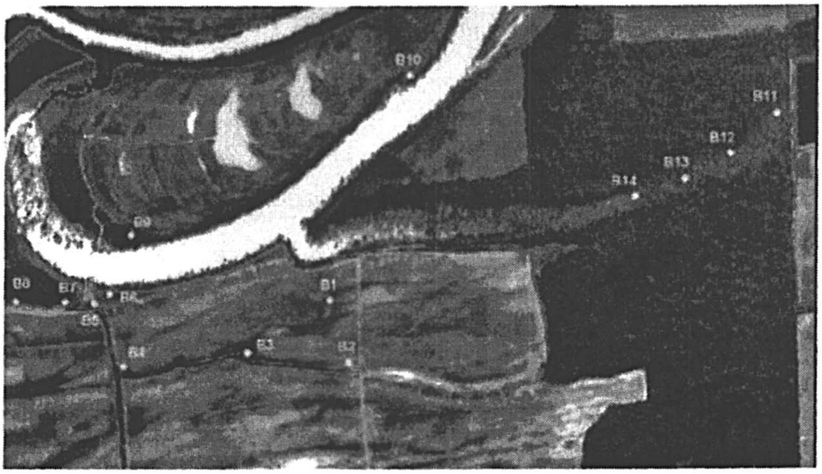

Figure 1. Aerial photograph indicating locations of groundwater sampling wells within Beasley Lake watershed.

In the summer and fall of 1995, ten nests of shallow groundwater sampling wells, designated B1 to B10, were established in cropland margins (Figure 1). Each nest comprised wells at depths of 1.5, 3, and 4.5 m. During July and August 1997, three additional well nests, designated B11 to B13, were established in the wooded riparian area. During February 1998, 0.6 m deep wells were added to the riparian nests as well as at an additional site designated B14. It was not possible to install 4.5 m deep wells at any of the riparian sites, nor at sites B6 and B9, because sandy soil horizons at these locations were saturated at 4.5 m depth and well holes collapsed as quickly as they were drilled.

Wells were installed by drilling 92 mm diameter holes 80 to 150 mm deeper than the nominal well depth. The holes were backfilled with pea gravel to the nominal depth and 51-mm diameter, flat-bottomed schedule 40 PVC wells were placed on top of the gravel. The lower 0.3 m of each well was screened and the hole outside this well screen was backfilled with gravel. The rest of the hole outside the well pipe was packed to the ground surface with 6-mm diameter bentonite pellets so that each well sampled water only from within about 0.4 m of the nominal well depth. Finally, each well pipe was trimmed at a height of about 0.3 m above the soil surface and fitted with a removable cap.

The agricultural shallow groundwater wells were sampled from October 1995 through December 1999 and the riparian wells were sampled from December 1998 through December 2001. Usually within 24 h of a rainfall event, a 500-mL sample was collected from each well (using a battery-operated ISCO AccuWell model 150 portable pump fitted with a teflon-lined intake line, into a 0.5-L amber bottle with teflon-lined screw cap. Each well was pumped dry and the excess well water was discarded. Shallow ground water samples were placed on ice, immediately transported to the National Sedimentation Laboratory, stored at 4°C (<48 h). Nutrient sample preparation and analyses for PO_4-P, NH_4-N, NO_3-N, Cl, and DOC was as previously reported (27). Briefly, samples were filtered through a 0.45 :m cellulose acetate membrane filter and analyzed using a Dionex DX-500 anion chromatograph, a Bran-Lubbe automated flow-through colorimeter, and a Rosemount Analytical Dohrmann DC-190 carbon analyzer with automatic liquid sampler.

Because nutrient concentrations spanned several orders of magnitude, data were log transformed to improve statistical variance homogeneity, a common procedure in analysis of environmental variables (28, 29). Observations with concentrations below the detection limit were coded as zero's and a constant equal to one-half of the detection limit (ie., 0.0005 ppm) was added to all N and P values prior to log transformation (8). Analysis of variance was used to test for significant differences due to well depth and season. Analyses were conducted separately for each land use because of differing well depths and sampling periods.

Results and Discussion

Land Use

During the period from 1995 through 2001, the watershed cropland was planted mainly to cotton (*Gossypium hirsutum* L.) with some soybean (*Glycine max*, Merrill) and corn (*Zea mays* L.), and small amounts of grain sorghum

Table I. Crop Distribution Within Three Regions of Beasley Watershed from 1995 through 2001.

	Cotton	*Soybean*	*Corn*	*Sorghum*	*Rice*	*Idle*
East (328 ha)						
1995	0.66	0.25	0.09			
1996	0.66	0.25	0.09			
1997	0.48	0.47	0.06			
1998	0.14	0.42	0.29		0.14	
1999	0.36	0.36	0.10	0.19		
2000	0.47	0.41	0.10			0.02
2001	0.73	0.05		0.20		0.02
North (88 ha)						
1995	0.66	0.34				
1996	0.66	0.34				
1997	0.66	0.34				
1998			0.94			0.06
1999	0.94					0.06
2000	0.96	0.04				
2001	0.85	0.15				
SWest (246 ha)						
1995	0.99	0.01				
1996	0.99	0.01				
1997	0.99	0.01				
1998	0.85	0.00	0.14			0.01
1999	0.99	0.00				0.01
2000	0.95	0.05				
2001	0.99	0.01				
Overall Average	0.70	0.08	0.18	0.03	0.01	0.01

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(*Sorghum bicolor* L. Moench), and rice (*Oryza sativa* L.) (Table I). Cropland was divided into three regions based on proximity to the water quality sampling wells: (1) Southwest (246 ha surrounding wells B1 to B8), (2) North (88 ha near wells B9 and B10), and (3) East (328 ha east of and draining through the riparian area). The Southwest area surrounding wells B1 to B8 was cropped almost exclusively to cotton, while the area upstream of the riparian area included 6 to 29% corn or sorghum each year. Overall, the Beasley watershed cropland averaged 70% cotton between 1995 and 2001.

The average amounts of fertilizer nitrogen (N) applied to grain crops varied from 119 kg ha^{-1} for rice to 213 kg ha^{-1} for corn while cotton average 135 kg ha^{-1} (Table II). All N was applied between 15 March and 20 June, usually split between preplant and sidedress applications, except for a rice crop that received a third split on 1 July during one study year. There were no Fall N applications, although some potassium was applied at that time. Very little phosphorus was applied to any cropland, reflecting high levels of native fertility. No fertilizer at all was applied to soybean cropland by any farmer, any year. Phosphorus removal in harvested crops is estimated to be from 15 to 30 kg ha^{-1} (30).

Table II. Average Annual Fertilizer Application from 1995 through 2000 for Each Crop Grown Within the Beasley Lake Watershed.

Crop	*Farmer Years (number)*	*N (kg ha^{-1})*	*P (kg ha^{-1})*	*K (kg ha^{-1})*
Corn	9	213	6	47
Cotton	25	135	3	70
Sorghum	1	157	0	0
Rice	1	119	0	0
Soybean	12	0	0	0

Water Quality

The number of samples obtained at each location and depth varied annually (Table III). During a four year sampling period, the largest number of samples (73) was collected from the 4.5 m deep well at location B10, which was located very close to the lake (Figure 1). The other low-lying well nests (B6, B9, and the riparian wells) probably would have yielded even more samples at a 4.5 m depth, but saturated sandy soil horizons at these sites prevented the deep well installation. Ten of the 14 sites had perched water tables such that sample frequencies were greater at shallower rather than deeper depths. Some of the sites (eg. B3 and B4) yielded few samples from any depth.

During the four years of study in the agricultural area, concentrations followed the order DOC>Cl>NO_3-N~NH_4-N>PO_4-P with mean values of 29.7, 11.9, 0.66, 0.65, and 0.18 mg L^{-1} and log-means of 22.5, 8.2, 0.10, 0.08, and 0.06 mg L^{-1}, respectively. Although log-means are always lower than arithmetic means, larger differences between mean and log-mean values reflect a wider range of data. Mean nutrient concentrations in groundwater from the riparian area were 93.51, 12.2, 0.87, 0.18, and 0.06 mg L^{-1}; and log-means were 43.1, 10.9, 0.08, 0.10, and 0.01, respectively (Table IV). Thus, on average, riparian samples were higher in DOC, and lower in NO_3-N, NH_4-N, and PO_4-P. Table IV also includes comparison values from an upland site, also within the Yazoo River Basin (27), that was cropped to soybean and received no fertilizer N. Log-mean shallow upland groundwater NO_3-N averaged about 4 mg L^{-1} under

Table III. Number of Groundwater Samples Obtained from Each Well Nest (December 1995 to December 2001)

	Agricultural										*Riparian*			
	B1	*B2*	*B3*	*B4*	*B5*	*B6*	*B7*	*B8*	*B9*	*B10*	*B11*	*B12*	*B13*	*B14*
All Depth	104	146	7	1	17	47	89	71	14	174	101	72	46	56
0.6	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	51	29	44	56
1.5	11	50	7	1	17	47	36	17	0	49	50	0	0	ns
3.0	24	68	0	0	0	0	51	52	14	52	0	43	2	ns
4.5	69	28	0	0	0	ns	2	2	ns	73	ns	ns	ns	ns
Year														
1995	1	2	0	0	0	0	1	1	0	3	ns	ns	ns	ns
1996	10	19	0	0	0	8	16	10	2	29	ns	ns	ns	ns
1997	11	19	1	0	2	11	21	18	0	29	ns	ns	ns	ns
1998	17	22	2	0	7	9	19	17	1	34	22	11	4	15
1999	65	84	4	1	8	19	32	25	11	79	45	25	25	22
2000	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	16	19	9	10
2001	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	18	17	8	9

NOTE: "ns" indicates that wells were not available or not sampled.

Table IV. Log-mean Shallow Groundwater Nutrient Concentrations in Two Physiographic Regions of the Yazoo Basin, Mississippi.

Region	*DOC*	*NO_3-N*	*NH_4-N*	*PO_4-P*
		mg L^{-1}		
Delta (Beasley watershed, Dec 1995 thru Dec 2001)				
Agriculture	22.50	0.10	0.08	0.06
Riparian	43.10	0.08	0.06	0.01
Upland (Nelson Farm, Oct 1992 thru Sept 1993)				
Conventional-till soybean	3.56	3.76	0.07	0.04
No-till soybean	4.83	4.32	0.06	0.02
Riparian	4.09	0.04	0.03	0.02

cropland, more than ten-fold higher than in the Delta. DOC values averaged about 4 mg L^{1} in both the upland cropland and riparian areas, five to ten-fold lower than in the Delta.

In the agricultural area, NO_3-N and PO_4-P tended to decrease with depth while DOC had an inverse trend, increasing with depth (Table V). In contrast, in the riparian area, PO_4-P was lowest in the shallow 0.6 m wells, while NO_3-N was lowest and DOC highest in the 1.5m well (B11) that provided samples at this depth (Table III). Differences in log-mean concentrations, based on analysis of variance, are indicated in Table V. Seasonal differences were also significant; generally DOC was highest and NO_3-N was lowest during summer for both riparian and agricultural areas. In the riparian area, minimum average DOC and maximum NO_3-N occurred during the fall (see below). For the agricultural area, the season of maximum NO_3-N concentrations was winter while the minimum depth-averaged DOC occurred during the spring, but average DOC always remained above 20 mg L^{1}. This level may reflect both the high frequency of water tables perched within 1.5 m of the soil surface and a climate in which some form of plant growth occurs throughout the year. Plant growth is periodically interrupted by short periods of cold weather, drought, or human intervention, thus releasing carbon, while degradation of this carbon under saturated soil conditions can lead to an accumulation of organic acids (15).

Seasonality and other data variability are illustrated in Figure 2, which presents the values of DOC, NO_3-N, and the NO_3-N to Cl ratio in samples

Table V. NutrientConcentrations of Shallow Groundwater at Beasley Lake Watershed as a Function of Land Use and Well Depth

Well Depth(m)	*Obs.*	*Parameter*	*DOC (mg L^{-1})*	*NO_3-N (mg L^{-1})*	*PO_4-P (mg L^{-1})*
Agricultural					
0.6	0				
1.5	235	Mean	22.2 (76)	1.50 (218)	0.21 (174)
		Median	19.8	0.27	0.10
		Log-mean	19.2 (18)b[H]	0.24 (164)a	0.09 (59)a
3.0	260	Mean	30.1 (77)	0.20 (236)	0.22 (148)
		Median	24.8	0.09	0.14
		Log-mean	22.6 (25)b	0.07 (62)b	0.09 (69)a
4.5	173	Mean	39.1 (74)	0.19 (245)	0.07 (239)
		Median	31.5	0.08	0.03
		Log-mean	27.7 (27)a	0.06 (61)b	0.02 (42)b
Riparian					
0.6	180	Mean	38.2 (66)	0.83 (302)	0.03 (135)
		Median	35.3	0.15	0.01
		Log-mean	32.1 (17)b	0.13 (103)a	0.01 (40)b
1.5	50	Mean	225.6 (63)	1.05 (404)	0.17 (196)
		Median	226.3	0.004	0.06
		Log-mean	160.3 (21)a	0.01 (57)b	0.05 (67)a
3.0	45	Mean	35.0 (36)	0.89(173)	0.05 (78)
		Median	35.2	0.13	0.05
		Log-mean	32.6 (11)b	0.18 (134)a	0.03 (44)a
4.5	0				

NOTE: [H] log-means followed by a different letter within a column and land use are statistically different ($P<0.05$).

obtained from the 1.5 m deep well at site B11. NO_3-N values were very low except for three discrete spikes when concentrations exceeded 1 mg L^{-1}. Two spikes occurred during the falls of 1998 and 1999 and coincided with decreases in DOC, suggesting some flushing of the aquifer with early winter rains or, possibly, metabolism of DOC by denitrifying bacteria. The third spike occurred during spring 2000, without a decrease in DOC. A general trend of declining DOC is also noted throughout record. This gradual change in groundwater quality followed the removal of a beaver dam immediately upgradient from the B11 well location on 22 Aug 1997. The beaver dam created a hyporheic zone (31) that was a rich source of DOC to shallow groundwater. The importance of such biological "hot spots," where saturated soils conditions and an available carbon source combine, has been stressed by others in explaining the denitrification process in riparian zones (22, 32, 33). During the four years after dam removal, DOC gradually declined to levels similar to that observed at the other riparian depths and locations (Tables III and V).

The ratio of NO_3-N to Cl (NCR) has been used as a means of separating the influence of dilution from those of plant uptake and denitrification on NO_3-N concentration reduction (22, 24, 34, 35, 36). At the B11 site, the NO_3-N peaks coincided with NCR values close to 1 (Figure 2), indicating the source of NO_3-N was probably agricultural fertilizers. The fact that the NCR rapidly declined, implies that dilution is not responsible for observed declines in NO_3-N. That the

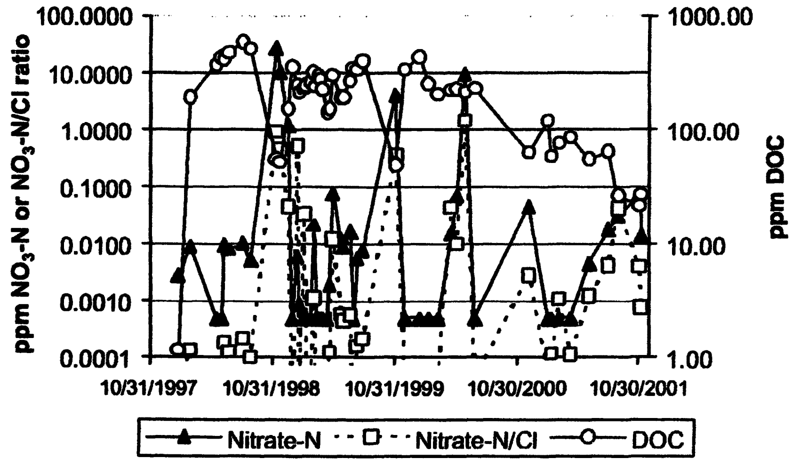

Figure 2. Nitrate-N, NO_3-N to Cl ratio, and DOC concentrations in the 1.5 m deep well at site B11.

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rapid declines often occurred during periods of the year when vegetative growth in the riparian zone was slowing (October to November) suggests that denitrification was thc dominant reason for low NO_3-N concentrations.

Each of the four 0.6-m deep riparian wells yielded frequent samples (Table III). While NO_3-N was similar in all the 0.6-m riparian wells, differences in seasonal NO_3-N least square log-means were significant: 0.62 mg L^{-1} during Fall, 0.29mg L^{-1} during Winter, 0.06 mg L^{-1} during Spring, and 0.12 mg L^{-1} during Summer. In contrast, PO_4-P did not vary seasonally, but a significant trend was observed along the transect of shallow riparian wells. Least squares log-mean PO_4-P in these shallow riparian wells was 0.0042 mg L^{-1} in B11, 0.0047 mg L^{-1} in B12, 0.0097 mg L^{-1} in B13, and 0.016 mg L^{-1} in B14. Even the largest of these values is surprisingly lower than those observed at deeper depths and in the agricultural field borders (Table V). Conditions that are reducing enough to promote denitrification usually increase P solubility where PO_4-P concentrations are below 10 mg L^{-1} (11,12). There are several possible explainations for lower PO_4-P in riparian wells. In addition to plant uptake in the riparian vegetation, frequent wetting and drying may create amorphous iron hydroxides with larger surface area and large P sorptive capacity (37). Another possibility is that soluble P might be complexed with organic and inorganic colloidal material of size greater than 1000 molecular weight but smaller than 0.45 :m, which would not be quantified as PO_4-P by anion chromatography. For example, in one unmodified soil, dissolved reactive P was only 10% of total dissolved P (38). Further research is underway to determine if there is significantly more total P in filtered and unfiltered shallow riparian groundwater samples than indicated by anion chromatography.

Comparison of Results with Water Quality Criteria

In both the agricultural and riparian areas, most NO_3-N concentrations were well below the U.S. drinking water maximum contaminant level (MCL) of 10 mg L^{-1} NO_3-N set by EPA (39). Only 1% of all shallow groundwater samples collected in the Beasley Lake watershed exceeded this MCL (Table VI). In fact, only 8% of samples exceeded the level of 2.0 mg L^{-1} NO_3-N identified by USGS as being a typical background level in groundwater (4); and 84% of the samples were below the level of 0.57 mg L^{-1} total N that was established by EPA (40) as a reference condition for lakes and reservoir in Ecoregion X, which includes the Mississippi Delta. It should be noted that all study agricultural samples were obtained at positions averaging about 5 m within grassed field borders and so may be lower than those in the cropped area. Other research has shown that the majority of denitrification can take place within the first 10 m of a buffer (34, 41) and that grass buffers can support as much denitrification as forested buffers (28, 36, 41).

Our sampling sites were located in areas where subsurface flow was expected and therefore should well reflect the quality of shallow groundwater reaching ditches, streams and lakes in the Mississippi Delta. Thus, despite the intensive cropping and high rates of fertilizer N application in the Beasley Lake watershed (Tables I and II), our data indicate that the local climatic, soil, and management contitions prevented shallow groundwater from contributing N in amounts that would lead to excessive eutrophication of Delta surface waters.

Table VI. Beasley Lake Watershed Shallow Groundwater NO_3-N Concentrations in Ranges Defined by Selected Environmental Criteria (%)

Well Depth (m)	*Below EPA Region X Lakes*[40] *<0.57 mg L^{-1}*	*Below USGS Background Groundwater*[4] *<2.0 mg L^{-1}*	*Above USGS Background Groundwater*[4] *>2.0 mg L^{-1}*	*Above EPA Drinking Water MCL*[39] *>10 mg L^{-1}*
Agricultural				
0.6				
1.5	62	80	20	3
3	96	99	1	0
4.5	97	99	1	0
Riparian				
0.6	84	92	8	3
1.5	90	92	8	4
3	64	84	16	0
4.5				
Overall	84	92	8	1

The low NO_3-N concentrations in the Mississippi Delta MSEA project are in sharp contrast with those of MSEA projects in Midwestern states. For example, in the Iowa MSEA, 33% of tile drainage waters exceeded 10 mg L^{-1} NO_3-N (42); shallow groundwater wells (<4.6 m) had a similar fraction of MCL exceedences (43). In Missouri, 25% of samples exceeded 10 mg L^{-1} NO_3-N, and 100% exceeded 1 mg L^{-1} NO_3-N (44). Fertilizer N application rates were not higher in the Midwest than in the Mississippi Delta; but important natural differences in topography, soil permeability, and climate resulted in completely different results. The extensive use of tile drainage in Midwestern states is another major difference between the Midwest and the Missippi Delta. By lowering the water table, tile drainage reduces the likelihood of denitrification and has increased

NO_3-N discharges from farmland in some areas (9,10). However, six years of research on Mississippi alluvium in Louisiana (Commerce clay loam soil) found that tile drainage actually lowered total N losses from corn production, and that drain-tile discharge contained 1.8 kg N ha^{-1}, and total N in tile discharge averaged about 1 mg N L^{-1} during the winter months (45). Further research into the costs and benefits of tile drainage in the Mississippi Delta is warranted.

In contrast to NO_3-N, no MCL for drinking water PO_4-P concentration has been set. While 0.01 mg soluble P L^{-1} has been a commonly accepted freshwater eutrophication limit (46), more recent assessments have recognized that differences exist between different ecoregions and that different levels will apply to rivers, lakes, and estuaries. USGS has set a national background levels of P shallow groundwater at 0.02 mg total P L^{-1} (4). Recently, EPA set a reference condition of 0.06 mg total P L^{-1} for lakes and reservoirs in ecoregion X (40) and of 0.128 mg total P L^{-1} for rivers and streams the ecoregion X (47). These values are higher than those of all other ecoregions in the nation and the criteria for rivers and streams is accompanied by a footnote that states, "This value appears inordinately high and may either be a statistical anomaly or reflects a unique condition."

The shallow groundwater PO_4-P concentrations observed in the Beasley Lake watershed frequently exceeded all of the total P environmental references levels (Table VII) even though only very low rates of fertilizer P were applied by farmers in the watershed (Tables I and II). We believe that this data set provides solid support for the proposition that the unusually high P reference condition for the ecoregion including the Mississippi Delta is not a statistical anomaly but reflects high levels on native P in the soils. Sharpley et al. (5) have stated that the only long-term solution to excessive P levels in surface waters is a regional balance between P inputs and P exports in crop harvests. Within the Beasley Lake watershed, more P is removed annually in harvested crops than is added in fertilizer. Thus the unusually high soluble P levels observed cannot be due to anthropogenic processes.

Conclusions

Nitrate-N concentrations in shallow groundwater within a Delta agricultural watershed were usually below accepted background groundwater levels. High dissolved organic carbon concentrations and water tables frequently perched within 1.5 m of the soil surface make denitrification the most likely reason for low NO_3-N concentrations. These natural factors apparently overcome the "moderately severe" risk of nitrate groundwater contamination associated with intensive agricultural production practices. In contrast, groundwater PO_4-P concentrations were greater than accepted environmental reference conditions despite more P being removed in crop harvests than was applied in fertilizers. The observed high levels of dissolved PO_4-P thus reflect the high native P fertility status of the soils and support the concept that appropriate reference levels for P in ground and surface waters in the Mississippi Delta may indeed be higher than in other ecoregions of the nation.

Table VII. Beasley Lake Watershed Shallow Groundwater Orthophosphate-P Concentrations in Ranges Defined by Selected Total-P Environmental Reference Levels (%)

Well Depth (m)	*Below USGS Background Groundwater*[4] *<0.02 mg L^{-1}*	*Above USGS Background Groundwater*[4] *>0.02 mg L^{-1}*	*Above EPA Region X Lakes*[40] *>0.06 mg L^{-1}*	*Above EPA Region X Rivers*[47] *>0.128 mg L^{-1}*
Agricultural				
0.6				
1.5	13	87	64	43
3	21	79	65	52
4.5	43	57	27	9
Riparian				
0.6	58	42	15	2
1.5	22	78	50	28
3	24	76	36	2
4.5				
Overall	30	70	46	29

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Chapter 7

Pesticides in Shallow Ground Water and Lake Water in the Mississippi Delta Management Systems Evaluation Area

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Many of the Mississippi Delta Management Systems Evaluation Area (MDMSEA) project best management practices (BMPs) that have been implemented are designed to slow surface runoff and enhance agrichemical processing/retention. These BMPs also tend to increase infiltration and the potential for dissolved agrichemicals (nutrients and pesticides) to leach into the soil profile. The determination/characterization of pesticide movement in shallow ground water during three water years (1996-1998) of the first 5-years of the project is presented. Findings on the presence of pesticides in monthly water samples collected from the three MDMSEA oxbow lakes during the years 1998-2000 are also presented.

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The Mississippi Delta Management Systems Evaluation Area project (MDMSEA) is part of a national research program entitled *Agricultural Systems for Environmental Quality (ASEQ)* and is being conducted by a consortium of Federal, State, and local agencies. The original five MSEA projects were established in 1991 with a planned duration of at least 5 years and located in the Midwest (Ohio, Iowa, Nebraska, Minnesota, and Missouri). The MDMSEA is the first outside the Midwest. Primary research agencies are the USDA Agricultural Research Service [ARS (Oxford and Stoneville, MS and Baton Rouge, LA locations)], the U. S. Geological Survey [USGS (Jackson, MS district office)], and the Mississippi Water Resources Research Institute [MWRRI (Mississippi State Univ.)].

The hot, humid climatic conditions and long growing season make the Mississippi Delta ideal for intensive row crop production, primarily cotton (*Gossypium hirsutum* L.), soybeans [*Glycine max* (L.) Merr.], rice (*Oryza sativa* L.), and corn (*Zea mays* L.). However, these same conditions also provide for enhanced weed growth and high insect infestations, resulting in the need for intense agrichemical pest control measures. Because of the level topography and high annual rainfall, numerous streams, wetlands, and lakes are present. Many of the lakes are known as "oxbow lakes" because of their shape. Oxbow lakes are remnants of meandering floodplain rivers, which have been cut off and physically isolated from their respective main river channels and usually capture only small relic drainages. Isolation has resulted in physical and chemical changes in the lake basin and in the floral/faunal assemblages present at the time of separation. Over time, organic materials introduced from elsewhere have been processed and energetically depleted, resulting in the lakes having become less heterotrophic and more autotrophic. If suspended sediment concentrations are low enough to provide suitable light penetration, isolated oxbow lakes provide conditions conducive to photosynthesis, primarily via phytoplankton, and may support sustainable fisheries production *(1)*. However, decades of traditional agricultural practices including clean tillage and no winter cover on land surrounding these oxbow lakes have resulted in continuous high lake turbidity due to fine sediment transport in runoff. Thus, light penetration has been reduced, photosynthesis inhibited, and productivity lost. In addition, runoff has often transported agrichemicals into the lakes causing further reductions in water quality. Consequently, many Delta oxbow lakes, long known for their fish productivity and recreational value, have become unattractive.

Development of region-specific alternative farming systems (composed of combinations of selected BMPs) is crucial to protecting the surface and ground water resources and improving ecological and environmental quality of the entire Mississippi Delta. Research is needed on the alluvial soils of this region because the significance of agrichemical percolation (leaching) to relatively shallow water tables, which are hydraulically connected to nearby lakes and rivers, is poorly understood. The effectiveness of adjacent riparian zones to trap sediment and to trap and process agrichemicals in runoff is also poorly defined. Essentially nothing is known about the ability of the Delta lakes to recover and/or to sustain fisheries production after sediment and agrichemical inputs are permanently reduced.

Potential benefits from conducting this research include: 1) an increased knowledge of how the various physical, chemical, and biological properties of soils affect water and agrichemical movement, 2) the development of improved agrichemical transport models that allow for management, edaphic (inherent in the soil), and environmental variables, 3) new knowledge of agrichemical filter/processing system design and effectiveness, 4) improvements in crop residue and agrichemical management, 5) a reduction in agrichemical application with a concomitant reduction in sediment as well as surface and subsurface agrichemical transport, and 6) ecologically healthy lakes and streams with sustainable fisheries.

Materials and Methods

Study Site

The project design involved a hierarchy of BMPs in three research watersheds located in Sunflower and Leflore counties in west-central Mississippi *(2)*. The watersheds are "closed systems" each with drainage into an oxbow lake. Thighman Lake watershed (south of Moorehead in Sunflower county) served as a control with no BMPs *initially*. Beasley Lake watershed (south of Indianola in Sunflower county also) received nominal BMP treatment consisting of grade stabilization and water control structures including slotted-board risers, slotted-inlet pipes, overfall pipes, and culverts. Numerous grass filter strips were established along major drainages into the lake and in selected fields. Deep Hollow Lake watershed (near Sidon in Leflore county) received an intense BMP effort consisting of winter wheat cover crop and all conservation-till cotton and soybeans in addition to drainage control structures.

Pesticides in Shallow Ground Water

Well Installation

Observation wells for sampling shallow ground water were installed in clusters of 3 (about 3 feet apart) at depths of 5, 10, and 15 feet at critical flow areas in the watersheds. Deep Hollow Lake watershed has 12 well sites designated DH_1 through DH_{12}. As mentioned above, this watershed has the most MDMSEA project-implemented BMPs, which are both agronomic (conservation tillage, winter wheat cover, weed sensor weed control) and edge-of-field (slotted-board risers, slotted-inlet pipes, grass filter strips, riparian areas). The 12 well sites are at these edge-of-field BMPs, as they are designed to slow surface flow with resulting increased infiltration. The other well sites in this watershed (designated Hg) are deeper wells related to special hydrogeology research (3). Since the Thighman Lake watershed was originally intended to serve as the 'control' watershed with initially no project-imposed BMPs. there are only 4 well sites (two in a riparian area, one on a main field drainage to Thighman Lake, and one along the inlet to Thighman Lake). The Beasley Lake watershed has only edge-of-field BMPs imposed by the project. The 10 well sites (outside and west of the large forested wetland/riparian area) are primarily located at the edge-of-field BMPs and along field drainage ditches.

A General 550 Dig-R-Mobile was used to drill a 3 5/8 inch diameter hole 3-6 inches deeper than the required well depth. The hole was backfilled with pea gravel to the required well depth and a commercially available 2-inch diameter well (schedule 40 PVC with 1 foot of well screen) cut to a length of about 1 foot longer than the required depth was inserted into the hole. The hole around the outside of the well was backfilled first with about 1 foot of pea gravel so as to encase the well screen in gravel. The rest of the hole around the outside of the well was then filled to the surface of the ground with commercially available ¼-inch diameter bentonite pellets. The pellets were packed every 2-3 feet using a piece of schedule 40 PVC pipe with an i.d. just large enough to fit over the well. Bentonite pellets (about 1 inch thick) were packed around the outside of the well at the surface of the ground, covered with soil, and packed again. This provided a watertight casing around the well to prevent surface water (possibly containing dissolved agrichemicals) from seeping down the outside of the well. (*Note: we have observed wells standing in surface water, but with no water in the wells*).

Sampling Procedure

The sampling of shallow ground water was similar to that previously reported (4,5). Usually within 24h of a rainfall event, a 500-mL sample was collected from each well (using a battery-operated ISCO Acu-well model 150 portable pump fitted with a teflon-lined intake line) in a 0.5-L amber bottle with Teflon-lined screw cap. Each well was pumped dry and the excess well water was discarded. Shallow ground water samples were placed on ice, immediately transported to the National Sedimentation Laboratory (NSL), and stored at 4°C (usually <72 h) for pesticide analyses via gas chromatography (GC).

Pesticides in Lake Water

Sampling Procedure

Once a month, a 4-L water sample was collected in a 10-L glass jar, fitted with a Teflon-lined screw cap, from each of the three oxbow lakes (Deep Hollow, Beasley, and Thighman). Samples were taken from about the middle of each lake and from about the middle of the water column. Samples were extracted onsite by adding 4 g KCl and 400 mL pesticide grade EtOAc and shaking vigorously by hand for about 1 min. Lake water samples were immediately placed on ice, transported to the NSL, and stored at 4°C (usually <72 h) for pesticide analyses via GC.

Pesticide analyses

The pesticides initially targeted for analysis in shallow ground water samples are shown in Table I.

Heptachlor, aldrin, endosulfan, dieldrin, endrin, methoxychlor and p,p'-DDT (metabolites p,p'-DDE and p,p'-DDD) are relatively persistent, chlorinated hydrocarbon insecticides with some history of past use throughout much of the Mississippi Delta. The other compounds are generally less persistent herbicides and insecticides that were in current use in the MDMSEA watersheds in 1995. ***Note: tralomethrin is the precursor to deltamethrin and is detected by GC as deltamethrin.*** Analysis of ground water (and lake water) samples was similar to the method of Smith et al. (*5,6*), with modifications by Bennett et al. (*7*). Ground water samples were allowed to come to room temperature (about 25°C) and the volume measured and recorded. The entire sample was extracted by sonification (1 min/pulse mode/80% duty cycle) with 1 g reagent-grade KCl and 100 mL pesticide-grade EtOAc, partitioning in a separatory funnel, and discarding the water phase. The EtOAc phase was dried over anhydrous Na_2SO_4 and

Table I. Initially Targeted Pesticides

Pesticide	*Pesticide*
Atrazine	Endrin
Methyl Parathion	p, p'-DDD
Heptachlor	Norflurazon
Metolachlor	p, p'-DDT
Aldrin	Methoxychlor
Endosulfan	Cyfluthrin
p, p'-DDE	λ-Cyhalothrin
Dieldrin	Tralomethrin
	Fluometuron

concentrated by rotary evaporation to near dryness. The extract was taken up in about 5 mL pesticide-grade hexane, cleaned up by silica gel column chromatography, and concentrated to 1 mL for GC analysis. Mean extraction efficiencies, based on fortified samples, were >87% for all pesticides from shallow ground water (and lake water).

Initially, the gas chromatographs were Tracor model 540s equipped with Dynatech Precision GC-411V autosamplers to facilitate unattended injection of samples. A PE Nelson 2700 chromatography data system, consisting of three model 970 interfaces, Turbochrom 4.11 software, was used for automated quantification and reporting of pesticide peak data. A multi-level calibration procedure was used with standards and samples injected in triplicate. Calibration curves were updated every tenth sample. The main analytical column for all pesticides except the pyrethroids (cyfluthrin, ?-cyhalothrin, and tralomethrin) was a 15 m x 0.53 mm i.d. J & W Scientific DB 1 (1.5-µm film thickness) Megabore column. The carrier gas was ultra-high purity (UHP) helium at 5.5 cc/min and the column makeup and electron capture detector (ECD) purge gas was UHP nitrogen at 60 and 10 cc/min, respectively. Column oven, inlet, and ECD temperatures were 185, 240, and 350°C, respectively. The main analytical column for the three pyrethroids was a J & W Scientific DB 210 Megabore column (15 m 0.53 mm i.d. x 1.0-µm film thickness). The carrier gas was (UHP) helium at 12 cc/min and the column oven temperature was 215°C. The other GC conditions were as before. Pesticide residues were confirmed with a second Megabore column (DB 17). Fluometuron analysis was performed with a DB 1 column and a nitrogen phosphorus detector (NPD).

The older Tracor gas chromatographs were replaced with two Hewlett Packard model 6890 gas chromatographs each equipped with dual HP 7683 ALS autoinjectors, dual split-splitless inlets, dual capillary columns, a HP Kayak XA chemstation. One HP 6890 was fitted with two HP µECDs and the other 6890 with one HP µECD, one HP nitrogen phosphorus detector, and a HP 5973 mass selective detector (MSD). All pesticide analyses of samples (surface and ground water, sediment, soil, and plant material) collected in the MDMSEA and other NSL projects [e.g. Demonstration Erosion Control (DEC)] are currently being conducted with this state-of-the-science technology, including MDMSEA shallow ground water samples collected and processed (extracted, cleaned-up, stabilized) since late 1998 and all monthly lake water samples (*6,7*).

Because of changes in scientific interest and changes in pesticide usage in the MDMSEA watersheds, a new list of pesticides has been targeted for analysis (Table II). LOD is limit of detection in ppt and LOQ is limit of quantitation in ppt for lake water.

The main analytical column is a HP 5MS capillary column (30 m x 0.25 mm i. d. x 0.25-µm film thickness). Column oven temperatures are as follows: initial at 75°C for 1min, ramp at 25°C/min to 185°C, hold at 185°C for 25min, ramp at 25°C to 235°C, and hold for 15min. The carrier gas is UHP helium at 27cm/sec flow velocity with the inlet pressure at 13.24 psi and inlet temperature at 250°C. The ECD temperature is 325°C with a constant make up gas flow of 65cc/min UHP nitrogen. The autoinjector is set at 1.0-µL injection volume in the fast mode. Under these GC conditions the first 15 pesticides on the list in Table II (including

Table II. Presently Targeted Pesticides

Pesticide	*LOD*	*LOQ*	*Pesticide*	*LOD*	*LOQ*
Trifluralin	0.1	1	Chlorfenapyr	0.5	5
Atrazine	1	10	p,p'-DDD	0.1	10
Methyl parathion	1	10	p,p'-DDT	1	10
Alachlor	0.5	5	Bifenthrin	0.1	1
Metolachlor	1	10	λ-Cyhalothrin	0.1	1
Chlorpyrifos	0.1	1	Cyfluthrin	0.1	1
Cyanazine	0.5	5	Zeta-cypermethrin	0.1	1
Pendimethalin	0.5	5	Esfenvalerate	0.1	1
Dieldrin	0.1	1	Deltamethrin	0.1	1
p,p'-DDE	0.1	1	Fipronil	0.1	1
			Fipronil sulfone	0.1	1

the first two pyrethroids bifenthrin and ?-cyhalothrin) can be analyzed in a single run of 47.4 min. Pesticide residues are confirmed with a HP 1MS capillary column (30 m x .25 mm i. d. x 0.25-µm film thickness) under the same GC conditions and/or with the MSD. The MSD was used only when there was a question as to the identity of a particular pesticide peak. Online HP Pesticide and NIST search libraries are used when needed. GC methodology for analyzing the 6 pyrethroids in Table II as a group in a single run has been reported elsewhere (*8*).

Results and Discussion

Pesticides in Shallow Ground Water

Over the three water years (1996-1998), a total of 622 well samples were collected. A water year is from October of the previous year through September of the so-called water year. Thus, water year 1996 (WY96) is from October 1995 through September 1996, and so forth. There were 103 well samples collected in WY96, 160 in WY97, and 359 in WY98. Of the 622 well samples collected, there were only 5 detections and all were in WY96. All 5 detections were in the Beasley Lake watershed. Norflurazon (Zorial) was detected once at 0.4 ppb and metolachlor (Dual) was detected 4 times at levels ranging from 3-8 ppb. All detections were at extremely low levels and present no shallow ground water quality problems, as they were transient in nature. There were no detections in WY97 or in WY98. It appears then that the project-imposed BMPs caused no shallow ground water quality problems in any of the three MDMSEA watersheds. Pesticides leached into the soil profile were likely degraded / processed in the biologically active upper soil horizons. Evaluation of shallow ground water quality in the MDMSEA watersheds continues, but at a greatly reduced level.

Pesticides in Lake Water

Deep Hollow

For Deep Hollow Lake, the only significant detections in 1998 were zeta-cypermethrin at levels ranging from about 0.5 ppb to about 2.3 ppb in the period of May-September. These detections are probably the result of applications of cypermethrin (Ammo) and/or zeta-cypermethrin (Fury) on cotton in the watershed on May 5, June 3, June 8, and August 1. Other pesticides applied but not detected in 1998 include cyanazine, λ-cyhalothrin, and deltamethrin. In 1999, the pyrethroids λ-cyhalothrin, cyfluthrin (Baythroid), and esfenvalerate (Asana XL) were each detected at least once (all at <1 ppb). Applications of λ-cyhalothrin occurred on May 30, June 15, July 31, and August 14. Applications of cyfluthrin occurred on June 9, July 17, and August 14. An application of esfenvalerate occurred on August 25. Detections of bifenthrin (Capture) cannot be explained, as there is no record of its application in Deep Hollow Lake watershed in 1999 . Since the Deep Hollow Lake watershed is relatively small, drift from cropped areas just outside watershed may have occurred and could account for bifenthrin detections. The herbicides alachlor (Lasso), metolachlor (Dual) and cyanazine (Bladex) were also detected in lake water in 1999. As with bifenthrin, there is no record of any of these herbicides being applied in 1999. In 2000, zeta-cypermethrin was found in lake water samples collected on April 4, May 3, and May 31. However, applications of Ammo occurred on May 4, May 10, and May 17. Cyanazine was found in lake water samples collected on July 21, August 18, September 20, October 18, November 8, and December 6. Applications of Bladex occurred during the period of July 1-3.

Thighman

In 1998, atrazine applications occurred in the Thighman Lake watershed during the period of March 25-30 and on May 11. However, the only lake water containing atrazine was collected on September 10. The only other pesticide detection (>0.1 ppb) in lake water was that of esfenvalerate in the lake water sample collected on October 9. Asana XL applications in this watershed had occurred much earlier in the year, on June 25 and July 2. Atrazine applications in 1999 occurred on March 15 and May 11 and during the periods of March 19-April 15 and May 20-June 1. Lake water samples collected on April 21 and May 25 contained atrazine at concentrations of about 7 and 5 ppb, respectively. Atrazine was also found in lower concentrations later in the year in lake water samples collected on October 20 and November 8. Metolachlor was found in lake samples collected on April 21, May 25, and June 22 and Dual had been applied in the watershed on March 25, April 26, and May 1. Cyanazine was found in lake water samples collected on September 22, October 20, and November 8 and Bladex had been applied in the watershed on July 6 and July 8. The pyrethroid insecticides λ-cyhalothrin, zeta-cypermethrin, and esfenvalerate were also applied several times in the watershed, but only trace concentrations (<0.1 ppb) in lake water samples. Atrazine applications in 2000 occurred on March 3, March 15, May 10, May 17, and June 2. Atrazine was found in lake water samples collected on May 31, June 22, July 21, August 18, September 20, October 18, and November 8. Metolachlor was found in lake water samples collected on April 4, May 3, May 31, June 22, and July 21 and Dual applications in the watershed occurred on March 3, March 9, March 10, March 15, April 10, April 25, and April 27. Cyanazine was found in lake water samples collected on June 22, July 21, and August 18 and had been applied in the watershed on June 14. The pyrethroid insecticides λ-cyhalothrin and cyfluthrin were also applied several times in the watershed, but only trace concentrations (<0.1 ppb) of λ-cyhalothrin were found in lake water samples.

Beasley

In 1998, atrazine was applied to corn in the watershed on April 13 and May 15, but was only found in lake water samples collected on October 9 and November 28. Metolachlor was found in the lake water sample collected on October 9, but had been applied in the watershed as Dual on March 19, March 27, April 1, and May 8. Cyanazine also was detected in lake water samples collected on October 9 and November 28. It had been applied in the watershed only on June 18. Multiple applications of methyl parathion occurred during the year in the watershed on June 1, June 3, June 9, June 12, June 17, June 26, July 11, August 3, August 4, August 10, and August 11. However, no methyl parathion was ever detected in the monthly lake water samples during 1998. The pyrethroid insecticides λ-cyhalothrin, cyfluthrin, and esfenvalerate were also applied several times in the watershed, but only esfenvalerate was ever found in a lake water sample, the one having been collected on August 18. A single application of Asana XL had occurred on July 4. Atrazine was found in lake water samples collected on April 21, June 22, July 29, August 24, September 22, and November 8, 1999. Atrazine applications in the watershed that year occurred on April 12 and April 13. Metolachlor was found in lake water samples collected on April 21, June 22, August 24, September 22, October 20, November8, and December 16. Metolachlor applications in the watershed occurred on March 23 and April 12. Bladex was applied in the watershed on June 12 and during the period of July 6-14, but was only found (as cyanazine) in trace amounts (about 0.1 ppb or less) in lake water during 1999. Karate and Ammo were applied in the watershed on several occasions in 1999 but only traces (<0.1 ppb) were ever found in lake water samples collected that year. In crop year 2000, atrazine was found in lake water samples collected on May 31, June 22, July 21, August 18, September 20, October 18, and November 8. However, only one application occurred in the watershed in 2000, and that was on May 18. Bladex was applied in the watershed on June 2, June 20, June 23, and July 4 and was found (as cyanazine) in lake water samples collected on June 22, July 21, August 18, September 20, October 18, November 8, and December 6. Dual was applied in the watershed on April 27, but was found in lake water samples (as metolachlor) collected on February 9, March 9, May 31, June 22, and November 8. As in the previous crop year, Karate and Ammo were applied in the watershed on several occasions in 2000 but only traces (<0.1 ppb) were ever found in lake water samples in 2000.

Summary and Interpretation of Findings

During the period 1998-2000, the number of monthly lake water samples collected totaled 104. There were 88 pesticide detections above the 0.10 ppb level. Of these, 76 detections were herbicides and 12 were pyrethroid insecticides. Atrazine was found in 28 lake water samples, alachlor in 2, metolachlor in 22, and cyanazine in 24. With regard to the pyrethroid insecticides found in lake water samples, λ-cyhalothrin was found once, cyfluthrin once, zeta-cypermethrin 7 times, and esfenvalerate 3 times.

Selected properties of the 8 pesticides found in lake water are shown in Table III (9) As mentioned earlier, many of the project BMPs (conservation tillage, grass filter strips, modified field drainage pipes, etc.) were designed to reduce sediment transport to the lakes. The detections of the herbicides in lake water generally occurred within a few weeks after application whenever runoff events occurred within a week or two after application. Because the herbicides have water solubilities (S_{H2O}) that are several orders of magnitude higher and organic carbon partition coefficients (K_{OC}) that are several orders of magnitude lower than those of the pyrethroid insecticides and because the herbicides were applied in the watersheds using ground equipment, the presence of the herbicides in lake water is likely the result of transport in solution during runoff events. In contrast, the finding of pyrethroids in lake water could not be correlated with runoff events and is likely the result of drift during aerial application.

Table III. Selected Properties of Pesticides Found in Lake Water

Pesticide	S_{H2O} *(mg/L)*	K_{OC} *(cc/g)*
Atrazine	33	147
Alachlor	240	124
Metolachlor	488	70
Cyanazine	155	218
L-cyhalothrin	0.005	180,000
Cyfluthrin	0.002	31,000
Zeta-cypermethrin	0.004	61,000
Esfenvalerate	0.0002	5273

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The concentrations of herbicides found in lake water were well below values reported to be harmful to aquatic organisms (*10*). The LC50 (96 hour) values for fish are in the range of 2.4-18 mg/L (ppm), whereas the highest herbicide concentration found in the lake water samples was about 13 ppb (3 orders of magnitude lower). For the pyrethroids, LC50 (96 hour) values for fish are in the range of 0.0002-0.0082 mg/L (0.2-8.2 ppb). Pyrethroid concentrations in lake water were in the range of about 0.2-1.6 ppb and with the exception of zeta-cypermethrin were transient in nature.

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Mention of a pesticide in this paper does not constitute a recommendation for use by the U. S. Department of Agriculture nor does it imply registration under FIFRA as amended. Names of commercial products are included for the benefit of the reader and do not imply endorsement or preferential treatment by the U. S. Department of Agriculture. All programs and services of the U. S. Department of Agriculture are offered on a nondiscriminatory basis without regard to race, color, national origin, religion, sex, marital status, or handicap.

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Appendix

Chemical names of pesticides mentioned in this paper

- alachlor (2-chloro-2′,6′-diethyl-*N*-methoxymethylacetanilide)
- aldrin [(1*R*,4*S*,4a*S*,5*S*,8*R*,8a*R*)-1,2,3,4,10,10-hexachloro-1,4,4a,5,8,8a-hexahydro-1,4:5,8-dimethanonaphthalene]
- atrazine (2-chloro-4-ethylamino-6-isopropylamino-1,3,5-triazine)
- bifenthrin [2-methylbiphenyl-3-ylmethyl (*Z*)-(1*RS*,3*RS*)-3-(2-chloro-3,3,3-trifluoroprop-1-enyl)-2,2-dimethylcyclopropanecarboxylate]
- chlorfenapyr [4-bromo-2-(4-chlorophenyl)-1-(ethoxymethyl)-5-(trifluoromethyl)-1H-pyrrole-3-carbonitrile]
- chlorpyrifos (*O*,*O*-diethyl *O*-3,5,6-trichloro-2-pyridyl phosphorothioate)
- cyanazine [2-(4-chloro-6-ethylamino-1,3,5-triazin-2-ylamino)-2-methylpropionitrile]
- cyfluthrin [*RS*-α-cyano-4-fluoro-3-phenoxybenzyl(1*RS*,3*RS*)-*cis*,*trans*-3-(2,2-dichlorovinyl)-2,2-dimethylcyclopropanecarboxylate]
- ?-cyhalothrin {[1a(*S**),3*a*(*Z*)]-cyano(3-phenoxyphenyl)methyl 3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethylcyclopropanecarboxylate]}
- DDD [1,1-dichloro-2,2-bis (*p*-chlorophenyl) ethane]
- DDE [1,1-dichloro-2,2-bis(*p*-chlorophenyl)ethylene]
- DDT [1,1,1-trichloro-2,2-bis(*p*-chlorophenyl)ethane]
- deltamethrin [(*S*)-α-cyano-3-phenoxybenzyl (1*R*,3*R*)-3-(2,2-dibromovinyl)-2,2-dimethylcyclopropanecarboxylate]
- dieldrin (1,2,3,4,10,10-hexachloro-6,7-epoxy-1,4,4a,5,6,7,8,8a,octahydro-1,4,5,8-dimethanonaphthalene)

- endosulfan (6,7,8,9,10,10-hexachloro-1,5,5a,6,9,9a-hexahydro-6,9-methano-2,4,3-benzodioxathiopin-3-oxide)
- endrin (1,2,3,4,10,10-hexachloro-1*R*,4*S*,4a*S*,5*S*,6,7*R*,8*R*,8a*R*-octahydro-6,7-epoxy-1,4:5,8-dimethanonaphthalene)
- esfenvalerate {[S-(R*,R*)]-cyano(3-phenoxyphenyl)methyl 4-chloro-a-(1-methylethyl)benzeneacetate}
- fipronil [(*RS*)-5-amino-1-(2,6-dichloro-*a,a,a*-trifluoro-*p*-tolyl)-4-trifluoromethylsulfinylpyrazole-3-carbonitrile]
- fluometuron [*N,N*-dimethyl-*N'*-(3-(trifluoromethyl)phenyl)-urea]
- heptachlor (1,4,5,6,7,8,8-heptachloro-3a,4,7,7a-tetrahydro-4,7-methanoindene)
- methoxychlor (2,2-bis(p-methoxyphenyl)-1,1,1-trichloroethane)
- methyl parathion (*O,O*-dimethyl-*O-p*-nitrophenyl phosphorothioate)
- metolachlor [2-chloro-6'-ethyl-*N*-(2-methoxy-1-methylethyl)acet-*o*-toluidide]
- norflurazon [4-chloro-5-(methylamino)-2-(*a,a,a* -trifluoro-*m*-tolyl)-3(2*H*)-pyridazinone]
- pendimethalin [N-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine]
- trifluralin (*α,α,α*-trifluro-2,6-dinitro-*N,N*-dipropyl-*p*-toluidine)
- zeta-cypermethrin [(*S*)-*a*-cyano-3-phenoxybenzyl (1*RS*,3*RS*;1*RS*,3*SR*)-3-(2,2-dichlorovinyl)-2,2-dimethylcyclopropanecarboxylate]

Chapter 8

Suspended Sediment and Agrochemicals in Runoff from Agricultural Systems in the Mississippi Delta: 1996–2000

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As part of the Mississippi Delta Management Systems Evaluation Area (MDMSEA) project, the U.S. Geological Survey (USGS) began operating an automated streamflow and water-quality sampling network in April 1996 to characterize edge-of-field runoff from agricultural systems in the Mississippi Delta. This report presents runoff quantity, concentration, and load data for sediment, nutrient, and pesticide samples collected from nine MDMSEA runoff sites from 1996 through 2000. The report also presents comparisons of the runoff data collected from fields managed with and without best management practices (BMPs).

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Within the next decade, agricultural communities such as those in the Mississippi Delta may be faced with greater restrictions on farming to reduce agricultural nonpoint source pollution. Total Maximum Daily Loads (TMDLs) are one such tool that regulatory agencies can use to limit the amount of nonpoint source pollutant loads to streams, rivers, and lakes. In order to reach recommended water-quality goals, resource managers will work with farmers to implement agricultural systems that utilize BMPs. BMP research is necessary in helping both the Delta agricultural community and regulatory agencies determine those systems that will meet potential TMDL loading restrictions without excessive impacts to overall profitability and productivity.

Many management practices are designed to reduce the amount of runoff or to slow water velocities from fields, thus reducing the quantity of pollutants transported to a receiving water body. The volume of runoff water from an agricultural field can be affected by the size and shape of the field, field slope, soil type, antecedent soil moisture, and ground cover. "Edge-of-field" structures such as slotted-board risers are designed to minimize gully erosion in fields by ponding runoff water in front of culverts. "Within-field" agronomic practices such as planting cover crops and using conservation tillage can reduce runoff in several ways. Cover crops and plant residues increase field roughness causing water velocities to decrease, and plant roots provide pathways for water to infiltrate into the soil. "Edge-of-field" and "within-field" BMPs can be implemented separately or in combinations to maximize pollutant reductions in runoff prior to their entering a water body *(1)*.

The Mississippi Delta Management Systems Evaluation Area (MDMSEA) project began in 1995 to study agricultural nonpoint source pollution within oxbow lake watersheds in northwestern Mississippi. Specifically, the purposes of the MDMSEA project were to assess the effects of agriculture on water quality and to evaluate BMP systems designed to improve water quality. As part of the MDMSEA project, the USGS began operating an automated streamflow and water-quality sampling network in April 1996 to characterize edge-of-field runoff from agricultural systems under different forms of management. This report presents runoff quantity, concentration, and load data for sediment, nutrient, and pesticide samples collected from nine MDMSEA runoff sites from 1996 through 2000. The report also presents comparisons of the runoff data collected from fields managed with and without BMPs.

Locations and Field Treatments

Three oxbow lake watersheds were chosen for the MDMSEA project [The MDMSEA project watershed descriptions and locations are found in Locke *(2)*]. Nine USGS streamflow and water-quality sampling sites were established in the three MDMSEA watersheds to help characterize runoff from several fields managed with BMPs and one field without BMPs (streamflow and water-quality sampling sites are hereafter referred to as runoff sites, and runoff site names used in the following paragraphs are based on downstream ordering of tributaries in these watersheds).

1. Thighman Lake watershed - Soil types in the watershed vary from loam to very heavy clay. Primary row crops grown during 1995-96 in this watershed were cotton and soybean, but corn was a major crop from 1997 to 1999 as a result of market changes (3). Thighman watershed was selected as the control watershed, and no BMPs were planned. However, producers in the upper Thighman drainage area began to utilize conservation tillage in 1997. Two runoff sites are located in the Thighman watershed:
   - TL2 is on the primary inlet tributary of Thighman Lake and drains about 600 ha. Data collected from this site were used to document chemical and sediment loads entering the lake during runoff events.
   - TL3 is an edge-of-field site located downstream of a cotton field that was in conventional tillage without BMPs for the entire study period. TL3 drains about 6 ha, and data collected from fields managed with BMPs were compared to data collected at this site.
2. Beasley Lake watershed - Soil types in this watershed are generally silt loam to clay, and the primary crops are cotton and soybean with some corn and rice. A large riparian area (about 320 ha) is adjacent to the eastern side of Beasley Lake and serves as a natural filter. BMPs planned in the Beasley watershed were edge-of-field and were either structural or vegetative (2). Five runoff sites were installed in the Beasley watershed:
   - BL1 drains about 40 ha of conventionally-tilled cotton and is located on a grassed open-channel ditch. Filter strips and slotted-board risers were installed at strategic locations within the BL1 drainage area. Data from BL1 were used to evaluate the combined effectiveness of the grassed drainage ditch, slotted-board risers, and filter strips as a BMP system.
   - BL3 drains about 7 ha of conventionally-tilled crops. Cotton was grown every year in this area of the watershed, except in 1998 when corn was grown. A slotted-board riser was installed at the drainage outlet directly upstream of the sampling point, and no other BMPs were used within the BL3 drainage area. Typically, boards were placed in the riser in late October shortly after harvest and were removed in late March approximately 1 month before planting. However, boards were installed for only 1 month in Fall 1997 (no runoff events) at the landowner's request of the landowner to enable him to prepare fields prior to planting corn in Spring 1998. Boards were not reinstalled until October 1998.
   - BL4, BL4A, and BL4B are located within the natural riparian area adjacent to the eastern side of Beasley Lake. Data from these three sites were used to assess effects of the riparian area on runoff. BL4A and BL4B drain about 150 and 69 ha, respectively, and are located at separate drainage ditches on the east side of the undisturbed riparian area. Cropped areas within the BL4A and BL4B drainage area were

primarily in conventional tillage. BL4 drains about 340 ha and is located on the west side of the riparian area near the outlet upstream of the lake entrance.

3. Deep Hollow Lake watershed (Leflore County) – Approximately two-thirds of the watershed has loam soils that support cotton; areas with heavier, clay soils were cropped with soybean. This watershed received a combination of BMPs including "edge-of-field" and agronomic practices (*2*). Winter wheat was planted on the entire cropped area in the fall of each year with cover lasting from late fall through late winter when it was desiccated with herbicide prior to planting in early spring. Two runoff sites were installed in the Deep Hollow Lake watershed:
    - UL1 drains about 17 ha where cotton and soybean were grown throughout the study period. Conservation-tillage cotton was grown in the upper elevations of the UL1 drainage area farthest from the sampling point, and no-till soybean were grown in the lower elevations nearest the sampling point. A slotted-board riser was installed as a BMP on the culvert entrance directly upstream of the sampling point at UL1.
    - UL2 drains about 10 ha where cotton and soybean were grown throughout the study period. Similar to UL1, conservation-tillage cotton was grown in the upper elevations and no-till soybean was grown in the lower elevations of the UL2 drainage area.

Materials and Methods

Continuous streamflow data have been collected at six of the nine runoff sites since 1996. The three remaining sites in the Beasley riparian area had diffuse flow and could not be instrumented. Water-quality samples were collected at each of the nine runoff sites. The samples were analyzed to determine sediment, nutrient, and selected pesticide concentrations for determination of contaminant loads. The following sections describe sample-collection procedures, sample analyses, and runoff and load calculations.

Sample Collection

Runoff samples were collected at each site using automated samplers (Isco Model 3700 Portable Sampler; Isco, Inc., Lincoln, NE). Quality assurance/quality control (QA/QC) measures were taken to determine potential contamination of the samples and to assess bias and variability in the analyses. Streamflow was measured at six sites using flumes, weirs, or acoustic Doppler instrumentation (Isco Model 4150 Flow Logger or Isco Model 4250 Flow Meter; Isco, Inc., Lincoln, NE).

Flow-proportional, bulk/composite samples were collected during each runoff event, and sub-sampled for analysis after retrieval from the field.

Sample Analyses

Sample aliquots were shipped to three USGS laboratories for sediment, nutrient, and pesticide analyses. Sediment analysis was performed at the Louisiana District Sediment Laboratory, Baton Rouge, LA. Nutrient analysis was done at the USGS Quality of Water Service Unit, Ocala, FL; nutrient analyses included nitrogen species - dissolved nitrite plus nitrate, dissolved nitrite, dissolved ammonia, and total ammonia plus organic nitrogen (dissolved nitrate concentrations presented later in this report were calculated values based on the difference between dissolved nitrite plus nitrate and dissolved nitrite); and phosphorus species - dissolved ortho-phosphorus and total phosphorus.

Aliquots were analyzed for herbicides at the USGS Organic Geochemistry Laboratory, Lawrence, KS. Gas chromatography/mass spectrometry (GC/MS) analyses included 15 parent compounds (acetochlor, alachlor, atrazine, cyanazine, metolachlor, fluometuron, metribuzin, molinate, norflurazon, prometryn, propachlor, propanil, propazine, simazine, and trifluralin) and 9 degradation products (deethylatrazine, deisopropylatrazine, cyanazine-amide, demethylfluometuron, 3trifluoromethyl phenyl urea, 3trifluoromethyl analine, demethylnorflurazon, deisopropylprometryn, and 3,4 dichloroaniline). Immunoassay kits were used for analysis of fluometuron (Magnetic particle RaPID Assay kit by Strategic Diagnostics, Inc., Newark, DE, and EnviroLogix Fluometuron Plate Kits by EnviroLogix, Inc., Portland, ME), atrazine (Magnetic particle RaPID Assay kit by Strategic Diagnostics, Inc., Newark, DE); and metribuzin (Magnetic particle RaPID Assay kit by Strategic Diagnostics, Inc., Newark, DE). Due to space limitations, concentrations for only the herbicide fluometuron are presented in this document.

Runoff and Load Calculations

As of this writing, flow data were available for only TL3, BL3, and UL2; therefore, runoff and load calculations were made only for those three sites. Annual runoff, reported in centimeters (cm), was calculated by dividing the total annual volume of runoff by the drainage area. Loads were calculated using procedures described by Porterfield (4). Some loads were estimated using regression techniques described by Porterfield for events when samples were not available, for example, when equipment malfunctioned. Finally, loads were normalized by dividing each individual storm load by the drainage area and are expressed as metric tons (or kg) per hectare.

Results and Discussion

The following sections present comparisons of sediment and chemical concentrations, runoff quantity, and sediment and chemical load data from the nine runoff sites. Soil types and crops, drainage basin size, and farming practices varied substantially among the runoff sites in the three MDMSEA watersheds. Although these site-to-site differences may introduce some uncertainty with regard to detailed interpretation of results, general conclusions may be drawn.

Sediment and Chemical Concentrations in Runoff

Median concentrations of sediment and selected chemicals for composite samples collected at the nine MDMSEA sites are presented in Table I.

Sediment

Conventional tillage was predominant in all of the watersheds at the beginning of the study. In some locations, fields were plowed nearly to the edges of the lakes. Crops grown in the TL3 drainage area remained in conventional tillage without BMPs throughout the study period. The median suspended-sediment concentration at TL3 was 1,700 mg L^{-1} (Table I), the highest for any of the MDMSEA sites during the study period.

The median suspended-sediment concentration was about 80 percent lower at TL2 than at TL3 (Table I). The lower part of the TL2 drainage area is considered to be a wetland/riparian area historically affected by periodic backwater conditions from beaver dams, damaged culverts, and high lake levels. As runoff drains from the fields through the long channel, backwater conditions could cause a decrease in runoff velocity, and thus, allow sediment to settle. The low sediment value at TL2 could also reflect changes in farming practices from conventional tillage to conservation tillage, which began in 1997 in the Thighman watershed.

The median suspended-sediment concentration was about 45 percent lower at BL3 than at TL3 (Table I). BL3 was in conventional tillage during the study period with a slotted-board riser installed at the outlet of the drainage. In 1998, the producer planted corn within the drainage area at this site and altered both row direction and a field road that bisected the drainage area. These alterations impounded water upstream causing runoff to reach the slotted-board riser only during extreme storm events. Heavier sediments settled out prior to reaching the sampling point thus influencing the lower median suspended-sediment

Table I. Median Sediment and Selected Chemical Concentrations for MDMSEA Runoff Samples, 1996-2000

Sites	*Suspended sediment*	*Nitrate*	*Ammonia*	*Total ammonia plus organic nitrogen*	*Ortho-phosphorus*	*Total phosphorus*	*Fluometuron**
TL3	1,700	2.4	0.08	3.8	0.06	1.0	2.3
TL2	330	1.6	0.19	2.2	0.09	0.44	0.48
BL3	930	0.94	0.05	3.7	0.12	1.2	0.54
BL1	1,500	0.77	0.03	3.6	0.12	1.5	0.4
BL4A	410	0.77	0.03	1.9	0.11	0.67	0.29
BL4B	150	0.34	0.05	1.2	0.09	0.32	<0.05
BL4	200	0.46	0.03	1.6	0.12	0.50	0.12
UL2	460	0.24	0.03	2.1	0.18	0.86	0.25
UL1	790	0.34	0.05	2.9	0.12	0.86	0.68

*Fluometuron data reflect the sum of the parent compound and degradation products.

NOTE: All concentrations are in mg L^{-1} except for fluometuron which is in μg L^{-1}.

concentration at BL3. The median suspended-sediment concentration was only 12 percent lower at BL1 than at TL3 (Table I), indicating that the edge-of-field structural and vegetative treatments installed within the BL1 drainage area had little effect in reducing suspended-sediment concentrations.

Median suspended-sediment concentrations were 76, 91, and 88 percent lower at BL4A, BL4B, and BL4, respectively, than at TL3 (Table I). The low concentrations at these sites reflected the efficiency of the drainage ditches and the undisturbed riparian area at Beasley to remove sediment from runoff.

Median suspended-sediment concentrations at UL2 and UL1 were 73 and 54 percent lower, respectively, than at TL3 (Table I). The low sediment concentrations at these two runoff sites were primarily the result of the cover crops and conservation tillage BMPs utilized in the Deep Hollow watershed. As far as within-basin comparisons were concerned, the only BMP difference between UL1 and UL2 was that UL1 had a slotted-board riser installed at the outlet of its drainage area. Theoretically, suspended-sediment concentrations should have been lower at UL1 than at UL2 due to the additional BMP at UL1. However, suspended-sediment concentrations were actually higher at UL1 than at UL2 (Table 1). The drainage area of UL1 is about two-thirds larger than that of UL2, and the channel slope within the UL1 drainage area was also higher, increasing the potential of in-stream erosion problems. Although slotted board risers are designed to prevent gully erosion near the outlet of a drainage area, some gully erosion, head-cutting, and channel degradation were, in fact, observed upstream of the slotted board riser at UL1 during the study period. Therefore, the higher suspended-sediment concentrations observed at UL1 in comparison to UL2 were likely caused by in-stream erosive processes rather than delivery of sediment from the fields in the UL1 drainage area.

Nutrients.

Prior to the study, none of the lakes appeared to be adversely affected due to excessive nutrients or over-production of aquatic plants. However, nitrogen and phosphorus in the runoff were excessive at times, especially at TL3.

Nitrate is easily transported in water. Much of the concern about nitrate as a pollutant is the possible contamination of ground-water supplies. Nitrate is also a concern in surface waters because high concentrations of nitrate can contribute to over-production of aquatic plant materials, which in turn, can deplete dissolved oxygen in the water. The median nitrate concentration (as N) at TL3 was 2.4 mg L^{-1}; and this was the highest value for any of the MDMSEA sites for the study period (Table I). The median nitrate concentration was 33 percent lower at TL2 than at TL3; however, the median nitrate concentration at TL2 was much higher than at the BMP sites. Median nitrate concentrations were 68, 68, 86, 81, 90, and 86 percent lower at BL1, BL4A, BL4B, BL4, UL2, and UL1, respectively, than at TL3 (Table I). These six sites had more organic material in their drainage areas than the other three sites: the channel directly upstream of BL1 was grassed; BL4A, BL4B, and BL4 were located in the densely forested riparian area in the Beasley watershed; and residue from winter cover and conservation tillage was abundant upstream of UL2 and UL1. A possible explanation for the low nitrate concentrations in runoff at these sites was that the nitrate was immobilized within the residue of the organic material (*5*).

In contrast, the median ammonia concentration was more than 100 percent higher at TL2 than at TL3 (Table I). The high concentrations of ammonia (and nitrate, as per the previous paragraph) in water samples collected at TL2 may reflect the greater application of nitrogen fertilizers in 1997-99, corresponding with the gradual crop changes from cotton and soybean to corn in 1997 in the upper drainage of TL2. The median ammonia concentrations at the other BMP sites were similar to the median concentration at TL3.

Two sources of ammonia plus organic nitrogen are fertilizers and the decay of organic material such as plant debris and animal wastes. Both ammonia and organic nitrogen are relatively immobile in soils and ground water because of sorption on soil surfaces and particulate filtering; however, both are susceptible to nitrification under aerobic conditions (*6*). Thus, the measure of total ammonia plus organic nitrogen represents the amount of nitrogen available for oxidation and could contribute to oxygen depletion in the oxbow lakes. Total ammonia plus organic nitrogen concentrations at the MDMSEA sites generally followed the same pattern as suspended-sediment concentrations. The median total ammonia plus organic nitrogen concentration at TL3 was 3.8 mg L^{-1} (Table I), the highest value at any of the MDMSEA runoff sites for the study period. Median ammonia plus organic nitrogen concentrations at BL1 and BL3 were similar to the median at TL3. Median ammonia plus organic nitrogen concentrations were 42, 50, 68, 58, and 45 percent lower at TL2, BL4A, BL4B, BL4, and UL2, respectively, than at TL3 (Table I).

Phosphorus typically is considered the limiting nutrient for growth of aquatic vegetation in many types of fresh waters (*7*). Large amounts of phosphorus in streams and lakes can result in nuisance growth of aquatic plants. Ortho-phosphorus is a soluble, inorganic fom of phosphorus and is considered the most biologically available form for aquatic plant uptake. The median dissolved ortho-phosphorus concentrations at the MDMSEA sites ranged from 0.06 mg/L at TL3 to 0.18 mg L^{1} at UL2 (Table I). Although median edge-of-field values were fairly high, Knight and others (*8*) reported that ortho-phosphorus concentrations averaged 0.049, 0.046, and 0.044 mg/L for Beasley, Deep Hollow, and Thighman Lakes, respectively, in 1999.

In an agricultural setting, high total phosphorus concentrations in runoff generally are associated with sediment-laden water from eroded fields. As expected, high total phosphorus concentrations occurred at runoff sites that also had high concentrations of suspended-sediment (sites that had conventional tillage within their drainage areas). For example, the median total phosphorus concentrations at TL3, BL3, and BL1 were 1.0, 1.2, and 1.5 mg L^{-1}, respectively (Table I). The total phosphorus concentrations were lowest where suspended-sediment concentrations were lowest, such as at TL2 and the riparian zone sites, BL4, BL4A, and BL4B (Table I).

Fluometuron.

Fluometuron was selected for inclusion in this report because it was the most frequently detected herbicide, ranging from 42 to 97 percent detections (data not shown) for runoff samples collected at the nine sites for the study period. Fluometuron is used primarily as a pre-emergent cotton herbicide applied at planting. Fluometuron is fairly soluble and has three major degradation products, demethylfluometuron, trifluromethylphenyl urea (TFMPU), and trifluromethyl aniline (TFMA). Data in Table I reflect the sum of the parent compound and the degradation product concentrations in each sample.

The highest median concentration of fluometuron in runoff samples occurred at TL3 (Table I). The lowest median concentrations of fluometuron were in samples from the riparian area sites in the Beasley Lake watershed (BL4, BL4A, and BL4B, Table I). From research conducted by other MDMSEA scientists, fluometuron degradation was enhanced in the riparian area likely due to higher levels of organic matter and soil moisture, and increased enzyme activities (*9*). The half-life of fluometuron was at least 49 days shorter (decreased from 112 to 63 days) within the riparian area (*10*). Research by Zablotowicz et al. (*9*) indicated that fluometuron degradation (by N-demethylation) in soil samples collected from the Beasley riparian area was from 2- to 4-fold greater than in soil samples from cropped areas.

Runoff Quantity and Sediment and Chemical Loads

Annual rainfall and runoff quantity, and sediment and nutrients loads for TL3, BL3, and UL2 for the study period are presented in Table II. Annual amounts of fluometuron applied and measured in runoff for the same three sites are presented in Table III.

Runoff

The average rainfall totals for TL3, BL3, and UL2 for the study period were identical (Table II). However, the runoff totals from these three sites were quite different. The average runoff was the greatest at TL3 (72 cm), which had conventional tillage without BMPs throughout the study period. The average runoff at BL3 was the least (51 cm) of the three sites. Runoff at BL3, however, was high (84 cm) in 1997 but averaged only about 40 cm for the years 1998-2000. The smaller runoff totals at BL3 starting in 1998 were likely due to drainage alterations mentioned previously rather than the presence of the slotted-board riser. The average runoff at UL2 was 56 cm, which is about 22 percent lower than the average runoff at TL3 (Table II). The lower runoff at this site was probably due to the use of agronomic BMPs such as winter cover crops and conservation tillage.

Sediment loads.

The average suspended-sediment load for the study period was 13 metric tons per hectare per year at TL3, which is the highest of the three sites (Table II). The average annual suspended-sediment load was 38 percent lower at BL3 than at TL3. The lower sediment loads at BL3 were probably the result of the lower annual runoff at this site, which was caused by drainage alterations within the basin that started in 1998. The average annual suspended-sediment load was 78 percent lower at UL2 than at TL3 likely due to the use of agronomic practices (Table II).

Nutrient loads.

In general, nutrient loads (except for dissolved ortho-phosphorus) were greatest at the TL3 site and least at the UL2 site. The average annual dissolved nitrate and dissolved ammonia loads were 79 and 44 percent lower at UL2 than at TL3, respectively (Table II). The lower dissolved nitrogen values could be caused by immobilization of nitrate at UL2 within the plant residues of the cover crop and shredded stalks of the crops under conservation tillage. Average annual total ammonia plus organic nitrogen and total phosphorus loads were 66 and 46 percent lower at UL2 than at TL3, respectively; because these nutrient constituents include those bound to sediment, the lower load values reflected lower sediment loads at UL2. The average annual ortho-phosphorus load at UL2 was the greatest of the three sites, and was more than double that at TL3 (Table II). Nutrient loads were lower at BL3 than at TL3. The lower values were likely the result of less runoff due to drainage alterations at this site. Most of the nutrient loads at BL3 were similar to loads at TL3 in 1997 before the drainage alterations took place.

Fluometuron loads.

The average amount of fluometuron applied over the 4-year period at TL3 and UL2 was similar (Table III); the average amount applied at BL3 was less because none was applied in 1998 when corn was planted. Fluometuron was not applied at any of the three sites in 2000. The average annual amount of fluometuron in the runoff at TL3 was about 6.8 percent of that applied, which is the highest percentage of the three sites. For 1997, 3.0 percent of the fluometuron applied at BL3 was present in the runoff, which is about half that at TL3. The average annual amount of fluometuron in the runoff at UL2 was about 2.0 percent of that applied, which is less than one-third the percentage of TL3. Work by other MDMSEA scientists suggests that the lower percentage of fluometuron in runoff from UL2 was because fluometuron was degraded by the abundance of organic material within this drainage area (*9,10*).

Table II. Annual Sediment and Nutrient Loads for Three MDMSEA Runoff Sites, 1997-2000

Year	Rainfall (cm)	Runoff* (cm)	Load					
			Suspended sediment	Dissolved NO_3^-	Dissolved NH_3	Total NH_3 plus organic N	Dissolved ortho-P	Total P
				TL3				
1997	150	100	14	14	0.89	29	0.75	6.9
1998	90	65	8.5	7.6	2	21	0.5	4.3
1999	100	58	10	16	0.44	23	0.53	4.4
2000	97	63	18	20	1.3	33	0.29	9.4
Avg.	**110**	**72**	**13**	**14**	**1.2**	**27**	**0.52**	**6.3**
				BL3				
1997	130	84	15	11	0.55	32	1	4.5
1998	100	38	7.9	8.9	1.2	25	0.52	6.1
1999	120	39	5.1	11	0.71	12	0.33	5.2
2000	99	42	4	2.3	0.21	9	0.36	3.3
Avg.	**110**	**51**	**8**	**8.3**	**0.67**	**20**	**0.55**	**4.8**
				UL2				
1997	130	61	3.7	2.7	0.48	10	0.78	3.3
1998	120	49	3.5	3.1	0.44	9.7	0.59	3.2
1999	110	59	2.8	4.1	1.2	12.1	1.6	4.6
2000	94	57	1.5	2	0.55	4.8	1.8	2.5
Avg.	**110**	**56**	**2.9**	**3**	**0.67**	**9.2**	**1.2**	**3.4**

NOTE: Suspended-sediment load, in metric t ha^{-1}; all other loads, as N or P in kg ha^{-1}

Table III. Quantity of Fluometuron Applied in the Watershed and Measured in Runoff for Three MDMSEA Sites, 1996-99

Date applied	*Quantity applied (kg)*	*Quantity in runoff prior to next application (kg)*	*Quantity in runoff/amount applied (%)*
5/04/1996	6.5	0.15*	N/A
5/1997**	6.5	0.48	7.4
5/05/1998	6.5	0.41	6.3
5/01/1999	3.3	N/A	N/A
5/1996**	4.0	0.01*	N/A
4/14/1997	4.0	0.12	3.0
4/29/1999**	5.6	N/A	N/A
5/0/1996	6.7	0.02*	N/A
5/17/1997	4.2	0.13	3.1
5/05/1998	5.6	0.05	0.89
5/09/1999	5.6	N/A	N/A

***Incomplete period of record; ** Actual application date unknown**

Summary

Some of the highest concentrations of sediment, nutrients, and pesticides occurred in runoff samples at TL3 where fields were managed with conventional tillage without BMPs for the study period. In addition, runoff quantities and suspended-sediment, dissolved nitrate, dissolved ammonia, ammonia plus organic nitrogen, and total phosphorus loads were the highest at TL3.

Runoff data from BL1 and BL3, where "edge-of-field" structural and vegetative BMPs were installed, either showed no significant differences when compared to TL3 or were inconclusive due to unforeseen circumstances. Median concentrations of sediment and nutrients for runoff samples collected at BL1 were similar or actually greater than median concentrations at TL3. Although runoff and constituent concentrations and loads at BL3 were lower in comparison to TL3, the differences were likely due to drainage alterations within the drainage area rather than the presence of the slotted-board riser installed at the outlet.

Sediment, nutrient, and pesticide concentrations and loads were substantially lower where agronomic practices such as conservation tillage with winter cover were utilized (UL1 and UL2). In addition, data from Beasley riparian area sites (BL4, BL4A, and BL4B) characterized the efficiency of an undisturbed riparian area for removal of sediment and nutrients. Median concentrations of suspended sediment and nitrogen and phosphorus species at BL4A, BL4B, and BL4 were among the lowest median concentrations at any of the runoff sites.

Disclaimer

The use of brand names in this paper is for identification purposes only and does not constitute endorsement by the U.S. Government.

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Chapter 9

Evaluation of Watershed Management Practices on Oxbow Lake Ecology and Water Quality

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Much of the worldwide loss of aquatic habitats has been attributed to draining and clearing for agriculture as well as non-point source pollution associated with agricultural runoff. The Mississippi Delta Management Systems Evaluation Area (MDMSEA) project was designed to develop and test land and agronomic treatments targeted to reduce sediment and associated pollutants entering oxbow lake watersheds. Lake water quality prior to the implementation of best management practices (BMPs) indicated ecologically impacted ecosystems due to excessive suspended sediment. Improvements in water quality were realized through the use of agronomic and edge-of-field BMPs. Sediments were decreased 34 to 59%, while Secchi visibility and chlorophyll content generally increased. Improvements in water quality occurred in lakes that featured agronomic practices and combinations of agronomic and edge-of-field practices respectively. Prior to BMP implementation fish species richness was relatively low and sports fishes were poorly represented. Post-BMP fish sampling indicate successful renovation of lakes with agronomic practices and combinations of agronomic and edge-of-field practices. Largemouth bass, lacking in two of the lakes before renovation and restocking, were successfully reestablished in these two lakes. Results indicate that agronomic BMPs played a significant role in improving lake water quality and may be needed in addition to edge-of-field measures to insure improved fisheries.

In Water Quality Assessments in the Mississippi Delta; Nett, M., et al.;
ACS Symposium Series; American Chemical Society: Washington, DC, 2004.

Introduction

Much of the worldwide decline in aquatic habitats over the course of the past century can be attributed to draining and clearing of agricultural lands. Fowler and Heady *(1)* reported that in-stream suspended sediments are, by volume, the most significant pollutants in the United States. It is estimated that 60% of the approximately 2.72 billion tons of sediment per year deposited in waterways originates from agricultural lands. The Mississippi River alone transports 300 million metric tons of soil to the Gulf of Mexico annually *(2)*. In addition, these sediments are often accompanied by other contaminants such as pesticides and nutrients. The natural lakes of the Mississippi alluvial plain, long known for their productivity and recreational value *(3)* have not escaped the detrimental effects of soil erosion. Their popularity as recreational resources has decreased as water quality and fisheries have declined *(4)*. Cooper and Knight *(5)* have attributed these declines, in part, to soil erosion and sedimentation. Detrimental impacts on stream and lake water quality due to erosion and sedimentation have been well documented *(6, 7)*.

Oxbow lakes are remnants of meandering rivers that have been cut off from their respective main river channels. Under ideal conditions, oxbow lakes provide conditions conducive to photosynthesis, and support an abundant and sustainable sport fishery. Traditional tillage practices often result in excessive soil erosion leading to increased turbidity in the oxbow lakes and subsequent inhibition of photosynthesis. Turbidity in oxbow lakes can be persistent in areas having soils with high clay content such as the Mississippi Delta. Although phosphorus is commonly associated with delta soils and isolated oxbow lakes tend to load this and other nutrients, these systems may become energy starved and very unproductive due to lack of light penetration.

Best management practices (BMPs) designed to reduce sediment-laden runoff should reduce suspended sediment concentrations in the receiving waters of oxbow lakes (Figure 1). Although some reduction in nutrient in-flow may be realized, most oxbow lakes should be eutrophic enough to boost primary productivity and consequently support a sustainable fishery. This study examines and documents pre-management water quality and ecological conditions on three oxbow lakes and resulting water quality and fisheries improvements following lake renovation and the implementation of best management practices designed to control erosion and non-point source pollution.

Materials and Methods

Project Overview

This research was conducted as a part of the Mississippi Delta Management Systems Evaluation Area (MDMSEA) project. The MDMSEA was intended to demonstrate the effectiveness of farming systems designed to reduce non-point

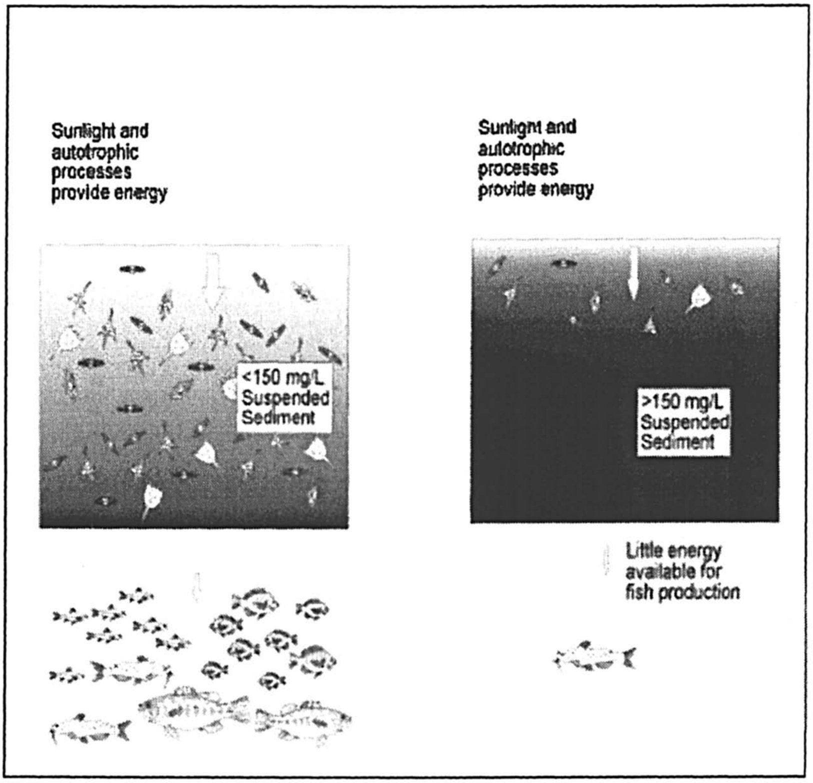

Figure 1. Representation of sediment effects on energy flow and productivity in oxbow lakes.

source pollution from agricultural runoff. These farming systems employed a variety of BMPs that fell into one of two categories, edge-of-field or agronomic. Three oxbow lake watersheds were selected to receive management practices based on these different categories. The MDMSEA study sites included the three oxbow lakes of Thighman and Beasley Lakes near Indianola, MS in Sunflower County and Deep Hollow Lake near Greenwood, MS in Leflore County. Beasley Lake watershed was protected solely with edge-of-field practices such as slotted pipes, slotted board inlets, grassed buffers and stiff grass hedges. Deep Hollow Lake was protected with a combination of the aforementioned edge-of-field practices as well as agronomic methods including conservation tillage and winter cover crops. The third watershed, Thighman Lake, was originally planned to be a "control" watershed that would demonstrate conventional tillage and typical farming practices of the region. While no edge-of-field or agronomic practices were recommended or encouraged, the farmers within this watershed began adopting conservation tillage at about the same time that the various BMPs were initiated in the other two watersheds. This resulted in a study where one watershed was protected with agronomic practices, one with edge-of-field practices and a third with a combination of both. Further details of the study sites and methodologies are included elsewhere in this volume *(8)*.

Data Collection

Three sampling sites on each of the three lakes were selected for water quality monitoring. Yellow Springs Instruments Model 6000 automated water quality monitoring equipment was used to obtain hourly measurements of temperature, pH, dissolved oxygen and conductivity. Surface water quality was sampled biweekly from May 1995 through December 1999 at three locations on each lake for total, suspended, and dissolved solids, total phosphorus, filterable ortho-phosphate, ammonium nitrogen and nitrate nitrogen, chlorophyll, coliform and enterococci bacterial counts and Secchi visibility.

Analytical and chemical methods were based on procedures from APHA *(9)*. Calculation of means and statistical analysis was completed using SAS statistical software *(10)*. All parameters were tested for differences at the 5% level of significance.

The existing community of fishes was eradicated using 5% rotenone solution on all three lakes. Pre-management standing stock and other fisheries characteristics were estimated for each oxbow by sub-sampling fish from approximately 0.56 hectares of block netted lake. Fish were weighed, measured for total length and identified to species.

Each lake was re-stocked with largemouth bass (*Micropterus salmoides*), a mix of bluegill (*Lepomis macrochirus*) and redear sunfish (*Lepomis* *microlophus*), and channel catfish (*Ictalurus punctatus*) at rates of 50, 500 and 150 per acre respectively. Sampling was accomplished using a boat mounted Coffelt Model VVP-2C electroshocker operating at 250 volts. Sampling effort was limited to one hour of electrofishing time per lake providing adequate survey coverage while minimizing damage to recovering populations. Captured fish were placed in holding tanks until they could be weighed, measured, and released. Capture mortality was generally limited to smaller individuals.

Results and Discussion

General Water Quality

Mean physical and chemical water quality data for the three MSEA lakes prior to establishment of erosion and pollution control structures and management practices may be found in Table I. Water quality of all MSEA lakes was statistically similar to one another prior to implementation of BMPs.

Thighman Lake had significantly higher conductivity, and concentrations of dissolved solids and nitrate than either Deep Hollow or Beasley Lakes, while Beasley and Deep Hollow had higher concentrations of ortho-phosphate.

Water quality prior to the implementation of management practices indicated that lakes were stressed and potentially ecologically damaged due to excessive inflowing sediment. Mean total water column sediment concentrations ranged from 351 mg/L to 505 mg/L with maximum values reaching 2365 mg/L for Beasley Lake, 1094 mg/L for Thighman Lake and 804 mg/L for Deep Hollow Lake. High suspended solid concentrations on Thighman and Beasley Lakes corresponded to lower concentrations of chlorophyll and lower Secchi visibility. Deep Hollow Lake had the highest mean concentration of chlorophyll (24.42 μg/L) as well as the lowest mean concentration of suspended sediment (269 mg/L). Temperature, conductivity and pH values fell within expected ranges for the oxbow lakes in the Mississippi Delta (5). While all three lakes experienced occasional periods of low dissolved oxygen concentrations, average annual dissolved oxygen concentrations were adequate to maintain warm water fisheries.

Nitrogen

Boyd *(11)* reported that ammonium nitrogen and nitrate nitrogen concentrations of unfertilized woodland ponds were 0.052 mg/L and 0.075 mg/L respectively while catfish ponds had concentrations of 0.50 mg/L ammonium nitrogen and 0.25 mg/L nitrate nitrogen. Although the MDMSEA lakes exceeded these values, they never exceeded the 1 mg/L ammonium standard at pH 7 and 30 °C nor the 0.02 mg/L standard for the highly toxic un-ionized form. MDMSEA lakes were also well below the 10 mg/L USEPA *(12)* standard for water ingestion and fish consumption. MDMSEA lakes had nitrate nitrogen concentrations that compared similarly to those values reported for Yazoo Basin lakes in 1969 *(13)*. Best Management Practices had little discernable effect on the concentration of nitrogen compounds in the MDMSEA lakes. Deep Hollow was the only lake to show a significant decrease in ammonium nitrogen (Table II).

Table I. Mean Physical and Chemical Data from MDMSEA Lakes Before Implementation of Best Management Practices in September 1996.

Lake	*Temp C*	*Conductivity mS/cm*	*Dissolved Oxygen mg/L*	*pH*	*Secchi cm*	*Solids Total mg/L*	*Solids Dissolved mg/L*	*Solids Suspended mg/L*
T	29.80	0.309	5.06)	7.21	11.5	505	115	405
	(2.44)	(0.127)	(2.17)	(0.39)	(8.52)	(256)	(52)	(273)
B	25.61	0.072	6.38	7.00	16.6	482	58	429
	(12.98)	(0.017)	(3.74)	(0.37)	(16.87)	(430)	(23)	(434)
DH	24.42	67.89	4.04	6.68	12.2	351	52	289
	(6.52)	(46.21)	(1.59)	(0.75)	(9.37)	(224)	(22)	(237)

Lake	*Filterable ortho-PO_4 Mg/L*	*Total P Mg/L*	*Coliform Colonies/ 100mL*	*Enterococci Colonies/ 100mL*	*NH_4 Mg/L*	*NO_3 Mg/L*	*Total Chlorophyll µg/L*
T	0.018	0.437	4593	27	0.168	1.157	9.89
	(0.021)	(0.218)	(5416)	(43)	(0.144)	(0.917)	(6.07)
B	0.032	0.496	86	7	0.123	0.534	16.56
	(0.018)	(0.301)	(86)	(16)	(0.067)	(0.617)	(26.71)
DH	0.019	0.522	863	0	0.189	0.393	24.42
	(0.062)	(0.256)	(958)	(0)	(0.144)	(0.375)	(34.70)

T= Thighman, B= Beasley, DH = Deep Hollow
Standard deviations are in parenthesis

Phosphorus

Phosphorus is typically the limiting factor in lake productivity and eutrophication *(14, 15)* and is routinely added to ponds to increase primary productivity and fish growth *(16, 17)*. Excessive amounts of phosphorus, however, may result in massive phytoplankton blooms and corresponding oxygen depletion. Boyd *(18)* reported that fertilized farm ponds in Alabama averaged 0.17 mg/L total phosphorus and 0.02 mg/L ortho-phosphate. USEPA *(12)* stated that lake or reservoir waters should not exceed 0.025 mg/L total phosphorus in order to prevent nuisance growth of plants and eutrophication. Total phosphorus in the three MDMSEA lakes prior to BMPs ranged from an average of 0.437 to 0.522 mg/L (Table I). Although these values are rather high, they are not unexpected given the relatively high phosphorus content of Mississippi Delta soils *(19)*. Decreases in total phosphorus occurred in all MDMSEA lakes following implementation of BMPs. These decreases ranged from 31 to 55% (Table II). While total phosphorus decreased, filterable ortho phosphate significantly increased on all lakes from 53 to 144%. Perhaps this increase in ortho-phosphate occurred as a result of previous phosphorus loading into the lakes.

Table II. Average Pre- and Post- BMP Water Quality Values for MDMSEA Lakes from 1996 through 1999.

	Beasley			*Deep Hollow*			*Thighman*		
Parameter	*Pre*	*Post*	*%*	*Pre*	*Post*	*%*	*Pre*	*Post*	*%*
Secchi (cm)	14	17	21	12	25	108*	11	15	36*
Total (mg/L)	482	265	-45*	351	143	-59*	505	334	-34*
Suspended (mg/L)	429	202	-53*	289	70	-76*	405	169	-58*
Dissolved (mg/L)	58	65	12	52	75	44*	115	166	44*
NO3 (mg/L)	0.534	0.553	4	0.393	0.387	-2	1.157	0.85	-27
NH3 - N (mg/L)	0.123	0.139	13	0.189	0.116	-39*	0.168	0.224	33
Total P (mg/L)	0.496	0.344	-31*	0.522	0.233	-55*	0.437	0.299	-32*
Ortho P (mg/L)	0.032	0.049	53*	0.019	0.046	142*	0.018	0.044	144*
Chlorophyll (µ/L)	16.6	118.9	616*	24.4	61	150	9.9	72.2	629*

* Indicates a significant difference (Prob. < 0.05)

Note that negative percent change indicates a decrease from pre to post conditions

Sediment and Chlorophyll

Few studies have been conducted to determine the effects of clay turbidity on warmwater fishes. Wallen *(20)* found that concentrations of suspended sediments as high as 100,000 mg/L were required for gills and opercular cavities to become clogged. However, stress related behaviors could be induced at concentrations as low as 20,000 mg/L. Wedemeyer et al. *(21)* reported that concentrations of 80-100 mg/L are considered the maximum that most species of fish can tolerate on a continual basis without causing gill damage. Longer term exposures (several months) to concentrations of 200-300 mg/L have caused bacterial tail and fin rot in salmonids, as well as pathological changes is gill structure *(22)*. While high concentrations of suspended solids rarely cause direct fish mortality, relatively low concentrations can affect lake productivity by adversely affecting light penetration *(23)*. Waters *(7)* detailed the sources, effects and control of sediment in streams and provided a summary of research on the effects of sediments on aquatic organisms.

Suspended and total solids concentrations prior to implementation of management practices were sufficiently high to consider the MDMSEA lakes sediment stressed systems. Suspended sediment concentrations exceed water quality standards established for Alaskan water reported by Lloyd *(24)*. The MDMSEA lakes also had suspended solids concentrations that were 84.2 % higher than that of Morris Pond, a 1.09 ha farm pond located in the hill lands of central Mississippi *(25)*. Annual mean suspended solids concentration was 55.0 mg/L for Morris Pond compared to 405 mg/L, 429 mg/L, and 289 mg/L respectively for Thighman, Beasley and Deep Hollow. When compared to historical turbidity data collected from Yazoo Basin lakes from 1969, the three MDMSEA lakes exceeded estimated suspended solids concentrations of all lakes with the single exception of Arkabutla Reservoir *(12, 26)*. It should be noted that this 1969 data was collected prior to the increase of intensive cultivation of soybeans in the Mississippi Delta that occurred in the 1970's, and is based on sediment-turbidity models developed by Sigler et al. *(27)*.

Cultural and edge-of-field management practices as well as combinations of the two reduced total and suspended sediments on all three MDMSEA lakes. The greatest percent reduction occurred in Deep Hollow Lake (76%), which features a combination approach to erosion control. This reduction in suspended sediment significantly improved Secchi visibility in two of the MDMSEA lakes. Prior to BMP establishment, Secchi visibility was exceptionally low averaging less than 17 cm and further supporting the contention that the MDMSEA lakes were sediment stressed. As a result of sediment reductions due to management practices, Secchi visibility increased to 25 cm on Deep Hollow Lake. This represents a 108% increase in water visibility. Secchi visibility also improved in Thighman Lake, increasing by 36%.

Cooper and Bacon *(28)* reported that primary productivity was adversely affected when suspended sediments exceeded 100 mg/L. At this concentration of suspended sediments, chlorophyll concentration was reduced to less than 20 µg/L. Cooper et al. *(29)* demonstrated that when suspended sediments were reduced through diversion of sediment-laden runoff, chlorophyll concentration doubled. Cooper and Bacon *(28)* reported mean annual suspended sediment concentrations of 117, 198, and 262 mg/L for the years 1977, 1978 and 1979, which were lower than the means for the three MDMSEA lakes. While chlorophyll concentrations were also impacted by high suspended sediments in the MDMSEA lakes, reductions in sediments due to management practices contributed to corresponding increases in chlorophyll on all MDMSEA oxbows, ranging from 150 to 629% (Figure 2).

Fisheries Evaluation

Renovation - Summary fishery characteristics prior to implementation of BMPs may be found in Table III. Fish species identified in the rotenone sampling were typical of oxbow lake fauna *(30)*. By number, gizzard shad (*Dorosoma cepedianum*), white crappie (*Pomoxis annularis*) and bluegill (*Lepomis macrochirus*) were the dominant species in Thighman Lake while white crappie, mosquito fish (*Gambusia affinis*) and gizzard shad where most abundant in Deep Hollow. White crappie, gizzard shad and madtom catfish (*Noturus gyrinus*) were numerically dominant species in Beasley Lake. Species richness was relatively low for all three MDMSEA lakes even though Mississippi is home to over 300 species of freshwater fishes *(30)*.

Table III. Fisheries Characteristics of MDMSEA Lakes Prior to Implementation of Best Management Practices

	Thighman	*Deep Hollow*	*Beasley*
Catch (kg)	157	163	85
Number	2139	1473	886
Number of Species	17	21	15
Kg/ha	282	292	152

By weight, gar (*Lepisosteus sp.*), common carp (*Cyprinus carpio*), white crappie and paddlefish (*Polyodon spathula*) were important in all MDMSEA lakes. Deep Hollow Lake had the greatest standing stock at 292 kg/ha, followed by Thighman with 282 kg/ha and Beasley with 152 kg/ha. These standing stocks roughly fall within the ranges reported in the literature for various natural and unfertilized man-made lakes. Swingle and Smith *(31, 32)* reported 168 to 337 kg/ha for bass bluegill ponds in Alabama. Carlander *(33)* reported natural lakes ranging from 196 to 1010 kg/ha. Cooper et al. *(34)* reported that standing

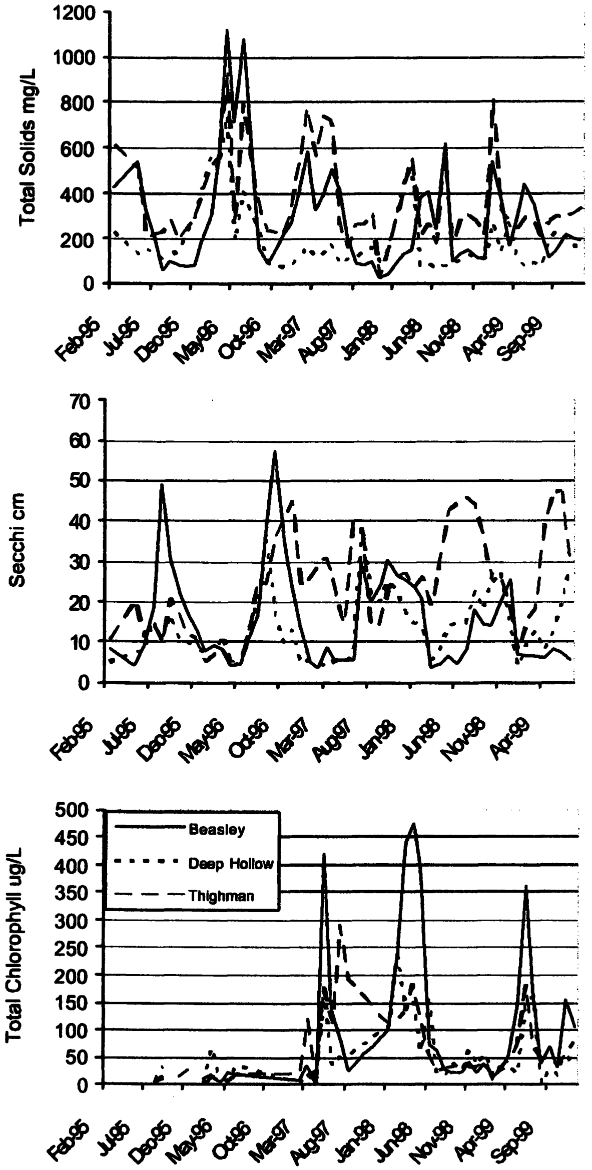

Figure 2. Monthly mean total solids, Secchi visibility, and total chlorophyll for MDMSEA Lakes from 1996 though 1999. Vertical lines indicate implementation of BMPs.

stocks in natural lakes ranged from 56 to 168 kg/ha while artificial ponds ranged from 224 to 499 kg/ha. Ponds in Oklahoma ranged from 64 to 1045 kg/ha with a mean of 383 kg/ha *(35)*. Carlander and Moorman (*36*) reported standing stocks of 1246 kg/ha in flood plain ponds in Illinois and 31 to 1386 kg/ha in Iowa. While the standing stock is in agreement with those reported in the literature much of the weight of fish from the MDMSEA lakes is made up of undesirable species such as gizzard shad, various species of gar (*Lepisosteus sp.*) and common carp.

Sports fishes were generally poorly represented with the exception of white crappie in all of the lakes and channel catfish (*Ictalurus punctatus*) in Thighman Lake. No largemouth bass were collected from Beasley or Thighman lakes. Catfish production ponds located nearby and draining into Thighman Lake may account for the number of channel catfish found in that oxbow. While all three lakes support large numbers of the popular game fish, white crappie, these fish were typically small averaging 19 to 29 grams.

First year fishery surveys evaluating BMPs for improving the water quality and fisheries of oxbow lakes indicate successful renovation of the two lakes with the greatest improvement in water quality. Monitoring of the three lakes shows little or no change in the water quality of Beasley Lake, but a marked improvement in Thighman and Deep Hollow. Fish numbers in Thighman Lake, which was treated with agronomic based BMPs, and Deep Hollow Lake affected by edge-of-field and agronomic BMPs, showed increasing populations (Figure 3).

Summary

This study examined and documented pre-management water quality and fisheries conditions on three oxbow lakes and resulting changes following the implementation of Best Management Practices. Analyses of water quality prior to the implementation of management practices indicated lakes that were stressed and ecologically damaged due to excessive in-flowing sediment. Mean total suspended sediment concentrations for the three MDMSEA lakes exceeded concentrations estimated for regional lakes in 1969 as well as levels acceptable for fish growth and health *(21, 26)*. Because all MDMSEA lakes had low concentrations of chlorophyll despite relatively high concentrations of phosphorus, it is reasonable to assume that high concentrations of suspended solid likely suppressed phytoplankton production. This conclusion was further supported by the fact that Deep Hollow Lake had the highest mean concentration of chlorophyll of the three lakes as well as the lowest mean concentration of suspended sediment. Reducing suspended sediment concentrations by using best management practices produces more favorable conditions for phytoplankton production as indicated by the increased water visibility and chlorophyll production.

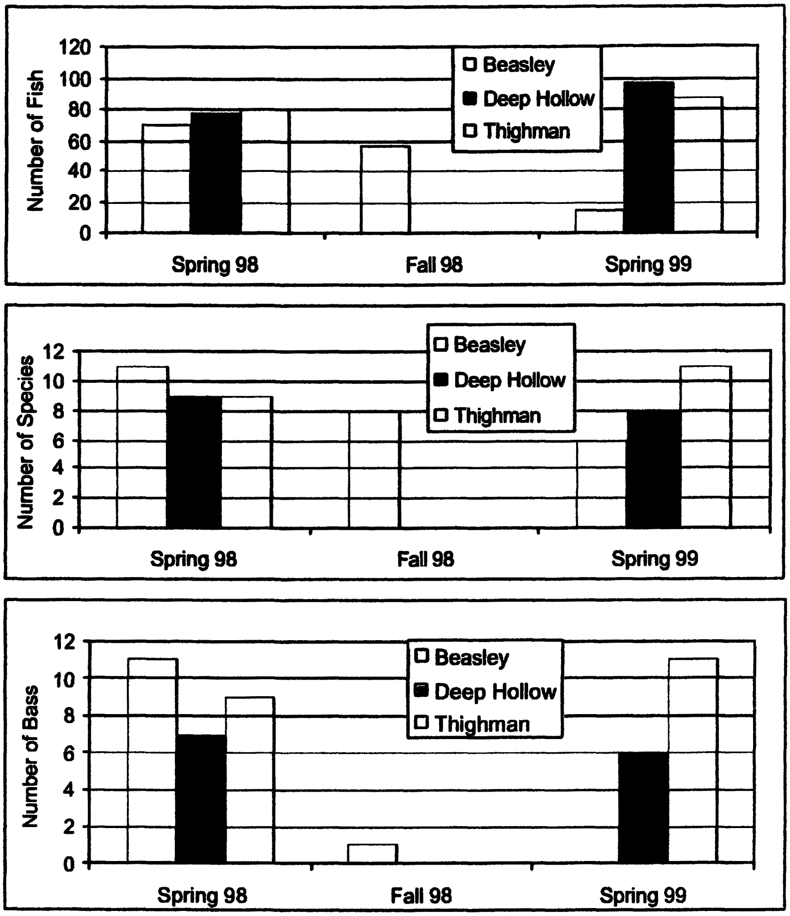

Figure 3. Number of fish, species and largemouth bass (Micropterus salmoides) from electrofishing catches from MDMSEA lakes following lake renovation.

Fish species identified in the rotenone sampling were typical of oxbow lake fauna (*30*). Species richness was relatively low for all three MDMSEA lakes. Deep Hollow Lake had the greatest standing stock followed by Thighman and Beasley. Standing stocks roughly fell within the ranges reported in the literature for various natural and unfertilized man-made lakes. While the standing stock is in agreement with those reported in the literature (*31, 32, 33, 35, 36*), much of the weight of fish from the MDMSEA lakes was made up of undesirable species such as gizzard shad, various species of gar (*Lepisosteus* sp.) and common carp.

Sports fishes were generally poorly represented with the exception of white crappie in all of the lakes and channel catfish (*Ictalurus punctatus*) in Thighman Lake. No largemouth bass were collected from Beasley or Thighman lakes.

Post-BMP fishery surveys indicated successful renovation of lakes protected with agronomic or edge-of-field and agronomic practices. While all three lakes demonstrated improved water quality, the most significant improvements occurred when agronomic (Thighman) or combinations of agronomic and edge-of-field practices (Deep Hollow) were used. Following renovation, fish catches and diversity were highest in Thighman and Deep Hollow lakes while Beasley lake showed a decline in both standing stock and diversity. Bass populations lacking in two of the lakes before renovation and restocking were successfully re-established in Deep Hollow and Thighman. In all likelihood, restocking in Beasley Lake failed due to continuing poor water quality despite the presence of edge-of-field BMPs. Land and farm management practices designed to control erosion and reduce transport of soil, organic matter, and agricultural chemicals have been shown to improve water quality. Results indicated that agronomic BMPs may play the more vital role in improving lake water quality and may be needed in addition to edge-of-field measures to ensure improved fisheries in oxbow lakes receiving agricultural runoff.

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Chapter 10

Dynamics of Herbicide Concentrations in Mississippi Delta Oxbow Lakes and the Role of Planktonic Microorganisms in Herbicide Metabolism

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The small oxbow lakes central to the Mississippi Delta MSEA project provided a model system for evaluating the effects of watershed management and cropping practices on the dynamics of herbicide concentrations and planktonic populations. In 1996 and 1997, cotton was planted in about 50% of the area of three watersheds, and maximum fluometuron concentrations of 5.7, 5.0 and 12.4 μg L^{-1} were observed in Beasley, Deep Hollow and Thighman lake water samples, respectively. The metabolite desmethyl fluometuron was present in all lakes (2.0 to 4.0 μg L^{-1}). In 1998, significant areas of Beasley and Thighman watersheds were planted in corn. Maximum concentrations of atrazine and metolachlor observed in Thighman lake water in 1998 were 15.0 and 7.2 μg L^{-1}, respectively, occurring in May. In Beasley Lake, maximum water concentrations of atrazine and metolachlor were 2.5 and 1.8 μg L^{-1}, respectively, occurring in late summer. Although differences in herbicide dissipation in the lakes may be partly explained by hydrology, cropping and management practices, the microbiological characteristics of the lake also need to be considered. Differences in planktonic populations and activity were observed among the lakes, e.g., Thighman Lake had the highest enzymatic activity and bacterioplankton populations, and Beasley the lowest.

In Water Quality Assessments in the Mississippi Delta; Nett, M., et al.;
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Typically, the lowest suspended solids and the highest algal populations were found in Deep Hollow Lake during the rainy season, when the other lakes were sediment stressed. Certain algae have the potential for metabolism of atrazine and fluometuron via *N*-dealkylation. Laboratory studies indicated increased rates of fluometuron degradation when lake water samples were inoculated with the algae *Selenastrum capricornatum*, demonstrating the contribution of certain algae in herbicide metabolism.

Crop production in the Mississippi Delta region is highly dependent upon agrochemical use, thus non-point contamination of surface waters by herbicides is an environmental concern. In recent years, cropping systems and agrochemical use in this region have undergone dramatic changes. Understanding the relationship between crop management practices, pesticide use and maintenance of surface water quality is an important component of environmental stewardship, and a major objective of the Mississippi Delta Management System Evaluation Area (MDMSEA) project.

The occurrence and magnitude of herbicide concentrations observed in surface waters of the corn- and soybean-producing areas of the Midwestern U.S. have been well documented (*1-6*). The herbicides alachlor, atrazine, cyanazine, metolachlor and their respective metabolites are commonly observed in surface waters of this region and subsequently these contaminants drain into the Mississippi River system. By contrast, only limited studies have critically assessed the occurrence of herbicides in the Mississippi Delta region. A three-year survey of four Eastern Arkansas counties demonstrated that metolachlor, atrazine, norflurazon and cyanazine were observed in 7 to 13% of the samples (*7*). The occurrence of cotton and rice herbicides were studied in three Mississippi Delta streams (*8*); total concentrations of all pesticides exceeded 5 $\mu g\ L^{-1}$ with the order of occurrence molinate > fluometuron > cyanazine > metolachlor > norflurazon > atrazine > prometryn > propanil.

Oxbow lakes are common in the Mississippi Delta landscape. These water bodies are often used for recreational purposes (fishing and boating) and are important in wildlife habitat management. Despite the abundance of oxbow lakes in the Mississippi Delta landscape, little is known about the occurrence of pesticides in these water bodies and about their associated planktonic communities. The studies presented in this paper have been conducted with the following objectives:

- To characterize patterns of herbicide dynamics and planktonic populations in the MDMSEA oxbow lakes and evaluate the relationship to BMPs practiced in the watersheds.

- To ascertain the role of planktonic communities in herbicide transformations. Initial studies focused on the occurrence of the herbicide fluometuron that is traditionally applied at cotton planting. With changing cropping patterns in the MDMSEA watersheds the research scope was broadened to also study herbicides applied to corn, specifically, atrazine and metolachlor.

Materials and Methods

Herbicide Assessments

The management practices, characteristics and maps of the watersheds of the three oxbow lakes studied, Beasley, Deep Hollow, and Thighman, are described in the overview chapter in this volume (*Chapter by Locke*). Surface water samples were collected monthly from triplicate permanent sampling rafts located in each of the three oxbow lakes as described elsewhere (*Chapter by Knight, this volume*). Samples were refrigerated immediately and stored at 5° C until processing, typically within 24 h. Water samples (a total of 500 mL) were centrifuged in 250 mL polypropylene centrifuge bottles (10 min 6,000 g). The supernatant was decanted into glass bottles and acidified with 1 N HCl to a pH of 3.0, and the pellets dried at 60° C for 24 h for determination of suspended solids. The acidified water samples were concentrated by passing through a 47 mm C-18 Empore® disc (3-M, distributed by Varian Instruments), thereafter herbicides and metabolites were eluted with 20 mL of ethyl acetate (*9*). Residual water was removed from the ethyl acetate by addition of 1.0 g anhydrous sodium sulfate and the volume reduced to 2.0 ml under N_2 gas. Fluometuron and its metabolites (desmethyl fluometuron [DMF], trifluoromethylphenylurea [TFMPU], and trifluoromethylaniline [TFMA] were determined by high pressure liquid chromatography (HPLC) with fluorescence detection as described elsewhere (*10*). Water samples collected in 1998 were analyzed for atrazine, cyanazine, de-ethyl atrazine [DEA], de-isopropyl atrazine [DIA], and metolachlor by gas chromatography/ion trap mass spectrophotometry. Gas chromatographic conditions, such as column type, temperature program, He flow rates, and injector type and settings were similar to that described by Thurman et al. (*11*). Ion trap mass spectroscopy was run in the selective storage mode to provide sensitivity in the low parts per trillion (ppt) range for all analytes. Efficiency of recovery of spiked herbicides and that of a surrogate (tetrabutylazine) from lake water samples from all three lakes was about 85% or greater using the Empore discs. As lower levels of fluometuron were observed in later years, fluometuron concentrations in 1998 and 1999 samples were confirmed by enzyme linked immunoabsorbant assays [ELISA] (*12*) using commercial kits (EnviroLogix Inc., Portland, ME) in addition to HPLC analysis.

Microbiological Assessment of Lake Quality

Bacterioplankton populations (total heterotrophic bacteria, gram-negative bacteria and fluorescent pseudomonads) were assayed by serial dilution and spiral plating as described elsewhere (*13*). Algal populations were estimated using a most-probable-number (MPN) technique using five replicate tubes and Bristol's mineral salts broth as media (*14*). Heterotrophic biological activity of water samples was assessed by determining fluorescein diacetate (FDA) hydrolytic activity (*13*).

Algal Herbicide *N*-Dealkylation

Laboratory incubation studies using ^{14}C-labeled herbicides were conducted to ascertain the role of green algae in the metabolism of atrazine and fluometuron, using *Selenastrum capricornatum* as a model system, because of its relatively high fluometuron and atrazine dealkylating activity. Eight tubes containing *S. capricornatum* cell suspensions (two mL of 10^7 cells mL^{-1} in Bristols media) were treated with 15 μM of either ^{14}C-atrazine or ^{14}C-fluometuron. Four replicate tubes of cells treated with ^{14}C-atrazine (1.07 kBq mL^{-1}) also received 15 μM of unlabeled fluometuron and four replicate tubes treated with ^{14}C-fluometuron (0.62 kBq mL^{-1}) received 15 μM of unlabeled atrazine. Two uninoculated controls were included for each of the four herbicide treatments. Tubes were incubated on an illuminated shaking incubator (25 μEinsteins m^{-1} s^{-1}, 24° C, 100 rpm). Aliquots (250 μL) were removed every 24 h over a 72 h incubation, extracted with 750 μL of acetone and analyzed for the corresponding herbicides and metabolites using radiological thin layer chromatography methods described elsewhere (*10*).

A second study evaluated degradation of ^{14}C-fluometuron in lake water collected from Deep Hollow and Thighman Lakes and the effects of augmenting with *S. capricornatum*. Lake water (60 mL, collected February 1999, prior to herbicide application) was added to sterile 250-mL flasks, and ^{14}C-fluometuron (73 Bq mL^{-1}) was added to attain a concentration of 180 nmole L^{-1}. No residual fluometuron (< 0.2 ppb) was detected via HPLC or ELISA in these water samples at initiation of the experiment. Three flasks from each lake were inoculated with *S. capricornatum* (2.5 mL log 7.5 cells mL^{-1}), or treated with 2.5 mL of Bristol's media and were incubated under static conditions (25 μEinsteins m^{-1} s^{-1}, 24°C). Aliquots (6 mL) were removed periodically (3 to 8 d), acidified to pH 3.0 with HCl, and phase partitioned twice with 6 mL of ethyl acetate. Radioactivity in aqueous and ethyl acetate fractions was determined, and the ethyl acetate was concentrated and analyzed by radiological thin layer chromatography. Algal populations in water samples were estimated at initiation and termination of the study using the MPN technique previously described.

Results and Discussion

Occurrence of Fluometuron In Lake Water

Fluometuron was detected in all three lakes during the 1996 and 1997 growing seasons (Table I), with the highest concentrations observed in Thighman Lake. The highest fluometuron concentrations were typically observed in June, one to two months after cotton planting. The fluometuron metabolite, DMF, also was found in all three lakes when fluometuron was detected (data only shown for 1997, Figures 1a-c). In 1998 and 1999, corn was planted on most of Thighman watershed previously planted to cotton and little fluometuron was applied to this watershed. Thus, limited detections of fluometuron or DMF (<0.1 μg L^{-1}) were observed in Thighman Lake water during these years. In Beasley watershed, corn replaced cotton on about 30% of the crop land in 1998, and maximum concentrations of fluometuron were about half that observed in 1996 and 1997. During 1998 and 1999, rainfall in the Delta during June and July was about 40% that of 1996 and 1997, which resulted in substantially reduced runoff. However, during 1998 and 1999, lower maximum fluometuron concentrations and less frequent detections were observed in water samples from Deep Hollow Lake compared to Beasley Lake, even though a similar percentage of the total watershed was planted in cotton in each watershed. The reduced fluometuron levels in Deep Hollow Lake may he attributed to the intensive best management practices e.g., reduced tillage and winter wheat cover crop that were implemented at the Deep Hollow watershed.

Table I. Maximum Fluometuron Concentrations Observed in the Three MDMSEA Oxbow Lakes, 1996 to 1999.

Year	*Beasley*	*Deep Hollow*	*Thighman*
	μg L^{-1}	*μg L^{-1}*	*μg L^{-1}*
1996	2.6 ± 2.2[a]	1.4 ± 0.8	12.4 ± 7.6
1997	5.7 ± 3.4	5.0 ± 0.6	11.2 ± 8.9
1998	1.6 ± 1.2	0.4 ± 0.1	< 0.1
1999	2.8 ± 0.6	1.2 ± 0.8	< 0.1

NOTE: Measurements are mean and standard deviation of three replicates

The seasonal dynamics of fluometuron and DMF concentrations for the three MDMSEA lakes in 1997 are presented in Figures 1a-c. In Thighman Lake, relatively high levels of fluometuron (11.2 μg L^{-1}) were observed in the June sample (about two months after planting) coinciding with the maximum level of DMF detected. By July, concentrations of fluometuron and DMF were about 80% lower than that found in June. In Beasley and Deep Hollow Lakes, lower concentrations of fluometuron were observed, with both fluometuron and DMF

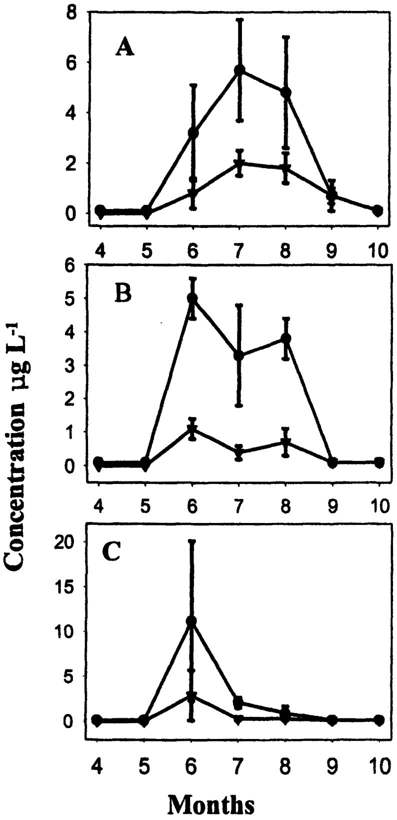

Figure 1. Fluometuron (●) and desmethyl fluometuron (θ) concentrations observed in Beasley Lake (A), Deep Hollow Lake (B), and Thighman Lake (C) in 1997, mean and standard deviation of three replicate samples per occasion.

being relatively more persistent in those lakes compared to Thighman Lake. The accumulation and persistence of DMF in Beasley and Deep Hollow Lakes suggests that *in situ* fluometuron degradation may have occurred in lake water. No other fluometuron metabolite, e.g., TFMPU or trifluoromethylaniline (TFMA) was observed in any water sample during this study. Studies by others have shown that TFMA but not TFMPU occurring in water samples from the Mississippi Delta (*8*) and Texas Playa lakes (*15*) where fluometuron was used in the watersheds. Patterns of fluometuron and DMF occurrence and dissipation in Beasley and Deep Hollow Lakes were similar to that described in the Mississippi Big Sunflower River (*8*).

Occurrence of Other Herbicides in Lake Water

As limited detections of fluometuron were observed in lake water samples in 1998, water samples were analyzed via GC/MS for other herbicides. The herbicides atrazine and metolachlor were applied to corn planted in Beasley and Thighman watersheds, and different patterns of accumulation and persistence of these herbicides were observed in Thighman compared to Beasley lake samples. Within a month following corn planting, peak concentrations were observed in Thighman Lake in May (Figure 2b). In Beasley Lake, peak concentrations of atrazine were observed in September (Figure 2a). The dealkylated metabolite, de-ethyl atrazine (DEA), accumulated in higher proportions to atrazine in Beasley Lake compared to Thighman Lake, suggesting that *in situ* degradation was perhaps occurring in the former. The second dealkylated metabolite, de-isopropyl atrazine (DIA), was also found in both lakes coincident with peak atrazine/DEA concentrations. Concentrations of DIA however were about 20 to 25% that of DEA (less than 0.4 µg L^{-1}). Atrazine concentration in Thighman Lake exceeded the Maximum Concentration Load (MCL) of 3 µg L'1 for

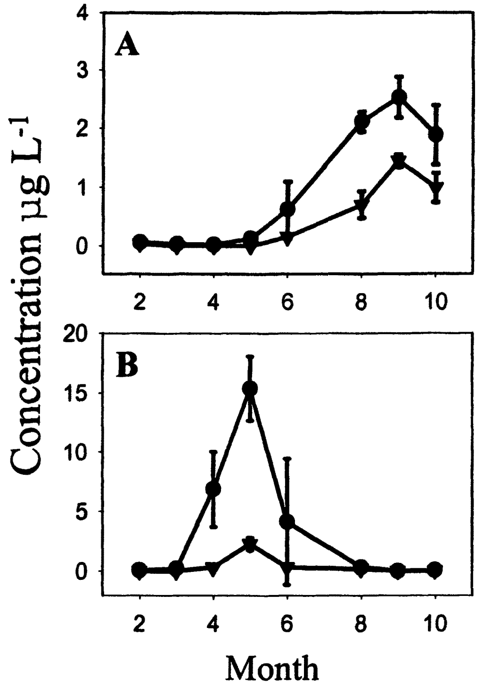

Figure 2. Atrazine (●) and de-ethyl atrazine (θ) concentrations observed in Beasley Lake (A) and Thighman Lake (B) in 1998, mean and standard deviation of three replicate samples per occasion.

drinking water set by the EPA (*16*), and Canadian water quality standards of 2 µg L^{-1} (*17*) for three months during the growing season. Levels of atrazine observed in Thighman Lake were greater than those reported in several Mississippi Delta streams (*8*), however concentrations are similar to those reported in the Midwest (*1-6*).

Metolachlor was applied at the same time as atrazine in the watersheds, and the dynamics of metolachlor appearance and dissipation followed the same dynamics as atrazine in Beasley and Thighman Lakes (Figure 3). Neither atrazine nor metolachlor were applied in Deep Hollow watershed, and neither was detected in water samples from Deep Hollow Lake. In Beasley Lake watershed, atrazine and metolachlor were incorporated in the soil, while they were surface applied in Thighman Lake watershed. This may have been one factor for delayed peak appearance in Beasley water samples. Studies on a small Pennsylvania watershed indicated that when atrazine was incorporated, its transport was reduced by about 50% (*18*). The presence of vegetative filter strips in Beasley watershed may have also temporarily impeded movement of both herbicides. The nature of the water flow through Thighman Lake suggests that hydrological characteristics were responsible for rapid flushing of atrazine, fluometuron and metolachlor following peak periods of run off, while Beasley Lake was a closed system, retaining herbicides that entered this system.

Cyanazine was applied at planting to corn and postemergence directed to cotton later in the growing season, so the cotton can avoid injury. In 1998, maximum concentrations of cyanazine were observed in August and September in water samples collected from Beasley and Deep Hollow Lakes, while maximum but much lower concentrations were observed in Thighman Lake in April corresponding with application to corn (Figure 4). Cyanazine

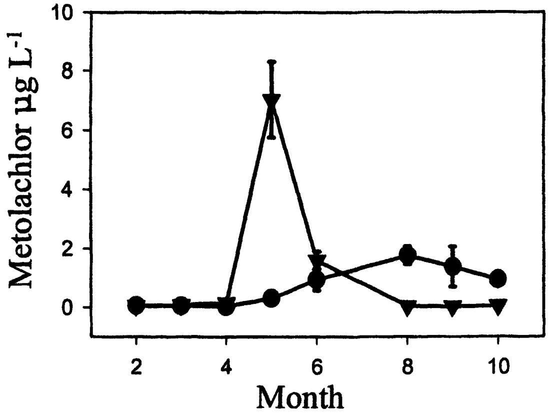

Figure 3. Metolachlor occurrence in Beasley (●) and Thighman (π) Lakes during 1998, mean and standard deviation of three replicate samples per occasion.

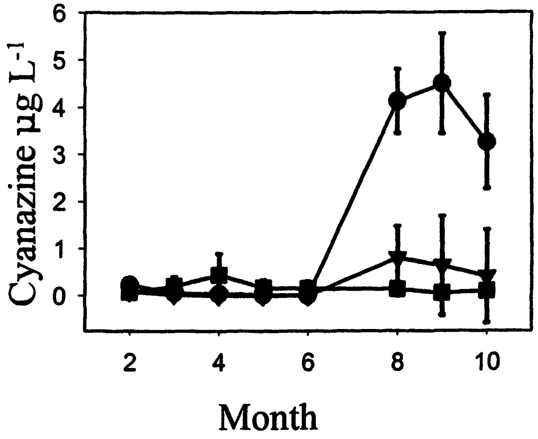

Figure 4. Occurrence of cyanazine in Beasley (●), Deep Hollow (π) and Thighman (■) Lakes, 1998, mean and standard deviation of three replicate samples per occasion.

concentrations detected in Beasley Lake were five-fold higher than in Deep Hollow Lake, although applied to a similar percentage of the watershed, indicating that filter strips and other edge of field practices alone were not effective in reducing cyanazine movement into the lake water. Lower cyanazine concentrations found in Deep Hollow Lake compared to Beasley Lake suggest that the conservation management practices (reduced tillage and cover crop) were successful in minimizing runoff of this herbicide.

Microbiological Characteristics of Lake Quality

Seasonal dynamics of suspended solids and FDA hydrolytic activity within the three lakes from January 1997 to July 1999 are summarized in Figures 5a and b. Maximum suspended solids were observed from January to June, corresponding with maximum precipitation and runoff. Relative levels of suspended solids observed in Deep Hollow during the rainy seasons ranged from 6 to 45% of suspended solids found in Beasley and Thighman Lakes. This dramatic reduction in suspended solids indicates that the combination of agronomic (reduced tillage and winter cover crop) and edge of field best management practices (filter strips and structural BMPs) used in Deep Hollow Lake watershed were effective in reducing runoff of sediment. Even though Beasley Lake watershed implemented edge of field BMPs, these alone were not effective in reducing sediment loss to the lake. The observations confirm other reports (*Chapter by Knight, this volume*) that both Beasley and Thighman Lakes were still sediment stressed.

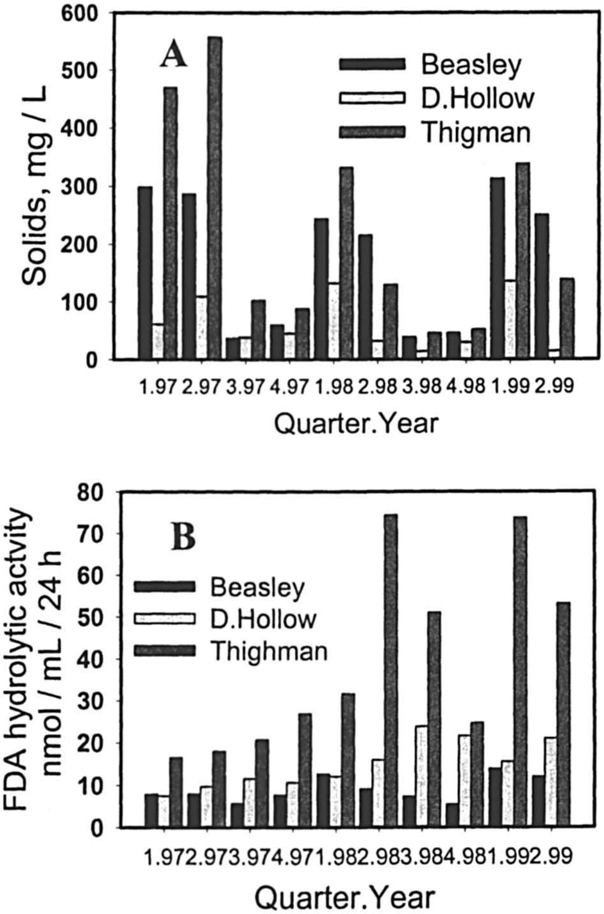

Figure 5. Quarterly mean suspended solids (A) and fluorescein diacetate hydrolytic activity (B) of the three MDMSEA oxbow lakes, 1997 to 1999.

Over the study period, levels of FDA activity were greatest in Thighman Lake, intermediate in Deep Hollow and lowest in Beasley Lake (Figure 5b). A 1996 assessment of these lakes did not show these differences in FDA activity (*13*). Seasonal populations of total heterotrophic bacteria, gram-negative bacteria and algae are presented in Figures 6a to 6c. No consistent seasonal pattern of total heterotrophic bacteria or gram-negative bacteria was obvious during this study. Overall, Thighman Lake typically maintained the highest bacterioplankton populations compared to the other lakes, corresponding with higher rates of FDA activity. Thighman watershed was the only MDMSEA watershed with catfish ponds. The catfish ponds may have contributed carbon,

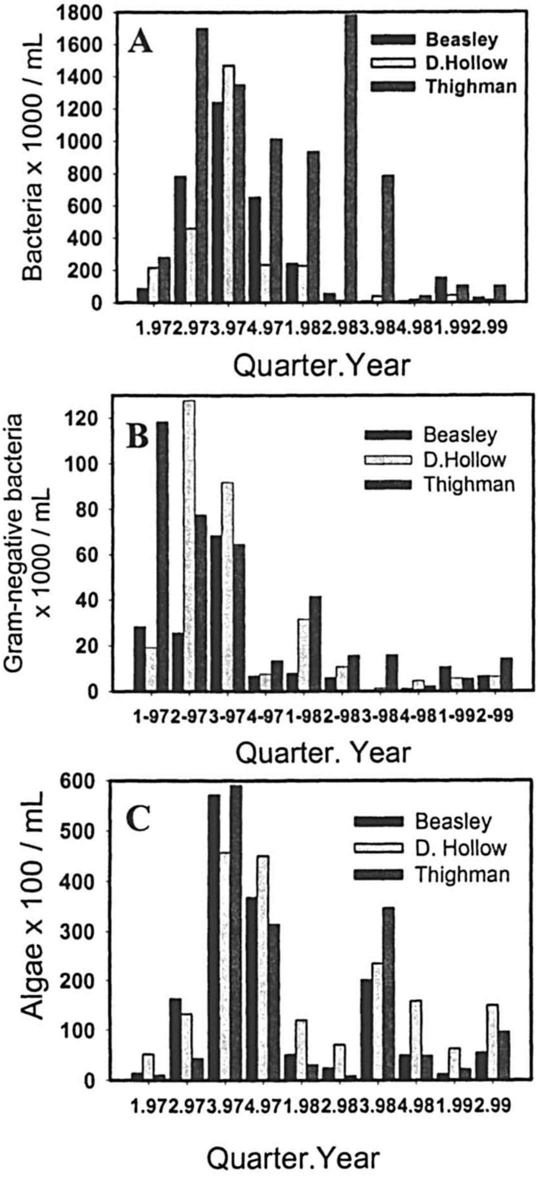

Figure 6. Quarterly total bacterioplankton (A), Gram-negative bacterioplankton (B) and (algal (C) population dynamics in three MDMSEA oxbow lakes 1997 to 1999.

nutrients and bacterial loading into this lake that might result in the higher populations of heterotrophic bacteria and subsequent FDA activity observed. In 1996, gram-negative bacteria, especially fluorescent pseudomonads, were a more abundant component of the bacterioplanktonic population in all three lakes (*13*). The highest density of algal populations occurred in late summer early fall corresponding with the warmest water temperatures. During periods of highest sediment load (winter and spring), Deep Hollow Lake typically maintained the highest algal populations, coinciding with the lowest levels of suspended solids. Thighman Lake has been shown to support the best establishment of introduced sports fish (*Chapter by Knight, this volume*). The productivity of Thighman Lake corresponds with certain biological indicators of lake productivity, e.g., highest levels of FDA activity and bacterial populations, although not evident in green algal populations. Herbicide biotransformations, especially co-metabolic transformations, are mediated by the magnitude, composition and activity of the indigenous microbial community. Based upon enzymatic FDA activity as an indicator of co-metabolic activity, Thighman Lake should support the highest level of herbicide degradation, Deep Hollow Lake intermediate and Beasley the least conducive, although not evident from these field assessments.

Planktonic Herbicide Transformations

There are many gaps in scientific assumptions that consider the toxicity of herbicides and other xenobiotics to aquatic organisms. The sensitivity of the planktonic community to various herbicides such as atrazine (*17, 19*) and fluometuron (*20, 21*) has been well established. The role of various terrestrial bacteria and fungi in the metabolism of herbicides in soil has been well characterized (*22, 23*). Although algae are dominant components of the aquatic microflora, the contribution of these planktonic organisms in aquatic herbicide metabolism is poorly understood.

Previous investigations assessed the potential of fifteen green algae and two cyanobacteria cultures to metabolize fluometuron (*10*). As summarized in Table II, seven of fifteen green algae strains studied transformed fluometuron to the *N*-demethylated metabolite desmethyl fluometuron. The highest activity was found in two genera, *Ankistrodesmus* and *Selenastrum*, with lower levels of activity observed in strains of *Chlorella* and *Pediastrum*. One of these fluometuron-metabolizing algal strains (*Ankistrodesmus nannoselene*) was isolated from Deep Hollow Lake. The dominant genera of green algae observed in the MDMSEA lakes is *Chlorella* (unpublished data), typically associated with disturbed, sediment stressed lakes. Of the *Chlorella* isolates tested either low of no fluometuron de-methylating activity was observed. These studies also demonstrated that algal strains that demethylated fluometuron were also capable of dealkylating atrazine with the ethyl group preferentially removed (*10*).

Table II. Fluometuron *N*-demethylation Activity in Cell Suspensions of Various Genera of Green Algae and Cyanobacteria.

Genus	*Strains tested*	*Activity nmol desmethyl fluometuron formed 24 h⁻¹*
Ankistrodesmus	2	2.2 - 2.4
Anabaena	1	< 0.1
Chlorella	4	< 0.1 – 0.2
Chlamydomonas	1	< 0.1
Oscillatoria	1	< 0.1
Pediastrum	1	0.4
Scenedesmus	2	< 0.1
Selenastrum	3	1.6 – 1.8
Spirogyra	1	< 0.1

NOTE: Data summarized from reference 12.

As both atrazine and fluometuron were applied in the MDMSEA watersheds, laboratory studies were conducted to assess the ability of *S. capricornatum* to transform atrazine and fluometuron when both herbicides were present (Table III). Similar levels of fluometuron demethylation were observed in the presence or absence of atrazine. Atrazine de-ethylation activity in this study was about 30% that of fluometuron demethylation activity, and a 70% reduction of atrazine dealkylation activity was observed in the presence of fluometuron. These studies indicate that when mixtures of the two herbicides were present fluometuron was preferentially metabolized by *S. capricornatum* versus atrazine. Although atrazine is considered algistatitic to *S. capricornatum* (*17, 19*), the potential of this species amid others to detoxify this and other herbicides needs to be considered in ecotoxicity studies.

Table III. Atrazine and Fluometuron *N*-dealkylation by *Selenastrum capricornatum* When Applied Alone or in Combination During a 72 h Incubation.

Treatment	*^{14}C-De-ethylatrazine*	*^{14}C-Desmethyl fluometuron nmol formed*
^{14}C-atrazine	1.4 ± 0.3	
^{14}C-atrazine + fluometuron	0.4 ± 0.1	
^{14}C-fluometuron		4.8 ± 1.8
^{14}C-fluometuron + atrazine		3.9 ± 2.0

Mean and standard deviation of four replicates

In the laboratory incubation study, minimal degradation of fluometuron occurred in non-inoculated lake water from either Deep Hallow or Thighman Lakes during a 28-d laboratory incubation (Figures 6 a and b), with only 3% of the radioactivity recovered as DMF. In this radiological laboratory study the concentration used (180 nM) is equivalent to 41 μ L^{-1}, several fold greater than maximum lake concentrations of fluometuron observed in the field. Augmentation of water with log 6.2 cells of *S. capricornatum* resulted in decreased ethyl acetate-extractable ^{14}C-fluometuron, with a corresponding increase in DMF. Ethyl acetate recovered greater than 98% of the initial radioactivity added from non-inoculated lake water throughout the study, while at the termination of the study about 90% was recovered from water inoculated with *S. capricornatum* (data not shown). The second demethylated metabolite, TFMPU, was only observed in augmented water from Thighman Lake (5% extractable radioactivity).

During the initial two weeks of incubation, there was a loss of chlorophyll from lake water augmented with *S. capricornatum*. Fluometuron herbicidal mode of action in plants is inhibition of photosynthesis II electron transport, which results in loss of chlorophyll amid other pigments (*24*). Fluometuron has been shown to cause a loss of chlorophyll in the algae *Chlorella vulgaris* and *Chlorococcum humicola* (*20, 21*), however, concentrations that inhibit chlorophyll accumulation were much higher than that used in the present study. Algal populations were initially log 6.4 cells mL^{-1} in augmented lake water samples and declined to about log 5.2 cells mL^{-1} at the termination of the study. Algal populations in non-inoculated lake water did not change during the study (about log 4.6 cells mL^{-1}). Predation by protozoa amid other zooplankton may have been responsible for the decline in algal population of the introduced *S. capricornatum* in inoculated water samples. Relative rates of fluometuron degradation observed in these studies using natural water samples, were similar to pure culture studies when low inoculum densities of *S. capricornatum* (*10*). These studies of atrazine amid fluometuron metabolism demonstrate the ability of certain green algae to transform herbicides commonly used in the Mississippi Delta.

Studies presented here describe the dissipation of herbicides in laboratory or microcosm systems, amid attempts to demonstrate the role of specific planktonic organisms using augmentation with pure cultures. Microbial pesticide transformations typically occur via activity of a consortium of microorganisms, thus more research needs to be conducted towards assessing the role of the total planktonic community. Molecular biology tools, e.g., reverse transcriptase polymerase chain reaction, offer the potential for studying *in situ* gene expression of pesticide metabolizing enzymes. Future assessments using these techniques may aid in defining the role of planktonic communities in metabolizing xenobiotics under natural conditions.

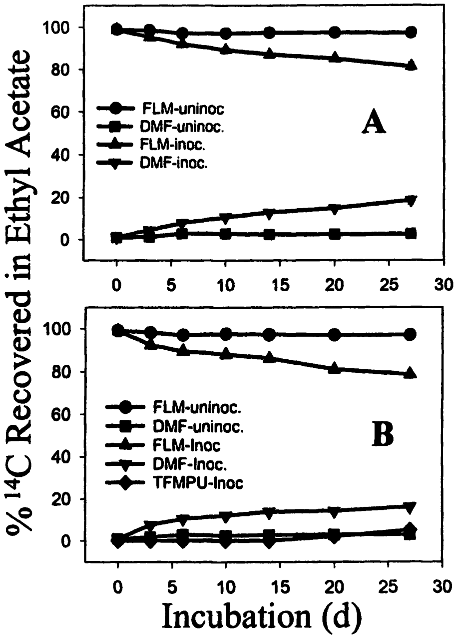

Figure 7. Degradation of ^{14}C-ring labeled fluometuron in water from Deep Hollow (A) and Thighman (B) Lakes as affected by inoculation with log 6.2 cells of S. capricornatum; mean of three replicates.

Acknowledgments

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Chapter 11

Precision Farming Technologies for Weed Control in the Mississippi Delta

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Studies were conducted to evaluate two precision farming technologies for weed control in a Mississippi Delta Management Systems Evaluation Area (MDMSEA) watershed. A sensor-controlled hooded sprayer that utilized spectral reflectance type sensors to detect and spray only where weeds were present was evaluated for three years in the Deep Hollow Lake watershed. The sensor-controlled sprayer provided adequate weed control and resulted in 3-year average reductions in pesticide usage of 73% and 49%, respectively for cotton (43 ha) and soybeans (47 ha). Additionally, evaluation of global positioning systems (GPS) and geographical information systems (GIS) for weed mapping confirmed that significant reductions in herbicide usage could be obtained with this technology. The geo-referenced maps indicated that weeds generally occur sporadically over a field and that prescription application of herbicides could be used with GPS-controlled applicators to treat only those specific areas where weeds had germinated in the fields.

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Introduction

Water quality and other environmental concerns associated with pesticide application have increased tremendously during recent years. These concerns have prompted investigations to identify the effects of current agricultural practices on the environment, to develop more efficient crop production management practices, and to develop environmentally sound methods of applying pesticides.

Herbicides are used annually in row-crop production systems to control weeds that would otherwise interfere with crop growth, causing significant yield and quality losses. Cotton production across the U.S. Cotton Belt has reported annual losses of $188 million due to weeds (*1*). Other crops have also experienced significant losses due to weeds. These significant losses in crop yield and quality due to weed infestations have motivated producers to apply herbicides annually. The normal practice for herbicide management is to apply herbicide uniformly over an entire field when specific pest threshold levels are met. The threshold level may vary with each individual producer, depending on the management strategy. In most cases, herbicide is applied to the entire field even though weeds may only be present in a small portion of the field. Studies have shown that weeds are normally not evenly distributed but occur sporadically over the field (*2, 3, 4, 5*). Although the concept of applying herbicide over an entire field has provided adequate weed control, significant amounts of herbicide are wasted and the excess herbicide increases the potential for environmental contamination.

An early attempt at reducing herbicide usage was through development of the concept of applying herbicides in narrow bands only on the crop row rather than broadcasting the applications over an entire field. The concept of banding herbicides was initiated with pre-emergence type herbicides (applied before the crop emerges) that were typically applied through nozzles attached to the planter, centered directly above each planted row. As seeds were planted into the soil, pre-emergence herbicide was dispensed through each nozzle in a narrow band where the crop would emerge. The concept of applying herbicides in narrow bands was broadened through development of post-emergence applicators for directed spray underneath the crop leaf canopy to control small emerging weeds. These concepts significantly reduced the amount of herbicide used and provided the crop with needed protection from weeds.

Mechanical cultivation was initially used to remove weeds between the crop rows or between the bands of herbicide. As conservation tillage began to replace conventional tillage practices, cultivation was replaced with chemical weed control between the crop rows. This led to the development of hooded sprayers that allowed non-selective herbicides to be applied between crop rows without injuring the crop. Although banding application technology is still used, its utility has been diminished with the development of selective herbicides and herbicide resistant crops. Adoption of these new technologies to reduce herbicide usage has indicated an interest by producers in minimizing herbicide inputs. Development of acceptable methods of reducing herbicide usage continues to be investigated.

Although precision farming is thought to be a new concept, it was used by farmers over two hundred years ago. Limited by the relatively small equipment available at the time, land was divided into small areas based upon soil type. Since fields were small, production requirements often were relatively uniform over the entire area, and management practices such as tillage could be tailored to the needs of the individual producer. This concept changed as tractors and equipment became larger and more powerful, allowing famers to combine several small fields into fewer larger fields. As fields were comprised of larger areas, significant variability was introduced.. Although production needs across a field became increasingly variable, farmers continued to manage each field uniformly.

Advances in computer technology have provided the basis for significant changes in agricultural crop production and management. Tractors, harvesters, sprayers and other farm equipment have computers and sensors to keep the operator informed as to the performance and operational parameters of the equipment. Farming needs have also changed and precision farming technologies such as global positioning systems (GPS), geographical information systems (GIS), satellites and remote sensing technologies provide tools that allow farmers to manage crop production with very precise accuracy, supplying inputs on an "as-needed" basis rather than uniformly monitoring an entire field.

Precision farming technologies can be divided into two categories: real-time sensor-based systems that use sensors to detect specific conditions and immediately respond with a needed input; or systems where data may be collected and appropriate action taken later. Examples of real-time systems include a sensor on a planter that monitors the soil moisture and adjusts the depth of planting; sensors that detect soil type and automatically adjust the seeding rate of a planter or output of a fertilizer applicator as it moves across a field; or sensors that detect weeds and apply herbicide only where weeds are detected. Selectively applying herbicide only where weeds are present could result in significant reductions in herbicide usage and cost of production for the grower (*6, 7, 8, 9, 10, 11, 12, 13, 14, 15*).

A prescription map is an example of precision farming technology that requires data to be collected and inputs supplied later. Geo-referenced data is collected and used to generate a map that provides the applicator with detailed information to allow the appropriate action to be taken at a specific location in the field. Prescription maps can be generated for seeding rates, fertilizer applications, herbicide applications, insecticide applications, tillage operations or virtually any type operations where geo-referenced data can be collected. Data from a crop yield monitor or remote sensing imagery can be used to generate prescription application maps. Efforts are underway to develop and evaluate both types of precision farming techniques. A significant amount of precision farming equipment is commercially available, but the most efficient methods of utilizing the technology are lacking and will require more investigation.

The Mississippi Delta Management Systems Evaluation Area (MDMSEA) project was organized as a consortium of several federal, state, and local agencies to evaluate the impact of agricultural production around oxbow lakes and develop best management practices (BMPs) to minimize adverse affects agricultural production may have on the ecology of the lakes. The MDMSEA project consisted of three oxbow lake watersheds in Mississippi, located within a twenty-five mile proximity of each other: (a) Beasley Lake (BL), located in Sunflower county; (b) Thighman Lake (TL), located in Sunflower county, and (c) Deep Hollow Lake (DHL), located in Leflore county. Commercial agricultural production conducted within each watershed prior to initiation of the project consisted of cotton (*Gossypium hirsutum* L.), soybeans (*Glycine max* (L.) Merrill), corn (*Zea mays* L.), and rice (*Sativa* L.). The commercial farming operation at DHL was by a single producer, whereas the other two watersheds had multiple producers. Edge-of-field BMPs such as slotted board risers and grass filter strips were evaluated at BL, without any change to agronomic practices. At DHL production BMPs such as conservation tillage, winter cover crops, and new application technologies were evaluated, as well as the edge-of-field BMPs utilized at BL. BMPs were evaluated independently on DHL and BL. TL served as the control watershed for evaluation of the overall project. Each lake was equipped with water quality monitoring stations to monitor run-off from the production areas and the water was monitored in each lake.

The objective of our research was to evaluate two methods of precision farming for weed control in the MDMSEA project. A sensor-controlled hooded sprayer that detected weeds and applied herbicide only where weeds were present was evaluated as a method of reducing herbicide usage. The second method evaluated was to use GPS and GIS to precisely map weeds in the fields and develop prescription application maps for site-specific and/or variable rate applications of herbicides.

Materials and Methods

Sensor-Controlled Sprayer

Field studies were conducted during 1996, 1997 and 1998 to evaluate sensor-controlled spray technology on 43 ha of cotton and 47 ha of soybeans in the DHL watershed (Figure 1) of the MDMSEA project. Sensors used were

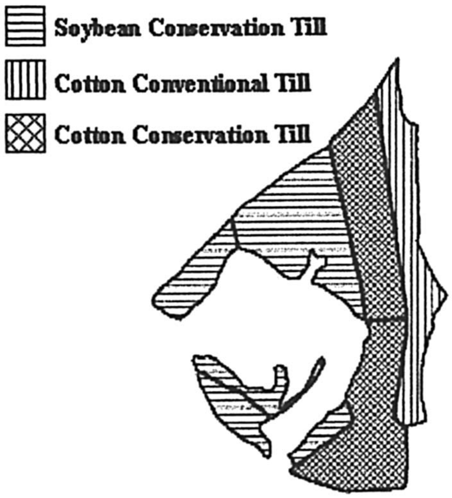

Figure 1. Crops in the Deep HollowLake watershed.

WeedSeeker™ Model PhD 612 (Patchen, Inc., Los Gatos, CA) that consisted of a modular unit with a plant sensor, internal light, and a single solenoid controlled spray nozzle. Since the sensors could not distinguish weeds from crop, the sensors were installed in hooded spray units that moved larger crop plants from the field-of-view of the sensors providing an unobstructed view of the soil between rows of crop and protected the crop from non-selective herbicides (Figure 2). Earlier evaluation of this system indicated plants approximately 2 cm in size could be detected and sprayer at speeds up to 22.5 km/ hr (Figure 3)

Crops were grown under conservation tillage practices and planted in rows spaced 1 m apart. Cultivation was eliminated to minimize erosion and herbicide movement. An 8-row sensor-controlled hooded sprayer was used for weed control in the areas between the crop rows. This system consisted of seven 0.7 m-wide hoods with three *WeedSeeker*™ Model PhD 612 plant sensors and two 0.5 m-wide hoods with two *WeedSeeker*™ Model PhD 612 plant sensors. The spray system was equipped with over-the-top and post-directed nozzles to allow banded applications between the hoods. Three tanks and pumps were used to allow simultaneous applications with hoods, over-the-top, and post-directed systems. The sensor system was calibrated to apply glyphosate at a rate of 1.1 kg a.i. ha^{-1} in a total spray volume of 94 L ha^{-1} at 11km h^{-1}. Total spray solution applied through the sensor-controlled hooded spray system was recorded for each field and the area of each field was determined with GPS and GIS units installed on an ATV. Savings were calculated by comparing total material

Figure 2. Eight-row sensor-controlled hooded sprayer in soybean field.

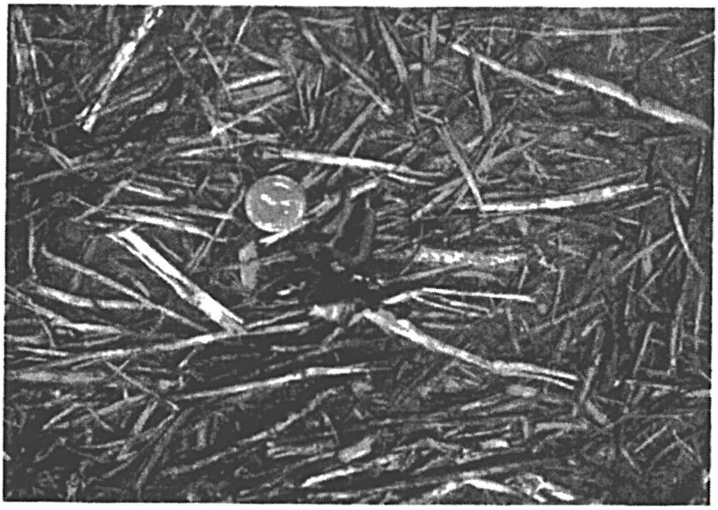

Figure 3. Weed detection size with sensor-controlled sprayer.

applied to a specific field with the sensor-controlled system to the theoretical amount that would have been required for the same field with a conventional hooded spray system without sensors.

Weed Mapping

Preliminary investigations to evaluate geo-referenced grid sampling of weeds were conducted in 1997, 1998 and 1999 in the conservation tillage cotton and soybeans within the DHL watershed, plus an additional cotton field in conventional tillage production adjacent to the watershed area. Grid points approximately 62 m apart were initially established in each field and geo-referenced using GPS. Grid coordinates were processed in a GIS unit and overlaid onto the geo-referenced field boundaries to generate field maps indicating the data collection sites (Figure 4). In 1998 and 1999, data collection

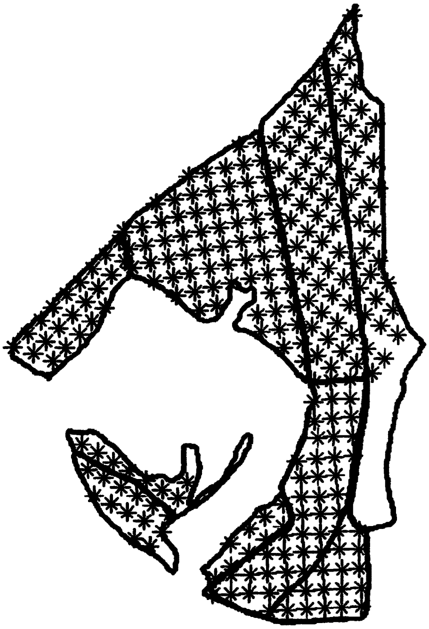

Figure 4. Geo-referenced data collection sites in Deep Hollow watershed.

points were located by downloading the coordinates for each point onto a computer interfaced with a GPS, navigating to each point, and marking the position with a flag. This method assured data was collected from the same location within each field and the same points could be located at any time, if needed.

Weeds by species were counted at each of the geo-referenced sites in a 3 m by 1 m area, centered lengthwise over the crop row and subdivided into two regions. Counts were made in a 20 cm wide band, 10 cm on each side of the crop row and a 40 cm wide band on each side of the 20 cm band. Data were collected twice annually at mid June and late June or early July, before crop canopy closure. In 1997, an additional count was made in mid August in one soybean field, due to late planting. Data from each collection date were matched to point coordinates and processed in a GIS to generate maps indicating distribution of specific weeds over the fields. These maps could then used to generate prescription application maps for variable rate or site-specific application of herbicides. Additional detailed information on the plant species and populations are presented in another chapter of this book (Bryson and Hanks).

Results and Discussion

Sensor-Controlled Sprayer

The number of applications made with the sensor-controlled sprayer during its three-year evaluation in the MDMSEA project varied by crop and season. During the 1996 season, four applications were made in cotton and reductions in herbicide usage ranged from 57% to 82%. In soybeans, the reduction ranged from 43% to 79% for the three applications made in 1996. The season-long averages in savings for 1996 were 75% and 62%, respectively, for cotton and soybeans. In 1997, only one application was made in cotton with the sensor-controlled sprayer and resulted in a reduction in pesticide usage of 80%. Soybeans received three applications where the savings ranged from 33% to 44% with a season-long average of 38% savings. Two applications were made in cotton and soybeans during the 1998 season. Reductions in herbicide usage for the two applications in cotton were 66% and 64% for a season-long average of 65%. In soybeans, reductions for the two applications were 53% and 38% resulting in a season-long average of 46%. The average savings obtained with the sensor-controlled sprayer over the three years in the MDMSEA project were 73% and 49%, respectively for cotton and soybeans (Tables I and II).

Table I. Herbicide Use Reduction with Sensor-Controlled Sprayer in Cotton.

Application	*1996*	*1997*	*1998*
		%	
1	82	80	66
2	81	-	64
3	57	-	-
4	80	-	-
Season Average	75	80	65
3-Year Average		73	

Table II. Herbicide Use Reduction with Sensor-Controlled Sprayer in Soybeans

Application	*1996*	*1997*	*1998*
		%	
1	65	33	53
2	79	41	38
3	43	44	-
Season Avg.	62	39	46
3-Year Avg.	49		

Results of this study indicate significant reduction in herbicide usage can be achieved by applying herbicide only where weeds are present with new intermittent spray technology. Results from other studies conducted in cotton and soybeans indicate yield difference when using traditional cultivation or the sensor-controlled sprayer.

Weed Mapping

Geo-referenced maps created with the GIS provided an excellent tool for visualizing how a specific weed species or groups of weeds were distributed over a particular area. The GIS allowed data to be processed, viewed and analyzed in a multitude of ways. Distribution and population data for individual weed species or any group of weed species for a specific data collection date could be viewed for an individual field, by crop, or for all fields. For example, Figures 5 and 6 illustrate the distribution of pitted morning glory (*lacunosa* L.) over all fields for the mid-June collection dates for 1997 and 1998, respectively. These figures indicate a significant reduction in the area infested with pitted morning glory from 1997 to 1998. Each weed species or group could be compared in a similar manner. A more detailed evaluation of the distribution of other weed species can be found in another chapter of this book (Bryson and Hanks).

The GIS not only provided a means of visually observing data, but also allowed prescription application maps to be generated for variable rate or site-specific (Figure 7) herbicide applications. The prescription application map contains a detailed set of instructions giving rate of application for each geo-referenced coordinate in the field. The prescription application map is downloaded onto a computer on a GPS controlled sprayer that will then apply herbicide only to specific areas in the field or vary the rate depending on density of weeds in the field.

In summary, the two technologies evaluated in this project have the potential to significantly reduce herbicide usage without sacrificing weed control. The sensor-controlled spray technology has advanced by interfacing the sensor-controlled spray system with a GPS. This provides a geo-referenced map of where weeds were located in a field. This information could be used to generate a prescription application map used to apply pre-emergence herbicide only where weeds have consistently appeared in the past. Sensor-controlled spray technology soon should be capable of distinguishing weeds from crop and applying the proper herbicide as needed. Precision application technologies will continue to rapidly advance in the future.

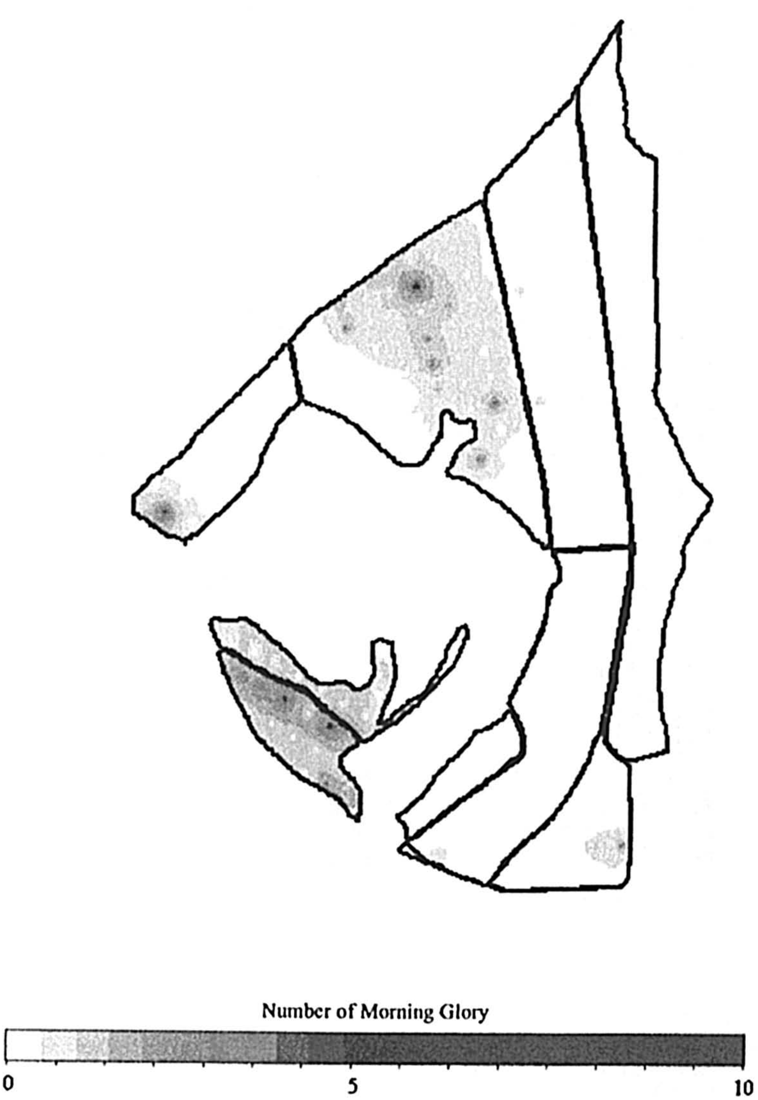

Figure 5. Distribution map of pitted morning glory for 1997.

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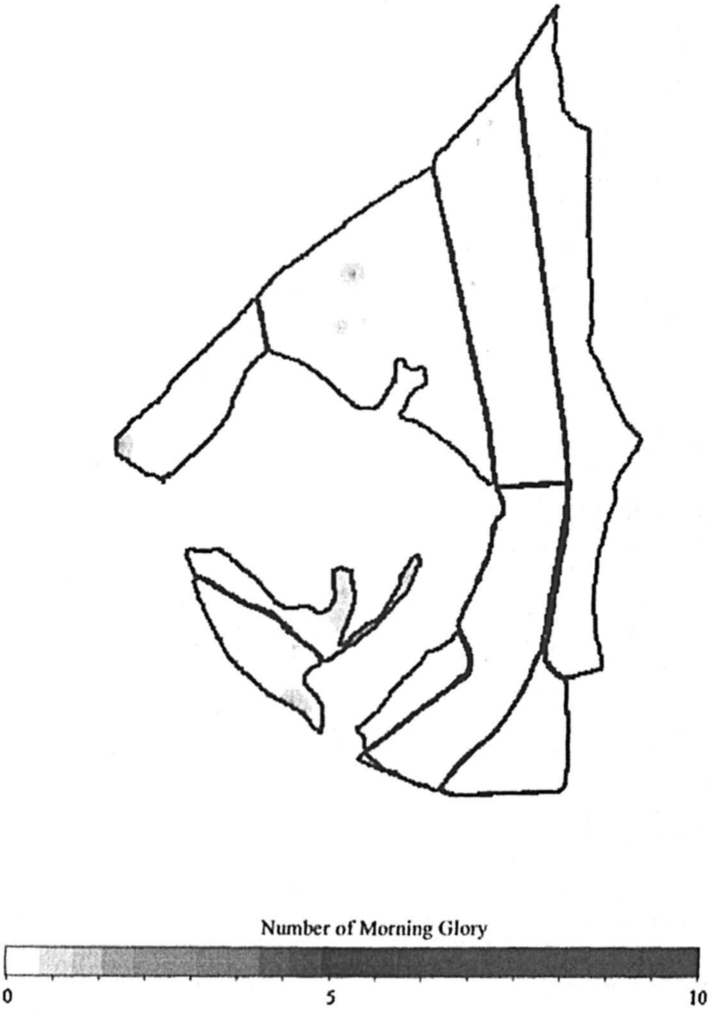

Figure 6. Distribution map of pitted morning glory for 1998.

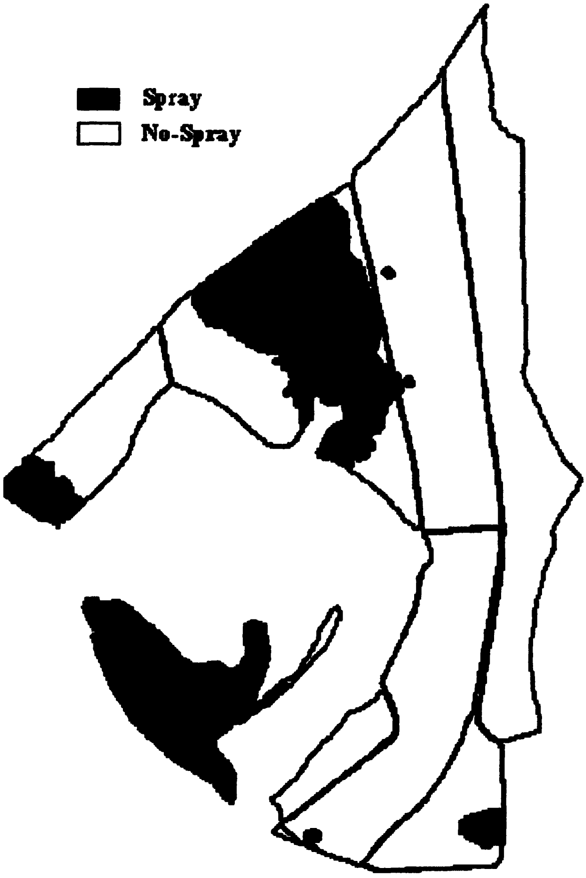

Figure 7. Prescription application map for pitted morning glory in 1997.

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Chapter 12

Fluometuron Adsorption to Soil Influenced by Best Management Practices: Established Filter Strip and Riparian Zones

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A study was established to determine soil properties and fluometuron adsorption in a Dundee silt loam collected from a cropped watershed and adjacent filter strip (0-2 cm depth); and a Dowling overwash phase of a riparian zone. Established (greater than 5 years) grass filter strip sampling points included a mixing zone (1 m prior to the filter strip edge, but not in cropped area), edge of filter strip, and locations at 1 m and 2 m into the filter strip. Sampling points in the riparian zone were: entrance and 10 m, 25 m, 50 m, 100 m, 200 m, 400 m, 600 m, and 800 m from the riparian entrance. Percent organic matter (OM), percent clay and cation exchange capacity (CEC) were higher with increased distance down slope from the established filter strip mixing zone to 2 m into the strip and ranged from 0.4% to 2.4%, 18% to 23%, and 12 to 18 cmol kg^{-1}, respectively. In the riparian zone, OM, clay, and CEC ranged from 2.3% to 4.5%, 22% to 40%, and 18 to 32 cmol kg^{-1},

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respectively, with increasing distance down slope from the drainage channel entrance, to 400-800 m from the entrance. Fluometuron adsorption to soil collected from locations at 1 m and 2 m from the established grass filter strip edge and within the riparian areas was higher than soil collected from the established filter strip mixing zone, strip edge, and adjacent cropped soil. Values of K_F were positively correlated with OM, clay and CEC ($r \geq 89$). Based on adsorptive soil properties, the use of filter strips and riparian zones as a BMP can improve surface water quality.

Introduction

The USEPA has stated that agricultural stresses, largely from excess nutrients, sediment, and pesticides, affect 58% of impaired lake acres, 55% of impaired stream miles, and 21% of impaired estuarine systems *(1)*. Due to the humid sub-tropical climate in Mississippi, both weed and insect pressures have a high impact on farm production compared to other areas of the nation. Similarly, increased microbial activity promotes oxidation of organic matter, requiring the consistent use of synthetic fertilizer for nutrient replenishment. As a consequence, the intensity of agrichemical use in crop production is exceptionally high, particularly in cotton. Spring rainfall amount and intensity are also high, and a primary object for crop producers is to expeditiously move water off the field through trenched water furrows. Since many agricultural contaminants move off-site with water, the potential for significant contaminant flux through the ecosystem exists.

Currently, the Mississippi Department of Environmental Quality (MDEQ) is tasked with establishing total maximum daily loads (TMDLs) of nonpoint-source pollutants for bodies of water, and is responsible for administering pollution abatement programs to assure water quality improvement for impaired watersheds. Therefore, management systems evaluation area (MSEA) projects provide an excellent opportunity to educate the public with scientific information concerning cropped watersheds as a nonpoint contaminant source. MSEA projects are part of a program titled Agriculture Systems for Environmental Quality (ASEQ). They were included in the 1989 Initiative on Water Quality to investigate water quality contamination from pesticides and fertilizers used in field crop production. In 1994, the Mississippi Delta MSEA (MDMSEA) project was initiated to identify, implement, and evaluate BMPs for use in the Delta. A BMP is the physical application of plant, land, and water management knowledge, in order to protect soil and water resources *(2)*. Many mitigative practices are designed to lower the kinetic energy of moving water and thereby reduce the off-site transport of nonpoint-source contaminants such as pesticides, nutrients, and eroded sediment. Once effective BMPs have been developed, states may incorporate them into nonpoint-source pollution abatement programs.

MDMSEA research is being conducted by several local, state and federal agencies at three watersheds located in Sunflower and Leflore counties in Mississippi. Each location has a watershed that drains into an oxbow lake. These lakes were once a part of natural meandering channels or floodplains of the Sunflower or Yazoo Rivers. However, a change in the course of river flow has left these lakes isolated from their adjacent river channels. The cropped area surrounding the oxbow lake creates a closed watershed system, hence an ideal environment to study the physicochemical processes in runoff influenced by various BMPs. Some BMPs for improving and preserving water quality include: ultra low selective agrochemical applications, conservation tillage, grass filter strips, slotted board risers, and riparian zone management. This report will focus on the use of grass filter strips and a riparian zone as BMPs for surface water quality improvement.

Farmers generally cultivate land to the edge of ditches and roads, leaving no vegetation to interact with agrichemicals in runoff. Edge-of-field grass filter strips are designed to remove sediment, organic matter, and other pollutants from runoff by filtration, deposition, infiltration, sorption, decomposition, and volatilization, thereby improving water quality. Grass filter strips have been shown to reduce sediment and herbicides in runoff by least 50% in small plot research *(3, 4, 5)*. In larger scale research conducted on a 0.41 ha watershed, filters strips retained 58, 73, and 69% of atrazine, metolachlor, and cyanazine, respectively, and sediment retention ranged from 40 to 100% *(6)*. Soil loss from a 1.6 ha watershed with a 2.4% convex slope was reduced by as much as 46% through the use of filter strips *(7)*. Depending on sediment retention, filter strips should effectively retain herbicide molecules that are strongly adsorbed to sediment in runoff. The strips may also reduce water loss, thus off-site losses of fluometuron suspended in the water phase would be minimized.

Historically, riparian zones and wetlands in the Mississippi Delta were viewed as undesirable swamps to be drained, and their benefits in water quality improvement went unnoticed. These zones are transitional between ecotones of land and water, and may serve as a BMP for water quality improvement *(8)*. Riparian zones can remove sediment and other pollutants in runoff exiting adjacent croplands. Studies have shown that a riparian zone can retain 70 to 90% of total nitrogen inputs and that most NO_3^- removal occurs within 20 m of the forest/field boundary *(9)*.

Fluometuron was chosen as our compound of study because it is commonly used in Mississippi cotton (*Gossypium hirsutum* L.) production and because detectable levels have been reported in surface water *(10, 11)*. Fluometuron is an effective herbicide for annual grass and broadleaf weed control in cotton. Fluometuron was labeled for use in 1965 *(12)* and is one of several compounds that belong to the herbicide group known as the phenylureas or substituted ureas. Fluometuron is considered to be a nonionic molecule that does not ionize over a wide pH range *(13)*. Fluometuron is also considered to be moderately water soluble, with reported solubility of 90 mg L^{-1} at 20 to 25 C *(14)*.

After application, the environmental fate of a herbicide depends on compound retention, transportation, transformation, and interactions of these processes *(15)*. Potential environmental sinks in the soil-plant-atmosphere relationship include: sorption and desorption to the soil colloidal fraction, runoff movement in the dissolved or sorbed state, plant uptake, volatility, photolysis, and hydrodynamic transport as soluble constituents of the aqueous phase (convection, transpiration, or evaporation) *(14)*. Herbicide retention primarily refers to adsorption, which is defined as the accumulation of a pesticide or other organic molecule at either the soil-water or the soil-air interface, resulting in the accumulation of molecular layers on the surface of soil particles *(15)*. Adsorption is an important reversible process that is generally measured by herbicide disappearance from solution. When a herbicide molecule is adsorbed, it can move into the interior matrix of the colloidal fraction (clay minerals and humus) or plant biomass and become tightly bound *(16)*. The influence of BMPs may change soil constituents, hence altering the physicochemical dynamics of compound retention, transportation, and transformation. Therefore, research was conducted to determine soil properties and fluometuron adsorption in soil from an established (> 5 yr) grass filter strip, riparian zone, and adjacent cropped watershed epipedon at Beasley Lake in Sunflower County, MS.

Materials and Methods

Soil Characterization

Research was conducted on a Dundee silt loam (fine silty, mixed, thermic, Aeric Ochraqualf) collected from a cropped area; adjacent established tall fescue (*Festuca arundinacea* Schreb.) filter strip (0-2 cm depth); and a Dowling overwash phase (fine, montmorillonitic, thermic, Vertic Epiaquept) of a riparian zone *(17)*. These areas surround Beasley Lake in Sunflower County, MS, in the Mississippi River alluvial floodplain. In some areas, runoff from the cropped area used for cotton production moves through an established tall fescue filter strip and a riparian zone before entering the lake. In other areas, runoff will pass through a filter strip and drainage channel before entering the riparian zone (Figure 1). Runoff in the drainage channel will be directed and released into the riparian zone and move in a slough through approximately 600 m of living hardwood trees. The distribution of vegetation changes at 400 and 600 m to a saturated region of mainly dead trees, with a thick understory of shrubs and phreatophytic (water-loving) plants prior to being discharged into an oxbow lake. Soil in the riparian zone will typically become saturated after a runoff event. The length of time saturated conditions persist depends on antecedent soil moisture, the amount of runoff water received, and other environmental conditions.

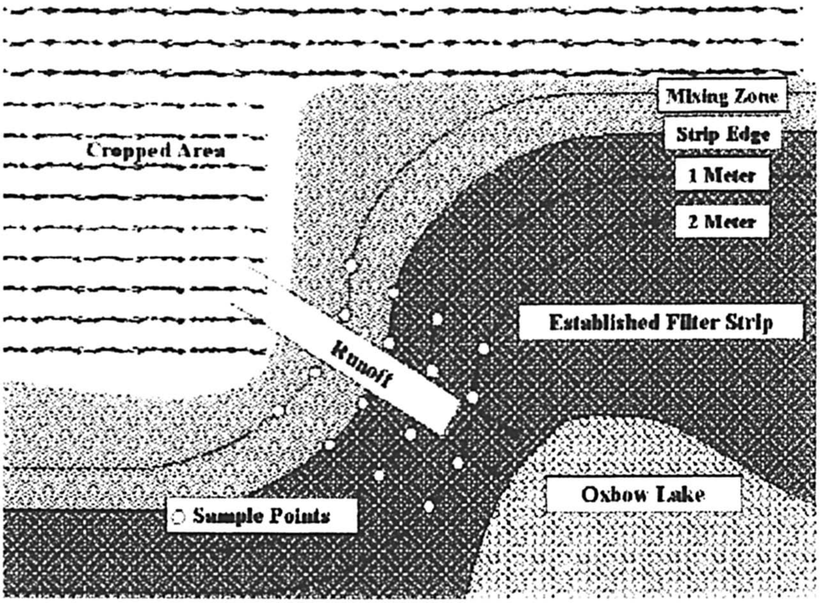

Figure 1. Diagram of established (greater than 5 years) tall fescue (<u>Festuca arundinacea</u> Schreb.) filter strip sampling points located at Beasley Lake in Sunflower County, MS.

All soil samples for this experiment were collected in the spring of 1996 prior to field preparation and agriculture chemical applications. The established filter strip was sampled at four points along a transect in the mixing zone (1 m prior to the filter strip edge, but not in the crop area), the front edge of the filter strip, and at 1 and 2 m from the edge into the filter strip, resulting in sixteen sampling points for each grass filter strip. At each point, ten samples taken to a depth of 2 cm were combined to make a single composite sample. Sampling points in the riparian zone were: entrance and 10 m, 25 m, 50 m, 100 m, 200 m, 400 m, 600 m, and 800 m from the riparian entrance (Figure 2). Ten samples were collected to a depth of 2 cm at each sampling point. These samples were combined based on soil characteristics, resulting in composite samples for 0-25 m (riparian entrance), and 50-200 m and 400-800 m from the riparian entrance.

All soils were air-dried, screened through a 2-mm sieve, and stored at room temperature until analysis. Samples were analyzed for organic matter (OM) content by a colorimetric procedure *(18)*, pH using a 1:2 soil to water suspension *(19)*, and cation exchange capacity (CEC) by extraction and summation of exchangeable acids and bases *(20)*. Particle size analyses were conducted using the hydrometer method *(21)*.

Fluometuron Adsorption

A batch equilibration method used by several researchers *(22, 23, 24, 25)* was employed to study fluometuron adsorption to soil. Soil (5 g) was transferred to 50-ml graduated polypropylene centrifuge tubes (Corning Incorporated, Pulteney St, Corning, NY 14831). Technical grade fluometuron (96.8% chemical purity)(Syngenta, 410 Swing Rd., Greensboro, NC 27409) was dissolved in 0.01 *M* $CaCl_2$ to achieve solution concentrations of 0.85, 4.7, 17.7, and 34.9 μmol L^{-1}. The highest concentration was equivalent to 15.7 times the recommended field rate of 2.2 kg ai ha^{-1} uniformly incorporated to a 15-cm soil depth. Fluometuron solutions contained 166.5 Bq ml^{-1} uniformly ring-labeled ^{14}C-fluometuron (specific activity 17.3 Bq g^{-1}, 99% radiochemical purity) (Novartis, 410 Swing Rd., Greensboro, NC 27409). Ten ml of each of these four solutions were added to the soil; samples were shaken for 15 h at room temperature to allow the soil-herbicide system to reach equilibrium. After equilibration, samples were centrifuged (400 x g for 20 min) and a 1-ml aliquot of supernatant was transferred to 15 ml of water-accepting scintillation cocktail (Scintiverse, Fisher Scientific Co., 711 Forbes Ave., Pittsburgh, PA 15219-4785). The ^{14}C radioactivity was counted for each sample using liquid scintillation spectrometry (Model LS 6000IC, Beckman Instruments, Inc., 2500 Harbor Blvd., Fullerton, CA 92634-3100) with internal quench correction standards. Fluometuron adsorption to soil was determined by a change in the amount of herbicide in solution, and blank samples were used to adjust for background.

Adsorption isotherm models were developed using the Freundlich equation *(26)* computed as $[Q] = K_F[C]^{1/n}$. Where [Q] = amount adsorbed (μg g^{-1}), K_F = coefficient (ml g^{-1}), [C] = equilibrium herbicide concentration (μg ml^{-1}), and 1/n = dimensionless coefficient. Freundlich coefficients were determined by the regression of log [Q] against log [C]. The K_F and 1/n coefficients are interpreted as indices of adsorption capacity and adsorption intensity, respectively *(27, 28)*. Data were subjected to analysis of variance, and mean values of K_F and 1/n were

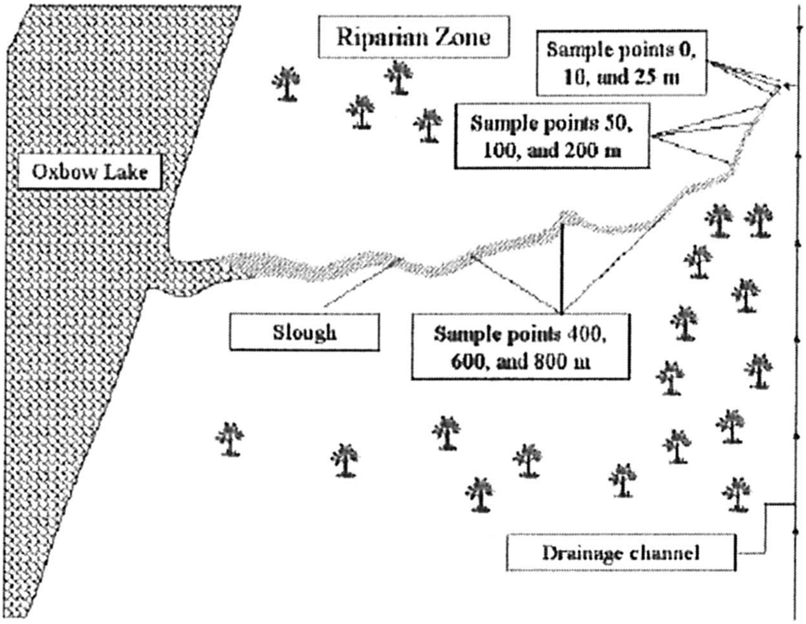

Figure 2. Diagram of riparian zone sampling points at Beasley Lake in Sunflower County. MS.

separated between soils using Fisher's protected Least Significant Difference (LSD) analysis at a probability level of $\alpha = 0.05$. Pearson correlation coefficients were used to relate effects of soil properties to fluometuron adsorption across soils.

Results and Discussion

Soil Properties

Soil samples collected from all areas of the established filter strip, riparian zone, and cropped area were compared to determine the difference in soil properties. Sand content was at least 38% in entrance areas of the established filter strip (mixing zone) and riparian zone (0-25m), with only 5% sand content just prior to entrance into the lake (Table 1).

Table I. Selected Chemical and Physical Properties of Cropped, Filter Strip, and Riparian Soils

Sample Point	*pH*[a]	*CEC*[b]	*OM*[c]	*Sand*[d]	*Silt*[d]	*Clay*[d]
		cmol kg^{-1}	%			
Crop	4.7	11.7	0.7	28	59	13
Established-strip mix	5.9	12.2	0.4	46	36	18
Established-strip edge	6.0	14.4	0.9	40	39	21
Established-strip 1 m	6.3	18.2	2.1	21	58	22
Established-strip 2 m	6.0	18.1	2.4	31	46	23
Riparian 0-25 m	6.8	18.4	2.3	38	40	22
Riparian 50-200 m	6.4	23.3	3.1	7	62	26
Riparian 400-800 m	5.8	31.7	4.5	5	55	40
LSD ($\alpha = 0.05$)	*0.3*	*2.7*	*0.6*	*7*	*6*	*4*

[a] Soil pH determined using 1:2 soil to water suspension. [b] CEC was determined by extraction and summation of exchangeable acids and bases. [c] Soil OM was determined by a colorimetric procedure. [d] Particle size analyses were performed using a hydrometer method.

Clay content was 13% in the cropped area, which was lower than any other area sampled. The clay content ranged from 18 to 26% in soil from all areas of the filter strip and areas within 0 to 200m of the riparian zone entrance. Clay content was highest in the 400 to 800m riparian area, which was the area of the riparian zone nearest to the lake. This suggests that runoff water kinetic energy decreased as it moved through the grass filter strip and riparian zone, causing coarser fractions to settle out of suspension, and finer sediment to remain suspended before being deposited as distance increased through these areas. Gilliam et al. *(29)* reported similar results where coarse sediment was deposited close to the field and sediment layers consisting of clay-sized materials developed with distance.

Soil collected 50-200 m and 400-800 m from the riparian entrance contained at least 3% OM and had a CEC of at least 23 cmol kg^{-1}, which was higher compared to soil from all other areas (Table 1). The OM content and CEC ranged from 2.1 to 2.4% and 18.1 to 18.4 cmol kg^{-1}, respectively, in soil collected from the entrance of the riparian area and interior areas (1 and 2 m from strip edge) of the established filter strip, which was lower compared to soil from other riparian areas. However, OM content was less than 1 % and CEC was lower than 14.5 cmol kg^{-1} in soil collected from exterior areas (mixing zone and strip edge) of the established filter strip and the cropped area.

The partial decomposition of fescue grass in the established filter strip interior areas likely contributed to higher OM *(24)*. The higher OM content in soil from riparian areas was due to well-decomposed forest litter. Also, slow drainage of surface and subsurface water contributed to saturated conditions in the riparian areas, which can reduce OM decomposition *(30)*. McLatchey and Reddy reported a threefold increase in OM decomposition with a change from anaerobic to aerobic conditions *(31)*. The higher CEC in these areas results from the combination of higher OM and clay content. Cation exchange capacity was correlated to OM (r = 0.61) and clay (r = 0.76), which emphasizes the importance of these two soil factors on the CEC (data not shown).

Fluometuron Adsorption

Freundlich constants, K_F and 1/n, ranged from 0.81 to 4.58 mL g^{-1} and 0.90 to 1.01, respectively, among all soils (Table II). Gaston and Locke reported similar parameter values of 1.45 mL g^{-1} for K_F, and 0.90 for 1/n for fuometuron adsorption to a Dundee silty clay loam collected from Mississippi *(32)*. Others reported values of 0.90 for K_F and 1.08 for 1/n with a Bosket very fine sandy loam *(33)*. In general, values of 1/n have been reported from 0.70 to 1.20 in adsorption experiments using 50 various pesticides *(34)*.

In the established filter strip, K_F values ranged from 0.81 to 1.21 with soil from the strip exterior (mixing zone and strip edge) and 2.35 to 2.51 with soil from the strip interior (1 and 2 m from strip edge) (Table II). Adsorption to soil from the established filter strip exterior was less than to cropped area soil, based on values of K_F. Adsorption to soil from the established filter strip interior was greater than to cropped area soil and at least 1.5 times higher than adsorption to soil from strip exterior areas. Fluometuron adsorption isotherms illustrate fluometuron retention in established filter strip and cropped soils (Figure 3).

Lower fluometuron adsorption to established strip exterior areas and cropped area was probably due to lower organic matter content in the mixing zone, strip edge, and cropped soil samples compared to the strip interior soil samples (Table I). Results from other research emphasize a strong correlation of

Table II. Freundlich Coefficients Determined from Batch Adsorption Techniques with Soils Collected from a Cropped Area, Established Filter Strip, and Riparian Zone.

	Freundlich Coefficients	
Sample Point	*K_F*	*1/n*
	mL g^{-1}	
Crop	1.48	0.92
Established-strip mix	0.81	1.01
Established-strip edge	1.21	1.00
Established-strip 1 m	2.51	0.98
Established-strip 2 m	2.35	0.95
Riparian 0-25 m	2.60	0.93
Riparian 50-200 m	3.01	0.90
Riparian 400-800 m	4.58	0.93
LSD ($\alpha = 0.05$)	*0.26*	*0.04*

fluometuron adsorption with soil organic matter *(35, 36, 37, 33)*. In addition, a similar experiment conducted by Benoit et al. illustrated that adsorption of isoproturon, a phenylurea herbicide, to surface soil (0-2 cm) collected from a perennial ryegrass (*Lolium perenne* L.) filter strip was almost three times higher than to cropped area soil *(24)*. They attributed higher adsorption to the high density of partially decomposed plant residues.

Values of K_F for riparian zone soil ranged from 2.60 to 4.58 with an increase in distance from channel entrance (0 to 25 m) to the area prior to the lake (400 to 800 m) (Table II). Fluometuron adsorption to soil collected from 50-200 m and 400-800 m from the riparian entrance was greater than to all other soils in the experiment. Adsorption of fluometuron to soil collected 0-25 m from the riparian entrance was no different than to soil collected from the established filter strip at 1and 2 m from strip edge. Isotherms illustrate fluometuron adsorption to soil from riparian forest and cropped areas (Figure 4).

In general, the adsorption of fluometuron to soils evaluated in this experiment followed the order: filter strip mixing zone < filter strip edge < cropped area < filter strip 2 m = filter strip 1 m = riparian entrance < riparian 50-200 m < riparian 400-800 m (Table II).

There was a strong relationship between fluometuron adsorption and soil OM, clay content, and CEC across all soil samples, with correlation coefficients of 0.98, 0.89, and 0.97, respectively (Table III).

As mentioned above, it is well documented that fluometuron adsorption is highly correlated to OM content. The positive correlation to clay content is consistent with some research *(38)*, while others have reported a very low correlation (r = 0.09 to 0.13) between adsorption and clay content of eight Czechoslovakian soils involving five phenylurea herbicides *(36)*. Weber et al. reported that fluometuron adsorption was higher when a montmorillonite, a 2:1 expanding clay was added to soil media compared to a kaolinite, a 1:1 nonexpanding clay *(39)*. Brown et al. reported a significant correlation (r = 0.82) between CEC and fluometuron adsorption *(35)*.

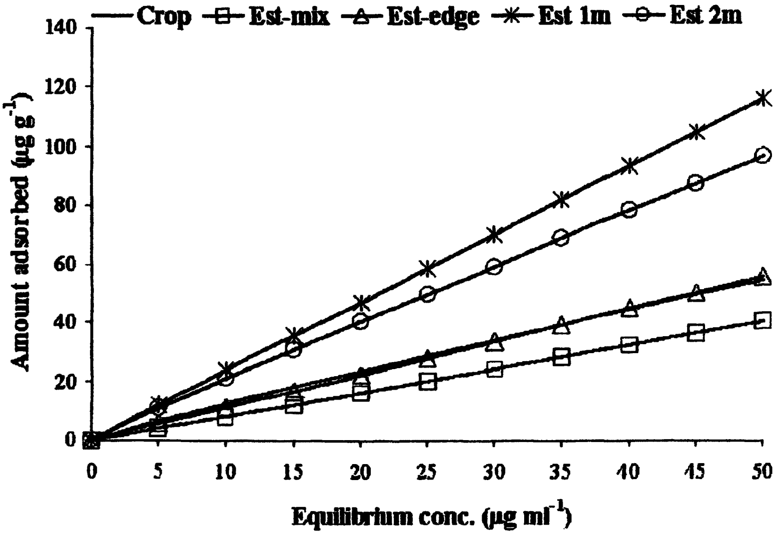

Figure 3. Adsorption isotherms that describe fluometuron adsorption to soil influenced by an established (greater than 5 years) tall fescue (Festuca arundinacea Schreb.) filter strip located at Beasley Lake in Sunflower County, MS. Strip sampling points include a mixing zone (1 m prior to edge), strip edge, 1 m into strip, and 2 m into strip.

Organic matter content and CEC were highest in soil collected from the riparian zone. This was due to the accumulation of well-decomposed forest litter, which can increase herbicide adsorption and prolong herbicide residence time *(22)*. Adsorption was likely higher with increasing distance into the forest due to increased clay content and an increase in anaerobic conditions, which enhances organic residue preservation *(30)*. As soil becomes saturated, gas exchange between soil and air is reduced, microbial populations change, and pH changes, which affects enzymatic activity and organic matter decomposition *(31)*. Spatial differences in texture were due to coarse particle deposition near the forest entrance followed by fine particle deposition as runoff moved downslope (Figure 2). The OM content and fluometuron adsorption in established strip interior soil

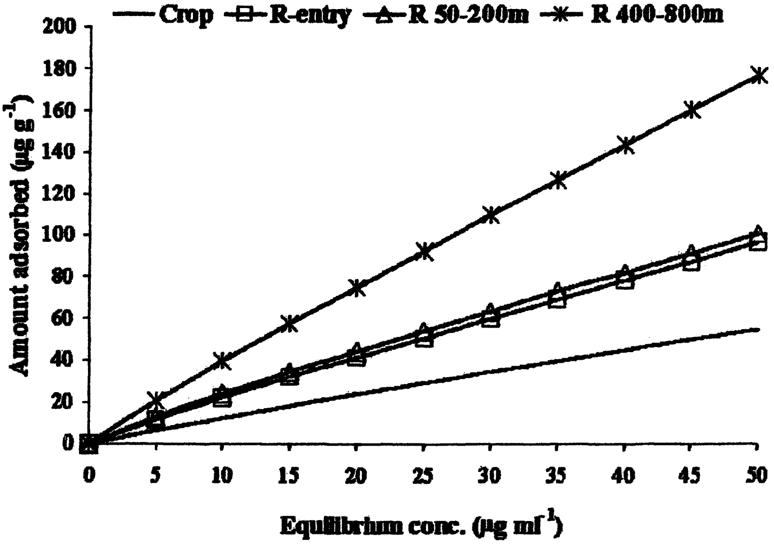

Figure 4. Adsorption isotherms that describe fluometuron adsorption to soil influenced by a riparian zone located at Beasley Lake in Sunflower County, MS. Sampling points include 0-25 m (entrance), 50-200 m from entrance, and 400-800 m from entrance.

(1 and 2 m from strip edge) was greater than strip exterior (mixing zone and strip edge), which was probably due to the presence of partially decomposed grass residue. This resulted in an adsorptive capacity for the established strip interior that was similar to the riparian zone entrance (0-25 m).

In conclusion, filter strip establishment and riparian zone management should promote soil properties such as OM and consequent CEC to enhance adsorption of fluometuron to soil in these areas. Therefore, adoption of filter strips and riparian zones as a BMP can improve surface water quality based on adsorptive soil properties and allow the continued use of valuable herbicides in the Mississippi Delta.

Table III. Correlation Coefficients for Various Soil Properties with Fluometuron Adsorption for Soil Samples from a Cropped Area, Filter Strips, and Riparian Zone at Beasley Lake in Sunflower Co., MS

Soil Properties [a]	*Pearson Correlation Coefficients Across Soil Samples*
PH	0.25
CEC	0.97
Sand	-0.84
Silt	0.51
Clay	0.89
OM	0.98

[a] Abbreviations: CEC, cation exchange capacity; OM, organic matter.

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Chapter 13

Spatial Variability of Cyanazine Dissipation in Soil from a Conservation-Managed Field

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Assessment of soil spatial characteristics may provide the basis for using precision application of herbicides to reduce chemical inputs. Spatial variability of cyanazine degradation and sorption in relation to soil characteristics were examined in soil from a reduced-tillage cotton field (2 ha, no-tillage, wheat cover crop) in the Mississippi Delta Management Systems Evaluation Area (MDMSEA) Deep Hollow Lake watershed. Soil was sampled in a grid pattern (n=100), and samples were collected in spring, 1999. Soil characteristics evaluated included pH, % organic matter (OM), texture, cyanazine sorption, and microbial metabolic activity. Cyanazine degradation during laboratory incubation (28 d) was assessed using ^{14}C-labeled cyanazine. Subsamples were extracted with methanol, processed, and analyzed by thin layer chromatography. Cyanazine sorption was measured using batch methods. Half-lives of cyanazine ranged from 5 to 26 days with the greatest persistence correlated with the highest soil clay content (r=0.73) and negatively correlated with pH (r=-.80). Major metabolites observed were cyanazine amide and polar hydroxy derivatives. Spatial trends were modeled using a surface quadratic equation and geostatistics, and data were detrended where appropriate. Many parameters, such as cyanazine sorption, showed highly significant trends across the field. Cyanazine half-life and metabolite accumulation had spatial structure that could be modeled with a semivariogram, while no spatial structure was observed for soil OM.

Considerable effort has been directed towards characterizing the fate of herbicides in agricultural systems. Laboratory experiments have examined herbicide sorption and degradation while field studies have provided insights into the roles of leaching and surface runoff. A few reviews have been published concerning the role of tillage practices, soil organic matter, clay, pH, and microbial activity on the dissipation of herbicides in the environment (*1*, *2*). Most current knowledge about herbicide dissipation comes from studies involving traditional small plot designs. However, agricultural lands are spatially heterogeneous, and relatively few studies have assessed variability of herbicide fate within fields and watersheds (*3*, *4*).

In the past decade, development of technologies such as global positioning systems (GPS) and geographic information systems (GIS) have spurred interest in evaluating relationships between the spatial properties of soil and agrochemical application (*5*). Spatial characterization of agricultural land, in particular soil properties, should provide the theoretical and practical knowledge needed for precision agricultural management (*6*). Application of fertilizer and herbicides can be varied to better match localized conditions within a field (*5*, *6*, *7*). Spatial studies have benefited from the use of geostatistics, a statistical approach developed by the mining industry for non-random situations (*8*). Specifically, variography is used to assess the presence of localized spatial dependence or autocorrelation for a parameter. This technique provides additional insight into the variability of soil properties (*9*). Although the spatial variability of herbicide fate has been investigated, few studies have incorporated geostatistics (*10*, *11*, *12*, *13*).

Cyanazine has been used in a variety of herbicide treatment regimes, including directed post-emergence in cotton for the control of broadleaf weeds and grasses. Degradation of cyanazine is generally thought to be a non-biological process, primarily hydrolysis, to amide and hydroxyl metabolites (*14*, *15*). Soil parameters such as OM, pH, and water content play a role in the fate of cyanazine in the agricultural environment (*16*, *17*). Further, soil properties such as OM content and cation exchange capacity influence the efficacy of cyanazine as a preemergence herbicide (*18*). Since surface soils in conservation tillage systems tend to have enhanced OM contents, herbicide dissipation may be influenced (*1*). Greater cyanazine sorption was observed in no-till and plant residue amended soils than in corresponding conventional tillage soils (*19*). Increased OM and plant residue accumulation can reduce cyanazine loss in surface runoff (*20*), but lower water runoff and increased preferential flow through soil profiles often results in greater herbicide leaching (*20*, *21*).

The objective of this study was to characterize the spatial variability of cyanazine fate in a cotton field managed using conservation practices.

Assessment of relationships between soil spatial characteristics and herbicide dissipation may provide a basis for using precision application of herbicides to reduce chemical inputs in conservation management systems.

Materials and Methods

Study Site and Sample Preparation

Soil from a MDMSEA study site under reduced-tillage management in Leflore County, Mississippi (Deep Hollow Lake watershed) was investigated in 1999. Winter wheat had been planted as a cover crop following cotton every year since 1995. The study site was last subsoiled and disked in the fall of 1997, and lime also was applied in the fall of 1997 (1100 kg ha^{-1}). Other details about the study area are described elsewhere in this volume (Chapter by Locke, this volume).

A grid following an equilateral triangle pattern (12.2 m between sampling points) was established (100 sampling locations) within approximately a 2-ha area. Surface (0-5 cm) soil samples were collected on April 30, 1999, after cover crop desiccation, but before cotton planting. Each sample was a composite of six cores (5 cm diameter) collected from within the seedbed area of the cotton rows. Field-moist samples from each grid were pooled, sieved (4 mm mesh) and stored at 4° C until further use. Air-dried soils were analyzed for soil pH (soil:water, 1:2) and OM content (Walkley Black method). Soil texture was ascertained using the hydrometer method. Microbial metabolic activity of field moist soil was estimated using triphenyl-tetrazolium chloride (TTC) dehydrogenase activity as described elsewhere (*22*).

Cyanazine Degradation

Soil, 24 g (air-dry weight equivalent) was added to Nalgene bottles and adjusted to 30% (g/g) moisture. Uniformly ring ^{14}C-labeled cyanazine (E.I. Dupont de Nemours and Co., Wilmington, DE) was added to the soil at a concentration of 10.4 μmol kg^{-1} (approximate equivalent to 2.1 kg ha^{-1}) and radioactivity of 485 kBq kg^{-1}. Treated soils were vortexed for uniform mixing and incubated at 25° C. The lids were placed loosely on the sample bottles, and moisture levels were adjusted periodically to compensate for drying. Subsampling was performed 0, 2, 5, 9, 17 and 28 days after cyanazine treatment (3.5 g of soil on the first four sampling days, 4.5 grams on the last two). Subsamples were individually placed in 25-mL Corex tubes with Teflon lids, and extracted with methanol (2:1, methanol:soil) by shaking for 24 h. After centrifugation at 7,700 x g, the supernatants were decanted, and the soil was re-extracted with methanol by shaking for 4 h. Supernatants from the two extractions were combined, weighed, and radioactivity determined by liquid scintillation counting (Liquid Scintillation Counter Model 4430, Packard Instruments, Downers Grove, IL). The remaining volume of each extract was reduced to approximately 4 mL under N_2. Aliquots (100 µL) were spotted on thin layer chromatography (TLC) plates (20 x 20 cm, 250 µm silica gel, Whatman, Clifton, NJ) and developed with an ethyl acetate:toluene:methanol (50:50:3, v:v:v) solvent system. Chromatography was analyzed using a Bioscan System 200 Imaging Scanner (Bioscan, Washington, D.C.). Cyanazine had an R_f of approximately 0.77. Two additional solvent systems were used for characterizing the metabolites in the 5 d and 28 d extracts: ethyl acetate:toluene:methanol 50:50:3; and ethyl acetate alone. Cyanazine metabolites were provided by E.I. Dupont de Nemours and Co. Air-dried soils from day 28 were oxidized to measure nonextractable ^{14}C (Oxidizer Model 306, Packard Instruments).

Cyanazine Sorption

Air-dried soil (5 g oven-dry equivalent) placed in 25-mL Corex tubes. Ten mL of ^{14}C cyanazine solution (10 µmol L^{-1} cyanazine; 162 kBq g^{-1}) were added to the tubes and shaken for 24 hours at 25° C. After centrifugation (8,000 x g; 10 min), radioactivity in aqueous samples was determined by liquid scintillation counting. Cyanazine K_d values were calculated as the distribution between cyanazine in solution at equilibrium and cyanazine sorbed to soil.

Data Analysis

The half-lives of extractable total ^{14}C and extractable ^{14}C cyanazine data were fit to first-order kinetics using PCSAS NLIN procedure (SAS, Cary NC) (*23*). The first order degradation rate constant (K) and the 95% confidence interval were calculated using the NLIN procedure, and the half-life was calculated from K. Evidence of spatial structure in the data was assessed in two steps. First, a surface quadratic model was applied to identify trends in the data. Linear correlations from above were also used to confirm trends and other relationships. The second step examined the residuals remaining after detrending for spatial structure that could be modeled using geostatistics (GS+, Gamma Design Software, Plainwell, MI). Log transformations were applied when trends existed in the residuals. Models normally included 6 lag classes and an active lag distance approximately twice that of the range. Maps of the trends and raw data were created using Surfer Version 6 (Golden Software, Golden, CO) using the radial bias function.

Results

A summary of soil characteristics and cyanazine dissipation parameters is presented in Table I. Linear correlations between soil characteristics and cyanazine dissipation were determined in order to evaluate relationships between cyanazine degradation and soil chemical, physical, and biological properties (Table II). Multiple regression response surface analysis was used to determine whether parameter response was a function of direction eastward or westward across the field, which corresponded to changes in elevation from the top of the slope to the bottom. The soil in the 2-ha area was slightly acidic to neutral pH, with relatively low organic matter content typical of many cultivated Mississippi Delta soils (Table I). Management under reduced tillage conditions resulted in an organic matter content only slightly elevated above adjacent conventional tillage soils (not part of this study) (*24*). Microbial activity as indicated by TTC-dehydrogenase activity was moderate (Table I).

All parameters except OM content were fit to significant multiple regression models as a function of direction. Two soil parameters, sand ($R^2 = 0.85$, Pr. > F = 0.0001) and clay ($R^2 = 0.88$, Pr. > F = 0.0001), had strong, but opposite trends across the field; sand tended to be higher at the top of the slope, while clay was higher at the bottom of the slope (*24*). Cyanazine sorption to soil also had a strong trend ($R^2 = 0.88$, Pr. > F = 0.0001), with increasing sorption to soils sampled from areas further down the slope. These trends are in agreement with the linear correlation of cyanazine sorption to clay (r = 0.93, Pr. > F = 0.0001) and sand (r = -0.90, Pr. > F = 0.0001), and support previous studies where clays had a higher capacity for cyanazine sorption (*25*). Several other parameters, such as extractable cyanazine amide at days 5 and 28, extractable hydroxy cyanazine derivatives and nonextractable ^{14}C at day 28, soil pH, and cyanazine half-life, had significant (Pr. > F = 0.0001), but moderate, surface response regressions as a function of direction across the field. Units for cyanazine sorption Kd are L kg^{-1} Cyanazine half-life, nonextractable ^{14}C at day 28, and soil pH tended to be higher in soil sampled from downslope, while cyanazine amide at day 5 and hydroxy cyanazine at day 28 were lower. Linear correlations between cyanazine half-life and clay were positive, while half-life was lower with increasing sand (Table II). Surface response regression with direction accounted for much less of the variability (Pr. > F 0.0001) in TTC-dehydrogenase activity ($R^2 = 0.25$), extractable polar hydroxy cyanazine at day 5 ($R^2 = 0.25$), and total extractable ^{14}C half-life ($R^2 = 0.27$). Polar hydroxy cyanazine derivatives at day 5 and extractable ^{14}C half-life were negatively correlated with clay and positively correlated with sand (Table II). There was limited relationship between microbial activity based upon TTC-dehydrogenase activity and cyanazine degradation parameters, except for non-extractable ^{14}C-residues and cyanazine amide at d 28.

Geostatistical evaluations were made to try to ascertain sources of variation other than direction across the field. Similar to the multiple regression analysis, all parameters, with the exception of OM content, had trends that could be modeled with a surface quadratic equation (Table III). For several parameters, including cyanazine half-life (Figure 1a) and sorption (Figure 1b), the greatest variations occurred at the west end of the field (bottom of slope). Trends were removed from the data and variography was performed on the residuals. No spatial structure could be modeled in the residuals for sorption, nonextractable ^{14}C on day 28, nor the polar metabolites and cyanazine amide on day 28 (Tables

Table I. Summary of Characteristics and Cyanazine Degradation Parameters in Soil from a No-Till, Wheat Cover Crop Managed Field.

*Parameter**	*Mean*	*Standard deviation*	*Minimum value*	*Maximum value*
Soil pH	6.40	0.48	4.54	7.07
Soil Organic Matter (%)	1.13	0.21	0.70	1.80
Clay (%)	17.9	7.3	10.1	36.7
Sand (%)	31.4	10.4	10.2	45.2
TTC-dehydrogenase	18.7	5.56	8.13	37.0
Cyanazine sorption (Kd)	1.08	0.38	0.73	2.27
Half-life total extractable ^{14}C (d)	24.6	4.10	11.3	34.8
Half-life cyanazine (d)	8.60	4.05	5.44	26.2
Hydroxy cyanazine derivatives, 5 d (%)	9.20	4.36	0	19.2
Cyanazine amide, 5 d (%)	18.0	4.09	7.07	27.7
Hydroxy cyanazine derivatives, 28 d (%)	38.6	12.30	3.57	56.5
Cyanazine amide, 28 d (%)	5.30	5.55	0	22.4
Non-extractable ^{14}C, 28 d (%)	26.4	6.08	15.6	41.4

*Units for TTC-dehydrogenase activity are nmole g^{-1} soil h^{-1}

III and IV). For these parameters, no spatial dependence existed over distances greater than 12.2 m (shortest distance between plots) other than the trend. However, this also suggests that spatial structure may have occurred at distances less than the shortest lag interval (12.2 m).

For parameters such as pH, TTC-dehydrogenase activity, and half-life of extractable ^{14}C, trends were removed, and it was determined that there was significant spatial structure in the residuals (Tables III and V). Semivariograms were modeled for the residuals of these parameters. These results suggest that for these parameters, in addition to the trend, spatial structure exists at distances greater than 12.2 m. Samples taken at these distances lack independence due to the trend (detected using the surface quadratic model) as well as localized autocorrelation (modeled using a semivariogram).

Discussion

No spatial structure, either trend or autocorrelation, was found for OM (Table III). In contrast, both a trend and spatial structure in the residuals for OM were observed in samples taken from the same positions the previous year (June, 1998) (24). These results demonstrate that the spatial structure of OM can change over a short period of time on sites where residue management is

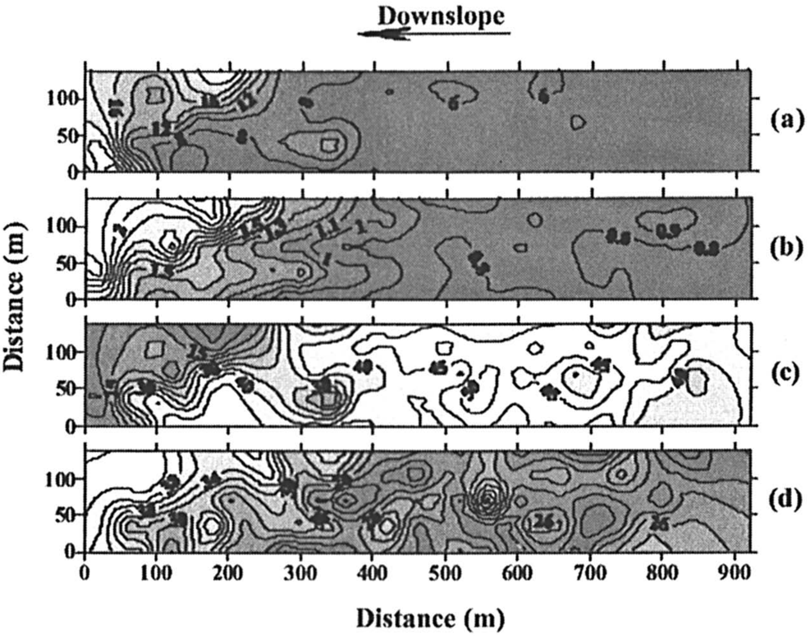

Figure 1. Semivariograms showing spatial distribution of selected parameters across the study area. (a) Cyanazine half-life (days); (b) Cyanazine sorption (K_d); (c) % polar cyanazine metabolites d 28; (d) % non-extractable ^{14}C d 28.

Table II. Correlation Coefficient (r) and Prob > F Between Soil Properties and Cyanazine Degradation Parameters.

Soil Characteristic	*Extractable Total ^{14}C Half-life*	*Cyanazine Half-life*	*Non-extractable ^{14}C (d 28)*	*Polar Hydroxy Cyanazine (d 5)*	*Cyanazine Amide (d 5)*	*Polar Hydroxy Cyanazine (d 28)*	*Cyanazine Amide (d 28)*
pH	0.69* 0.001**	-0.80 0.001	-0.61 0.001	0.62 0.001	0.50 0.001	0.84 0.001	-0.71 0.001
Soil Organic Matter	0.09 NS	-0.20 0.05	0.13 NS	0.31 0.002	-0.06 NS	0.22 0.03	-0.30 0.003
Clay (%)	-0.50 0.001	0.73 0.001	0.72 0.001	-0.50 0.001	-0.69 0.001	-0.74 0.001	0.62 0.001
Sand (%)	0.41 0.001	-0.69 0.001	-0.75 0.001	0.45 0.001	0.67 0.001	0.69 0.001	-0.58 0.001
Cyanazine Sorption (%)	-0.57 0.001	0.80 0.001	0.78 0.001	-0.51 0.001	-0.69 0.001	-0.79 0.001	0.63 0.001
TTC	-0.06 NS	0.12 NS	0.25 0.01	-0.02 NS	-0.21 0.04	-0.10 NS	-0.01 NS

* Pearson Correlation coefficients (r); ** Probability > F; NS=Not Significant

practiced. Overall, OM for 1998 was 1.02 % (0.7 to 1.5) versus 1.13 % (0.7 to 1.8) for 1999. With time, reduced tillage management at this location may result in even higher OM contents (*24*). The changes in OM are dependent on the growth of plants and subsequent plant material decomposition. Within a field, accumulation of plant residues and subsequent decomposition may be extremely variable, not necessarily related to soil characteristics, such as clay. This may have resulted in the lack of spatial structure observed in this area for OM.

The highest levels of cyanazine sorption occurred at the west end of the field (Figure 1a), an area that had highest levels of clay in the field. Sorption, however, did not appear to be related to OM in this study. These results vary with other studies (*18*) where the amount of cyanazine needed for weed control was directly related to soil organic matter. Reddy et al. (*19*) observed that cyanazine sorption was greater in no-tillage surface soil that had higher OM content than a corresponding conventional tillage soil. In this study, there was higher cyanazine sorption in the more acidic soil samples, reflecting increased affinity of the protonated herbicide with soil (*16*). Cyanazine sorption was also positively correlated with nonextractable ^{14}C at 28 days (Table II), indicating that some of the same factors enhancing sorption are also related to irreversible binding. For example, methanol-extractable hydroxy cyanazine was negatively correlated with sorption (Table II) and nonextractable ^{14}C ($r = -0.62$, Pr. > F = 0.0001). Other research has shown that hydroxy atrazine and cyanazine have a high affinity for soil and may not be completely extractable in methanol (*17, 26*). Since methanol was used as an extractant in the present study, it is likely that a portion of the hydroxy cyanazine derivatives were not extracted, thus contributing to the negative correlation with sorption and nonextractable ^{14}C.

Half-lives for cyanazine (5 to 26 days) are consistent with those reported in other studies (*27, 28*). Cyanazine half-life in soil was correlated positively with clay and negatively with pH (Table II, Figure 1a). Blumhorst and Weber (*16*) also observed an inverse relationship between pH and cyanazine half-life. In other research (*18*), however, they did not find a relationship between cyanazine bioactivity and clay content. The half-life of cyanazine was also positively correlated with sorption (Table II). Previous research supports evidence that herbicide sorption to soil contributes to protecting herbicide from degradation (*16; 29*). Either an increase in clay or more acidic conditions would increase sorption and reduce cyanazine degradation, thereby supporting the correlations observed with sorption and half-life.

Chemical degradation of cyanazine is pH-mediated, occurring under both low acidic (pH 4) and alkaline conditions (pH 10), with both dechlorination and nitrile hydrolysis occurring (*30*). Other research (*14*) indicated the major pathway for cyanazine degradation in soil was hydrolysis of the nitrile first to the amide, secondary hydrolysis of the amide to the acid, followed by dechlorination, with the major metabolite, the hydroxylated acid derivative, accumulating. In these present studies, the relationship between soil pH and extractable cyanazine metabolites was evident (Table II), but the pH range (Table I) was not at the extremes for pure chemical hydrolysis.

Table III. Spatial Characteristics of Soil Properties from a No-Till, Wheat Cover Crop Managed Field.

Parameter	*Significance of Trend*	*Nugget (Co)*	*Sill (Co+ C)*	*Q* $\frac{C}{(Co+C)}$	*Range*[1] *(Meters)*	*Model*
pH**	P < 0.0001	0.0221	0.1162	0.810	22.5	Spherical
Clay	P < 0.0001	0.0024	0.0048	0.500	62.4	Spherical
OM***	No Trend	NSS				
TTC*,**	P < 0.0001	0.0043	0.0147	0.707	23.5	Exponential

[1] Value is the effective range when exponential model is used.

*Log transformations were performed to removed trends in the residuals.

**Indicates that spatial structure is not conclusive.

***NSS found in raw data

Table IV. Summary of Spatial Characteristics of Cyanazine Metabolite Accumulation in Soil from a No-Till, Wheat Cover Crop Managed Field, Based on Thin Layer Chromatography Analysis 5 and 28 d after Treatment.

Parameter	*Significance of Trend*	*Nugget Co*	*Sill Co+ C*	*Q* $\frac{C}{(Co+C)}$	*Range*[1] *(Meters)*	*Model*
Polar metabolites (d 5)*	$p < 0.0001$	7.78	27.27	0.715	29.3	Exponential
Cyanazine amide (d 5)*	$p < 0.0001$	2.59	10.79	0.760	21.9	Spherical
Polar metabolites (d 28)**	$p < 0.0001$	NSS				
Cyanazine amide (d 28)**	$p < 0.0001$	NSS				

[1] Value is the effective range when exponential model is used.

*Indicates that spatial structure is not conclusive.

**No spatial structure (NSS) value is over short lag distances (<100m) - semivariance did increase at larger lag intervals but no sill/range could be modeled

Table V. Summary of Spatial Characteristics of Cyanazine Dissipation, (^{14}C Half-Life, Cyanazine Half-Life, Non-Extractable ^{14}C at 28 d, and Cyanazine Sorption) in Soil from a No-Till, Wheat Cover Crop Managed Field.

Parameter	*Significance of Trend*	*Nugget Co*	*Sill Co+ C*	*Q* $\frac{C}{(Co+C)}$	*Range meters*	*Model*
Extractable ^{14}C Half-life	P = 0.0216	24.20	63.64	0.620	77.7	Exponential
Cyanazine half-life*,**	P < 0.0001	0.0015	0.0090	0.831	28.1	Spherical
Non-extractable ^{14}C, (d 28)***	P < 0.0001	NSS				
Sorption***	P < 0.0001	NSS				

[1] Value is the effective range when exponential model is used.

*Log transformations were performed to removed trends in the residuals.

**Indicates that spatial structure is not conclusive.

***No spatial structure (NSS) value is over short lag distances (<100m) - semivariance did increase at larger lag intervals but no sill/range could be modeled

As soil pH approaches neutrality, biological degradation becomes more important, even though it was not evident by TTC levels in this study. TTC, although typically an indicator of microbial respiration (*22*), did not correlate with any parameter of cyanazine degradation, except for nonextractable ^{14}C at day 28. Blumhorst and Weber (*16*) suggested that formation of cyanazine amide and acid under neutral conditions was likely due to microbial activity. Wagner et al. (*31*) found that enhanced cyanazine degradation occurred upon the addition of crop residues or poultry manure that stimulated microbial activity.

Numerous bacterial cultures, e.g., *Pseudomonas* sp. ADP (*32*), *Rhizobium* strain PATR (*33*), *Alcaligines* strain SG1 (*34*), *Agrobacterium radiobacter* J14a (*35*), and *Ralstonia picketti* (*36*), have been shown to hydrolytically dehalogenate the related triazine, atrazine, via atrazine chlorohydrolase activity. The only atrazine-dechlorinating bacterial strain that has been shown to metabolize cyanazine is the *A. radiobacter* strain, thus limited information is available on microbial dechlorination of cyanazine (*35*).

In the present study, the polar derivatives (remaining at the origin in all three TLC solvents) corresponded with the R_f of hydroxy cyanazine derivatives (hydroxy cyanazine and hydroxy cyanazine acid). The highest accumulation of hydroxy derivatives (40 to 56%) was observed under more neutral soils at day 28, while the cyanazine amide (R_f 0.23) was found to be present only under slightly more acidic soil conditions. Very little cyanazine acid (<5%) was detected in the samples. Since cyanazine amide is one of the first byproducts of cyanazine degradation and is transient, its degradation pattern during incubation is a reflection of that of the parent, cyanazine. More extractable cyanazine amide was observed earlier (day 5) in the incubation period for most soils, regardless of variation in soil parameters (Table I). Extractable cyanazine amide early in the incubation, however, was positively correlated with soil pH and negatively correlated to clay (Table II), both soil factors important to cyanazine degradation. Cyanazine was degrading slower in soils with higher clay and lower pH, and corresponding lower cyanazine amide in these soils is likely a direct result. The opposite trends were observed for soil pH and clay correlations with cyanazine amide extracted four weeks later (day 28) (Table II).

In conclusion, the fate of cyanazine varied across the field. Regions with more acidic pH and higher clay contents had longer cyanazine half-lives. In the remainder of the field, hydroxy cyanazine derivatives appeared to be the primary metabolite produced, especially during the latter part of the incubation period. These observations may have implications for precision farming strategies. If an objective is to determine where changes in soil characteristics occur so that varying rates of chemicals can be applied, it is important to know where trends in soil characteristics occur within the field. Spatial structure is a significant issue for sampling in a research setting. For statistical purposes, samples must be independent, and this condition is not met if samples are taken where a trend or localized autocorrelation exists.

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Chapter 14

The Role of Vegetated Drainage Ditch Research in the Mississippi Delta: Current Results and Future Directions

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Since 1998, two vegetated agricultural drainage ditches within the Mississippi Delta Management Systems Evaluation Area (MDMSEA) have been used to determine whether ditches can effectively mitigate concentrations of pesticides associated with runoff. Through simulated storm events, pesticides and water were amended into drainage ditches at concentrations indicative of a typical runoff event. Study results allude to the value of ditch vegetation in transferring pesticides out of the aqueous phase, thereby mitigating potential risks to aquatic receiving systems. Between 95 and 97% of the total mass of pyrethroid insecticides amended was successfully transferred from the aqueous to plant material within three hours following the simulated runoff events. Pesticide toxicity evaluations provided data indicating remediation of contaminated ditch water and sediment following simulated storm events. Analysis of fate data indicated that ditches can effectively mitigate pesticide transport and risk of aquatic exposure within reasonable ditch lengths (50 to 400-m), depending upon contributing drainage area and assumed rainfall and runoff percentages.

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Introduction

Encroachment of human activities upon natural ecosystems has increasingly caused problems over the last century. In recent years the urbanization of formerly rural areas has transformed hill, forest, and farm land into housing subdivisions, retail outlets, and parking lots. These trends are not without an environmental cost. Land use changes may result in increased erosion and non-point source pollution. Historically agriculture has been targeted as a major contributor of non-point source pollution, and for draining wetlands and clearing timber in order to establish production acreage to meet growing demands of America's food and fiber requirements. There is little argument that agriculture is responsible for a proportion of the nation's water quality problems (*1*). Issues of suspended sediments, erosion, contaminant loads of bacteria (animal operations), nutrients, and pesticides are of concern to the agricultural community. In the cases of soil erosion and nutrient or pesticide runoff, both the farmer and users of the receiving water body are negatively affected. While the farmer is losing valuable soil and applied nutrients or pesticides, the receiving water body is negatively impacted by pollution.

Since agriculture is a major contributor of non-point source pollution, government agencies [primarily the United States Department of Agriculture's Agricultural Research Service (USDA-ARS) and Natural Resource Conservation Service (USDA-NRCS)] and universities have intensified their commitment to decreasing effects of non-point source pollution through developing and improving best management practices (BMPs). Several "edge-of-field" and agronomic BMPs exist with current guidelines for implementation widely available (*2-9*). Now, a new, innovative BMP is being suggested for implementation—vegetated agricultural drainage ditches.

Most agricultural production acreage is surrounded by a network of drainage ditches, which often leads to a receiving stream, river, lake, or reservoir. Historically these ditches have been managed according to their capacity to transport water discharged from fields following controlled releases (e.g. rice rields) or storm runoff events (*10*). In actuality, these ditches have additionally served as sites for contaminant transfer and transformation. The objective of this research is to evaluate the effectiveness of vegetated drainage ditches in mitigating concentrations of agricultural contaminants. If pollutants can be transferred from the water column to plant material via sorption, potential effects upon flora and fauna in aquatic receiving systems can be mitigated. On a broader scale, it is anticipated that this research will help develop a greater understanding of overall drainage ditch function and ecology and how those relate to issues of total maximum daily loads (TMDLs).

Materials and Methods

The Mississippi Delta Management Systems Evaluation Area (MDMSEA) is comprised of three experimental watersheds: Beasley Lake and Thighman Lake (both located in Sunflower County, Mississippi) and Deep Hollow Lake (located in Leflore County). Drainage ditch simulated runoff experiments were conducted within the Mississippi Delta Management Systems Evaluation Area (MDMSEA) in 1998 and 1999. One drainage ditch was chosen each year, with the first located in the Beasley Lake watershed (1998), while the second study was located in a drainage ditch within the Thighman Lake watershed. Both studies specifically examined the capability of a vegetated drainage ditch to reduce pesticide transport and the risk of aquatic exposure..

Beasley Lake Study

For evaluation in 1998, a 60-m portion of a drainage ditch leading into the riparian zone adjacent to Beasley Lake was chosen for evaluation. Sampling stations were located at 10 m up-ditch of the simulated runoff injection point, as well as 10-m, 20-m, 40-m, and 50-m down-ditch of the injection point. Pesticides examined in this study included the triazine herbicide atrazine (2-chloro-4-ethylamino-6-isopropylamino-s-triazine) and the pyrethroid insecticide lambda cyhalothrin [alpha-cyano-3-phenoxybenzyl-3-(2-chloro-3,3,3-trifluoro1-enyl)-2,2-dimethyl cyclopropanecarboxylate]. Assumptions for the simulated runoff event included a 2 ha contributing area subjected to a 0.64-cm rainfall (with 10% of the rainfall actually "running off"), and 5% of the applied pesticides (based on recommended application rates on 2 ha) being transported with the runoff. A total volume of 6400-L of water amended as simulated rainfall/runoff. No sediment was added to the simulated runoff mixture ensuring that the applied chemicals were biologically available. This is a conservative assumption relative to the real world. Pesticides and water were mixed in a 110-L polyethylene mixing chamber before being gravity fed into a 2-m length of 7.6-cm PVC pipe where delivery into the ditch occurred. In addition to pre-study sample collections, water was collected at time intervals 0.5 h, 1 h, 1.5 h, 2 h, 2.5 h, 3 h, 24 h, 7 d, 14 d, and 28 d post-exposure. Sediment and plants were collected prior to initiation of experiment, as well as 1 h, 3 h, 24 h, 7 d, 14 d, and 28 d post-exposure. Sediment collected for analysis came from approximately the top 4 to 6-cm of the ditch bed. Only those plant materials exposed in the water column (from top of sediment to top of the water column) were collected for analysis. All collected samples were analyzed for the presence of atrazine and lambda cyhalothrin using gas chromatography-electron capture detection (Tracor 540 gas chromatograph equipped with a Dynatech Precision GC-411V autosampler and a 15 m x 0.53 mm i.d. J&W DB-1 Megabore® column (*11,12*).

Thighman Lake Study

A similar study was conducted in 1999 evaluating a 650-m portion of a drainage ditch in the Thighman Lake watershed. Sampling stations were located 10 m up-ditch of the simulation injection point, as well as 10-m, 20-m, 40-m, 60-m, 80-m, 100-m, 200-m, 400-m, and 650-m down-ditch. Lambda cyhalothrin and bifenthrin [[2 methyl (1,1'-biphenyl)-3-yl] methyl 3-(2-chloro-3,3,3-trifluro-1-propenyl)-2-2-dimethyl-cyclopropanecarboxylate] were the pesticides evaluated in this ditch study. Assumptions for this simulated event included subjecting a 20 ha contributing area to a 0.64 cm rainfall (however, only 1% of rainfall actually "running off"), and 1% of the applied pesticides (based on recommended application rates for 20 ha) being associated in the runoff. Approximately 12,850-L of water were amended for the simulated rainfall/runoff. Pesticides were mixed and delivered to the drainage ditch system identically to the 1998 study. Water sampling collection times were every 15 minutes for 3 h, followed by collections at 6 h, 12 h, 24 h, 7 d, 14 d, 28 d, and 56 d. Sediment and plant samples were collected (as noted in previous section) at 30 min, 3 h, 6 h, 24 h, 7 d, 14 d, 28 d, and 56 d. Sample preparation and analyses were performed according to previously cited methods (*11,12*).

Results

Beasley Lake Study – Atrazine

Substantial initial sorption of atrazine to plant material took place at the injection point within 1 hour following initiation of the simulated runoff event (Table I). Mean atrazine concentrations for water, sediment, and plant material (including all sampling sites) 1 hour following the simulated storm event were 13.1 ± 5.58 mg/L, 2.78 ± 2.19 mg/kg, and 45.0 ± 36.0 mg/kg, respectively. Atrazine concentrations in plant material 3 h following the event ranged from 0.162 mg/kg (50-m site), which was 85% of measured atrazine at that site, to 37.5 mg/kg (injection point), which accounted for 80% of measured atrazine at the injection point. Concentrations of atrazine in plant material 24 h following the simulated event ranged from 0.404 mg/kg (50-m site), which was 57% of

Table I. Measured Concentrations of Atrazine in Beasley Lake Ditch at 1, 3, and 24 h Post-Runoff Event, 1998.

Time	*Sample*	*Units*	*Injection*	*10m*	*20m*	*40m*	*50m*
1 h	water	mg/L	19.50	28.50	16.80	0.452	0.005
	sediment	mg/kg	9.23	1.75	0.10	0.014	na
	plant	mg/kg	187.00	34.70	2.08	0.537	0.661
3 h	water	mg/L	6.82	21.20	31.70	1.24	0.008
	sediment	mg/kg	2.27	0.59	0.27	0.02	0.020
	plant	mg/kg	37.50	6.01	0.77	na	0.162
24 h	water	mg/L	0.01	0.049	0.051	0.170	0.241
	sediment	mg/kg	19.30	0.300	0.080	0.050	0.060
	plant	mg/kg	1.23	0.771	0.648	0.830	0.404

na = no sample available
Limit of Detection = 0.34 μg/L

measured atrazine at that site, to 1.23 mg/kg (injection point), which represented 6% of measured atrazine at that site. At 24 hours, 94% of the measured atrazine at the injection point was associated with the sediment (19.3 mg/kg). The initial mean atrazine water residue across sampling sites was 23 ± 14 mg/L, and within 7 to 14 days, concentrations had dropped below the ecotoxicity threshold of 20 μg/L (*13*).

Beasley Lake Study – Lambda cyhalothrin

Lambda cyhalothrin rapidly sorbed to aquatic vegetation within 1 hour (Table II). Mean lambda cyhalothrin concentrations in water, sediment, and plant (including all collection sites) were 0.11 ± 0.06 mg/L, 0.06 ± 0.03 mg/kg, and 3.2 ± 1.9 mg/kg, respectively. Lambda cyhalothrin concentrations in plant material 3 hours following the simuated event ranged from 3.01 mg/kg (at the 10-m site), which accounted for over 99% of the measured lambda cyhalothrin at that site, to

6.91 mg/kg at the injection point, which also represented over 99% of the measured lambda cyhalothrin at that particular site. Concentrations of lambda cyhalothrin in plant material at 24 h post-event ranged from 1.74 mg/kg (at the 50-m site), which accounted for 99% of measured lambda cyhalothrin at that site, to 11.3 mg/kg (at the 40-m site), again representing 99% of measured lambda cyhalothrin at that particular site. Of all the samples taken during the study duration, 97% of the measured lambda cyhalothrin was associated with plant material (0 = 3.3 ± 0.55 mg/kg), 2% was associated with sediment (0 = 0.06 ± 0.03 mg/kg), and 1% was associated with the water (0 = 0.03 ± 0.01 mg/L).

Table II. Measured Concentrations of Lambda cyhalothrin in Beasley Lake Ditch 1, 3, and 24h Post-Runoff Event, 1998.

Time	*Sample*	*Units*	*Injection*	*10m*	*20m*	*40m*	*50m*
1 h	water	mg/L	0.015	0.300	0.090	0.008	nd
	sediment	mg/kg	0.130	0.040	0.020	na	na
	plant	mg/kg	8.340	3.920	0.550	0.023	na
3 h	water	mg/L	0.015	0.034	0.208	0.003	0.0001
	sediment	mg/kg	0.030	0.010	0.010	na	na
	plant	mg/kg	6.910	3.010	3.510	na	na
24 h	water	mg/L	0.0003	0.001	0.001	0.002	0.003
	sediment	mg/kg	0.610	0.010	0.080	0.010	0.001
	plant	mg/kg	4.020	4.270	6.790	11.300	1.740

nd = non-detectable (< 0.05 μg/L)
na = no sample available

Thighman Lake Study – Bifenthrin

Within 3 hours, 98% of the measured bifenthrin within the entire ditch was associated with aquatic plant material (Table III). Mean concentrations of bifenthrin in water, sediment, and plant (incorporating all sampling sites) at 3 hours were 0.04 ± 0.03 mg/L, 0.018 ± 0.018 mg/kg, and 3.31 ± 1.79 mg/kg, respectively. At 24 h, bifenthrin concentrations averaged along the entire 650-m ditch were 0.002 ± 0.001 mg/L, 0.004 ± 0.003 mg/kg, and 3.2 ± 2.1 mg/kg for water, sediment, and plants, respectively. Bifenthrin was never detected in aqueous samples at the 650-m site.

Thighman Lake Study – Lambda cyhalothrin

Like bifenthrin, lambda cyhalothrin rapidly sorbed to aquatic vegetation by the 3 hour sample collection (Table IV). Overall ditch lambda cyhalothrin mean concentrations in water, sediment, and plants at 3 h were 0.02 ± 0.01 mg/L, 0.02± 0.01 mg/kg, and 3.37 ± 1.88 mg/kg, respectively. At 24 hours, mean lambda cyhalothrin concentrations in ditch water, sediment, and plants were 0.001 ± 0.0005 mg/L, 0.001 ± 0.001 mg/kg, and 1.2 ± 0.95 mg/kg, respectively.

Table III. Measured Concentrations of Bifenthrin in Thighman Lake Ditch at 3 h and 24 h Post-Runoff Event, 1999.

Time	*Sample*	*Units*	*Injection*	*50m*	*100m*	*200m*	*400m*	*650m*
3 h	water	mg/L	0.00001	0.051	0.028	0.0007	nd	nd
	sediment	mg/kg	0.09000	nd	nd	nd	nd	na
	plant	mg/kg	7.30000	8.030	1.140	0.0300	0.03	na
24 h	water	mg/L	0.011	0.006	0.0004	0.0005	0.0002	nd
	sediment	mg/kg	0.050	0.010	nd	nd	nd	nd
	plant	mg/kg	1.730	10.770	na	na	0.0700	na

No plants were available to sample at 650m
nd = non-detectable (< 0.05 µg/L)
na = no sample available

Discussion

With increased concern over water quality issues, renewed emphasis has been placed on development and implementation of TMDLs (*14*). Even though only about 50% of all 303(d) (Clean Water Act) impaired waters actually listed a

Table IV. Measured Concentrations of Lambda cyhalothrin in Thighman Lake Ditch at 3 h and 24 h Post-Runoff Event, 1999.

Time	*Sample*	*Units*	*Injection*	*50m*	*100m*	*200m*	*400m*	*650m*
3 h	water	mg/L	0.00003	0.031	0.017	0.003	nd	nd
	sediment	mg/kg	0.05400	0.009	0.006	0.005	0.003	na
	plant	mg/kg	8.79000	7.040	0.950	0.040	0.050	na
24 h	water	mg/L	0.00400	0.001	0.0004	0.0003	0.0001	nd
	sediment	mg/kg	0.00500	0.002	nd	nd	nd	na
	plant	mg/kg	0.52300	3.090	na	na	0.0200	na

No plants were available to sample at 650 m
nd = non-detectable (< 0.05 μg/L)
na = no sample available

suspected pollutant source, agriculture was the largest single contributor, potentially responsible for 24.6% of listed impairments. Using a moderately cost-effective TMDL program, it has been estimated that the annual cost for TMDL implementation for impairments due to cropland runoff alone will range between $183 million - $1.632 billion (*15*). Corrective action must be taken at the individual farm level in order to see improvement on a watershed scale. Because of the enormity of potential TMDL implementation costs, it is important to investigate practical, economical, yet environmentally-beneficial BMPs to combat non-point source runoff. Vegetated agricultural drainage ditches are proposed as one such example.

Various researchers have examined nutrient and herbicide trends in agricultural runoff through subsurface tile drainage and attendent effects upon receiving water quality (*16-22*). Most processes in research regarding surface agricultural drainage networks have been performed in the Netherlands. Research has primarily focused on models and relationships between ditch vegetation and eutrophication (*23,24,25*). Some intensive studies have examined fate and effects of various pesticides within "experimental" ditches (*26,27*). The primary difference between the current study and those previously reported is that ditch vegetation is now suggested as a valuable, manageable asset for mitigation of pesticide-associated agricultural runoff.

Findings on lambda cyhalothrin and bifenthrin sorption to plants in drainage ditches corresponds well with available literature (*28*). Most available literature examining atrazine fate in plants focuses more on phytotoxicity rather than actual sorption for mitigation purposes (29). Successful research using subsurface flow, gravel-bed constructed wetlands for mitigation of atrazine has been reported. This same research determined that microbial activity in plant roots was the major contributor for degradation and removal of atrazine (*30*).

While it is important to note the strength of pesticide sorption to ditch vegetation, another key goal within this research is to remove the pesticides from the water column. By partitioning pesticides out of the water into either the sediment or plants, the risk to aquatic receiving systems (e.g. rivers, lakes, streams, reservoirs, etc.) is diminished. If further studies continue to indicate the success of vegetated drainage ditches in mitigation of agricultural runoff, it will substantially aid the implementation phase of the TMDL program. Through continued research into the balance of vegetative cover and composition, as well as necessary length of drainage ditches, a more accurate and beneficial BMP for pesticide mitigation can be provided to the agricultural community.

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Chapter 15

Weed Populations as Related to Conservation Tillage and Reduced Herbicide Management Systems: Mississippi Delta Management Systems Evaluation Area

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Over a 5-year period, shifts in weed species composition and populations within weed species were detected in conservation tillage cotton (*Gossypium hirsutum* L.) and soybean [*Glycine max* (L.) Merrill] at the Mississippi Delta Management Systems Evaluation Area (MDMSEA) Deep Hollow (DH) site near Sidon, Leflore County, MS. At DH, plant populations were monitored to determine plant species composition, population levels, and weed shifts in cropland areas including conventional, conservation tillage, and reduced herbicide management systems. Plant species composition was determined for non-cropland areas including grass filter strips, field borders, riparian zones, and in and around the watershed lake. The number of weed species and number per species were greater in conservation tillage than in conventional planted cotton and soybean. Four primary types of weed shifts were detected in reduced input cotton and soybean production systems at DH: 1) populations decreased in cotton and soybean; 2) populations increased in cotton and soybean; 3) populations increased initially and then decreased; and 4) populations increased in one crop while remaining constant or decreasing in the other crop.

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Introduction

About 8,000 species or 3% of all known plants are considered to be weeds in agriculture. Of these, about 200-250 species, or less than 0.1% of the total of all plants, are recognized as major problems in world agriculture. Holm (*1, 2, 3*) estimated that about 200 species are involved worldwide in 95% of our agricultural weed problems. Of these, about 80 species are categorized as the primary or most troublesome species (*1, 2*). In the U. S., about 70% of the most troublesome and invasive weeds of row crops are exotic, having a center of origin somewhere else in the World (*4*).

Currently, over 200 species of plants have been recorded as weeds in cotton production in the U. S. (*5*). Weeds of cotton belong to 43 plant families and 19% are monocots (Monocotyledonae) while 81% are dicots (Dicotyledonae). About 30 to 40 species are important weeds throughout the U. S. Cotton Belt regardless of the tillage level (*6*). The number of weeds in soybean production is higher than in cotton. Soybeans are usually planted on a broader spectrum of soil types (e.g. lighter sandy to heavier clay soils), with less seedbed preparation in the spring, and usually with fewer tillage operations and herbicide applications (*6*). In addition, soybean production includes a larger portion of the United States and ultimately more environmental conditions than cotton (*6*).

Weed importance is not necessarily defined as abundance within the crop and may vary with differing herbicide regimes (*7*). In other words, the most common weeds are not necessarily the most troublesome. Some weeds may be very abundant in crops without causing interference, i.e. winter annuals that emerge, flower, and set seeds early enough that crop growth and yield are unaffected. The most troublesome and important weeds are those that are difficult to control and compete effectively with crops for light, nutrients, water, and space (*8*). In addition, some weeds interfere with crop harvest efficacy and reduce seed and lint quality (*5, 6, 7*). Ultimately, the most important weeds reduce economic returns to producers by interfering with crop growth, yield, harvest efficiency, and seed and fiber quality.

Recent changes in governmental regulations, scrutiny, and public opinion have motivated the agricultural community to examine current crop management practices (*9*). Research to develop new sustainable weed control technologies that reduce production costs and decrease environmental concerns is a high priority. Historically, post-emergence weed control is typically applied over entire fields. One of the recent technology advances was the development of hooded sensor sprayers that are able to detect and spray weeds only where they occur between crop rows (*10, 11, 12, 13*). Early research demonstrated that the sensor sprayers were very effective in controlling weeds, eliminating the need for cultivation. Additional reports on the use and economics of this technology are presented in this volume (Hanks and Bryson 2003).

MDMSEA was established as a consortium of federal, state, and local agencies to improve water quality and incorporate safe and effective innovative agricultural management systems in the Mississippi Delta. One of three MDMSEA sites, DH near Sidon, Leflore County, MS, was established to include edge-of-field and agronomic best management practices including erosion prevention structures, grass filter strips, conservation tillage, and reduced herbicide management systems.

The objective of our research was to establish a baseline list of plant species in the DH watershed and environs, to determine weed populations levels at the initiation of the project, and to detect shifts in weed species composition and populations at DH as a result of conservation tillage and reduced herbicide management systems.

Materials and Methods

The DH site selected for the study area included an area of cropland (soybean, cotton or cotton and soybean rotation) that had been under cultivation for more than a half century. In addition to the cropland areas, DH and environs included established grass filter strips along selected field borders (established in 1996), field borders, typical Delta Region bottomland hardwood forest, the levee along the Yazoo River, DH Lake and adjacent shore line with aquatic and semi-aquatic vegetation.

Plant species data were determined by two methods. The first method of sampling was to record each species by habitat for crop areas (cotton and soybeans), grass filter strips, field borders, riparian areas, and in and around the oxbow lake at DH. Plants were collected, and vouchers were placed in the Southern Weed Science Research Unit Herbarium (SWSL) at Stoneville, MS. Data were recorded and updated following the addition of the discovery of species new to the area or with a given habitat including cropland areas, grass filter strips, field borders, and riparian and aquatic areas.

In the second method, plants were counted by species in a 3 m long by 1 m wide area at points 62 m apart in reduced-tillage cotton and soybean fields in the DH watershed and in a conventional-tillage cotton field on the island and adjacent to the DH watershed area (ca. 250 ha). Points were measured and flagged in 1996 and GPS data were recorded for each point. In subsequent years (1997-1999), points were located again by GPS and flagged so that all data were obtained from the same plot area each year. Each 3 m^2 area was divided into two subunits, a 20 cm wide band along the drill (10 cm either side of the crop) and 80 cm row middles (40 cm either side to the 20cm band). Base-line weed species data were gathered at grid points in 1996 on May 9, May 30-31, June 19, June 27, and July 12, 1996. In 1997-1999, data were gathered twice (mid June and late June or early July) during each summer for each field, except for one third date in mid August 1997 for one soybean field. In each year, data were gathered prior to canopy closure, thus the late date of sampling in 1997 was due to late planted soybean. Weed nomenclature follows the accepted common and scientific names in Composite List of Weeds published by the Weed Science Society of America (*14*).

Soil survey data for DH (*15*) indicated that Dundee fine-silty, mixed, thermic Typic Endoaqualfs), Forestdale (fine, semectitic, thermic Typic Endoaqualfs), and Dowling (very-fine, semectitic, thermic Vertic Epiaquepts) are in decreasing area of occurrence and the major soil series of this study area. Spatial variability of these soil series and properties to selected weeds at DH and one of the other two MDMSEA sites, Beasley watershed, are described by Gaston et al. (*16*). Soil types, elevation, and slope varied between and within fields, but are not included here.

Conventional-tillage operations in cotton included fall sub-soiling, creation of rows, and spring double incorporation of preplant incorporated herbicides, rebedding, knocking the tops of the beds down, planting, and up to three subsequent cultivations for weed control per year. Reduced-tillage operations in cotton included fall subsoiling and row bedding and excluded spring tillage associated with preplant incorporated herbicide application and cultivations. In soybean, tillage operations were limited to bedding in the fall as needed to maintain the integrity of rows for the next planting season.

Because the data between crops (cotton and soybean) were unbalanced, means and standard error of means were calculated utilizing SAS (*17*) for each weed and for grass, sedge, and broadleaf weeds. Means and standard error of means were then converted to plants/ha.

Results and Discussion

From 1995 through 2001, 473 plant species were detected at DH and environs, representing 94 families (or > 60% of the documented flora of the Mississippi Delta Region). These included six species of ferns (Pteridophyta) and 467 species of flowering plants (Spermatophyta) of which two species in two families are conifers (Gymnospermae); 136 species and 14 families are Monocotyledoneae (monocots, including grasses, sedges, rushes, lilies, orchids, etc.); and 329 species in 74 families are Diccotyledoneae (dicots or broadleaf plants) (Figure 1). The number of species increased annually since the DH study surveys were begun in 1995 (*18*). Although there may be additional species that were not recorded (rare or overlooked), these data are sufficient to serve as a baseline for future species shifts within the DH watershed and environs.

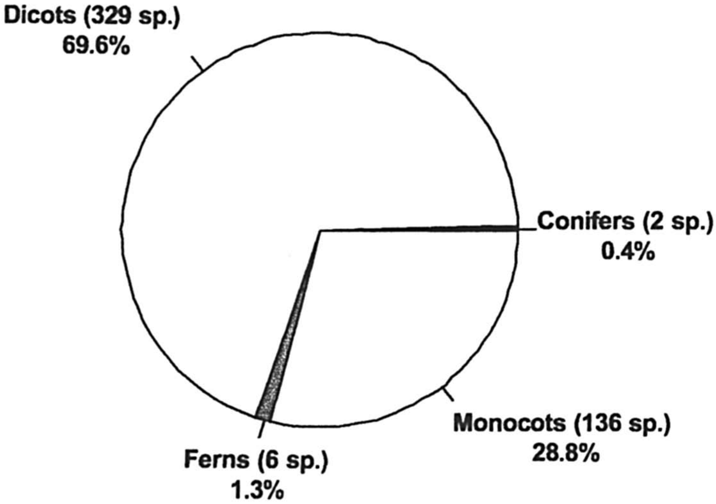

Figure 1. Composition of plant species at Deep Hollow Mississippi Delta Management Systems Evaluation Area (1995-2001).

The DH riparian area consisted of a typical bottomland hardwood forest predominated by oaks (*Quercus* spp.), pecan [*Carya illinoensis* (Wang.) K. Koch], elm (*Ulmus* spp.) and hackberry (*Celtis laevigata* Willd.) on the sandy, slightly elevated soils to oak, maple (*Acer* spp.), boxelder (*Acer negundo* L.), gum (*Nyssa* spp. and *Liquidanbar styraciflua* L.), bald cypress [*Taxodium distichum* (L.) Richard], cottonwood (*Populus* spp.), water hickory [*Carya aquatica* (Michaux f.) Nuttall], and locust (*Gleditisia* spp.) dominated areas in poorly drained, fine-textured soils along field drainage or near the lake. The forest understory was dominated by scattered shrubs and woody vines and numerous herbaceous species.

A total of 195 weeds (58 monocots and 137 dicots) were present in cropland at DH (Figure 2); however, only 76 species (24 monocots and 52 dicots) were present in both cotton and soybeans. In cropland areas, 29 weeds (2 monocots and 27 dicots) were detected in cotton exclusively, while 90 weeds (32 monocots and 58 dicots) were present in soybeans exclusively. Thus, more weeds were detected in soybeans (166 species) than in cotton (105 species). In cotton, 26 species were monocots and 79 were dicots, while in soybeans, 56 species were monocots and 110 were dicots. Likewise, the number of species (25, nine monocots and 16 dicots) was greater on the borders of soybean fields than the number of species (15, six monocots and nine dicots) on the borders of cotton fields. No conifers or fern species were found in crop areas.

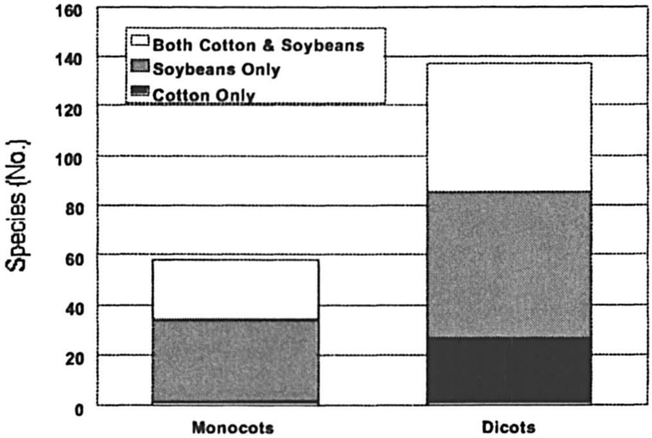

Figure 2. Composition of weed flora in cotton and soybean at Deep Hollow Mississippi Delta Management Systems Evaluation Area (1995-1999).

Weeds from the general surveys were classified into two distinct groups, 1) those that were historically reported as common or troublesome weeds of cotton, soybean, or other row crops and 2) those that were of incidental occurrence (data not shown). Sixty-eight species or species groups (closely related species within the same genus), i.e. 17 monocots and 51 dicots or 52 annuals and 16 perennials, were present in at least one of the grid point sites in cropland areas (Figure 2). These 68 weeds were previously recorded as weeds of cotton or soybean (*5, 18*). Fewer species were present in conventional cotton production than in reduced-tillage cotton and reduced-tillage soybean. Six woody species were found exclusively in the reduced-tillage crop areas (data not shown). Tansy mustard [*Descurania brachycarpa* (Richards.) O. E Schulz] was the only species reported by Gaston et al. (*19*) at another MDMSEA site in neighboring Sunflower County, MS, that was not present at DH.

Of the 25 most common weeds (plants/ha) presented in Table I, four were

Table I. Twenty-five Most Common Weeds at Deep Hollow, Mississippi Delta Management Systems Evaluation Area

Common name	*Scientific Name*
Annual bluegrass	*Poa annua* L.
Broadleaf signalgrass	*Brachiaria platyphylla* (Link.) A.S. Hitchc.
Carpetweed	*Mollugo verticillata* L.
Common chickweed	*Stellaria media* (L.) Vill.
Common purslane	*Portulaca oleracea* L.
Curly dock	*Rumex crispus* L.
Cutleaf eveningprimrose	*Oenothera laciniata* Hill
Cutleaf geranium	*Geranium disectum* L.
Honeyvine milkweed [2]	*Ampelamus albidus* (Nutt.) Britt.
Horsenettle	*Solanum carolinense* L.
Ivyleaf morningglory [1, 2, 3]	*Ipomoea hederacea* (L.) Jacq.
Johnsongrass	*Sorghum halepense* (L.) Pers.)
Pitted morningglory [1, 2, 3]	*Ipomoea lacunosa* L.
Prickly sida [1, 2, 3, 4]	*Sida spinosa* L.
Purple nutsedge [1]	*Cyperus rotundus* L.
Redvine [4]	*Brunnichia ovata* (Walt.) Shinners
Sibara	*Sibara virginica* (L.) Rollins
Sicklepod [3,4]	*Senna obtusifolia* (L.) Irwin & Barneby
Southern crabgrass [1, 2]	*Digitaria ciliaris* (Retz.) Koel.
Spurges [1, 2, 3, 4]	*Euphorbia* ssp.
Swinecress	*Coronopus didymus* (L.) Small
Trumpetcreeper [3, 4]	*Campsis radicans* (L.) Seem. ex Bureau

Among the most common [1] and most troublesome [2] weeds of cotton and most common [3] and most troublesome [4] weeds of soybean in Mississippi according to Dowler et al. (*20*).

winter or early spring annuals {one monocot [annual bluegrass (*Poa annua* L.)] and four dicots [common chickweed [*Stellaria media* (L.) Vill.], cutleaf geranium (*Geranium disectum* L.), sibara [*Sibara virginica* (L.) Rollins, and swinecress [*Coronopus didymus* (L.) Small]} and were detected only at the earliest survey dates in reduced-tillage cotton and reduced-tillage soybean areas. These winter and early spring annuals flowered, fruited, and died prior to mid season.

The most common summer annuals were southern crabgrass [*Digitaria ciliaris* (Retz.) Koel.], prickly sida (*Sida spinosa* L.), pitted morningglory (*Ipomoea lacunosa* L.), cutleaf eveningprimrose (*Oenothera laciniata* Hill), common purslane (*Portulaca oleracea* L.), ivyleaf morningglory [*Ipomoea hederacea* (L.) Jacq.], carpetweed (*Mollugo verticillata* L.), spurges {*Euphorbia* spp. [including *E humistrata* Engelm. ex Gray, *E. hyssopifolia* L., *E. nutans* Lag., *E. maculata* L.]}, broadleaf signalgrass [*Brachiaria platyphylla* (Link.) A.S. Hitchc.], and sicklepod *Senna obtusifolia* (L.) Irwin & Barneby (=*Cassia obtusifolia* L.) (1 monocots and 11 dicots), while the most common perennial weeds were purple nutsedge (*Cyperus rotundus* L.), redvine [*Brunnichia ovata* (Walt.) Shinners], curly dock (*Rumex crispus* L.), horsenettle (*Solanum carolinense* L.), and trumpetcreeper [*Campsis radicans* (L.) Seem. ex Bureau] (1 monocot and 4 dicots).

Weed population shifts were detected over the four-year study period (1996-1999) at DH. Within the DH watershed area, weed populations declined during the growing season each year and over the four-year study period, regardless of the species group. Species groups presented are sedges and grasses (monocots) and broadleaf weeds (dicots). Because total weed populations varied over time each year, average weed population data are presented for each year. Regardless of the weed group (broadleaf, grass, or sedge), weed populations were greater in soybean than in cotton from 1996 to 1999.

In 1996, sedge weed populations were greater in reduced-tillage soybean than in reduced- or conventional-tillage cotton production systems (Table II). In reduced-tillage soybean, sedge weed populations declined from 30,280 plants/ha in 1996 to 230 plants/ha in 1999. The number of sedges/ha in reduced-tillage cotton was less than in reduced-tillage soybean. In reduced-tillage cotton sedge populations declined from 1996 (11,080 plants/ha) to 1999 (0 plants/ha). With exception of 1996 (0 plants/ha), sedge weed population levels were similar in conventional-tillage cotton in 1997 and 1999 (6,850 and 4,050 plants/ha), but were higher in 1998 (12,300 plants/ha). In addition to sedge control with herbicides, an increase or decrease in sedge weed populations from one year to the next might be due to environmental conditions during April and May (i.e. rainfall during April and May of 1998 was greater than in 1999 at DH).

Table II. Average Sedge, Grass, and Broadleaf Weed Populations at Deep Hollow Mississippi Delta Management Systems Evaluation Area (1996-1999).

		Weed density (standard error)			
Crop	*Tillage*	*1996*	*1997*	*1998*	*1999*
		No./ha			
		Sedge weeds			
Soybean	Reduced	30,280	5,490	4,030	230
		(11,660)	(2,960)	(1,560)	(160)
Cotton	Reduced	11,080	3,980	2,410	0
		(5,150)	(1,590)	(1,430)	
Cotton	Conventional	0	6,850	12,300	4,050
			(4,620)	(10,640)	(3,830)
		Grass weeds			
Soybean	Reduced	64,440	7,860	18,480	970
		(13,250)	(1,190)	(3,080)	(570)
Cotton	Reduced	7,670	710	990	1,420
		(1,570)	(320)	(250)	(820)
Cotton	Conventional	0	0	50	0
				(50)	
		Broadleaf weeds			
Soybean	Reduced	83,130	41,580	38,970	90,00
		(8,650)	(4,210)	(4,460)	(2,730)
Cotton	Reduced	35,990	6,500	8,880	4,430
		(5,930)	(1,290)	(1,300)	(1,160)
Cotton	Conventional	0	970	3,200	315
			(5200	(1,720)	(180)

Grass weed populations were lower in reduced- and conventional-tillage cotton than in reduced- tillage soybean over the four-year period (Table II). In reduced-tillage soybean, grass weed populations decreased from 1996 (64,400 plants/ha) to 1997 (7860 plants/ha), but increased in 1998 (18,480 plants/ha), then sharply declined in 1999 (970 plants/ha). Grass weed populations declined in reduced-tillage cotton from 1996 (7670 plants/ha) to 1997 (710 plants/ha). In 1997, 1998, and 1999, grass weed populations were not significantly different in reduced-tillage cotton (710, 990, and 1,420 plants/ha, respectively). In conventional cotton production, grass weed populations were less than 50 plants/ha from 1996 to 1999.

As with sedge and grass weed populations, broadleaf weed populations were greater in soybean than in cotton during the four-year period (1996-1999) (Table II). After a decline in broadleaf weed populations in reduced-tillage soybean from 1996 (83,130 plants/ha) to 1997 and 1998 (41,580 and 38,970 plants/ha, respectively), populations increased in 1999 (90,000 plants/ha). Broadleaf weed populations were greater in reduced-tillage cotton each year (1996 to 1999) when compared to the conventional-tillage cotton. Broadleaf weed populations were 35,990, 6,500, 8,880, and 4,430 plants/ha in reduced-tillage cotton and 0, 970, 3,200, and 315 plants/ha in conventional cotton for 1996, 1997, 1998, and 1999, respectively.

Weed species shifts were detected within a crop, between crops (cotton and soybean), and between conventional and reduced-till cotton. Because weed populations varied during the season as well as between seasons, data are presented as means for the most troublesome weeds. Examples of weed shifts are presented in Tables III and IV. Weed shifts were most commonly categorized as 1) populations decreased in both crops (cotton and soybean) and examples included crabgrass (*Digitaria* sp.) and honeyvine milkweed; 2) populations increased in both crops such as trees and woody vines (data not shown); 3); populations increased initially and then decreased in both crops (cotton and soybean) and examples included barnyard grass [*Echinochloa crus-galli* (L.) Beauv.], ivyleaf morninglory, pigweeds (*Amaranthus* spp.), and trumpet creeper; and 4) populations increased, decreased, or remained the same over time in one crop while remaining constant or decreasing in the other crop and an example included goosegrass [*Elucine indica* (L.) Gaertn.

In glyphosate-resistant soybean in 1998 and 1999 and bromoxynil-resistant cotton in 1997 and 1998, many of the most troublesome grass, sedge, and broadleaf weeds were effectively controlled. However, weed populations of certain annual species increased, including pigweed when bromoxynil-resistant cotton was planted. In reduced-tillage and glyphosate-resistant soybean or bromoxynil-resistant cotton cropping systems, some perennial species, especially woody and viney species, increased early in the growing season, but acceptable weed control was obtained by the use of a hooded-sprayer or herbicide rotation.

Although weed populations fluctuated over time, population levels of only 12 of the 68 weed species (or species complexes) were higher in 1999 than at the initiation of this study (Table V). Thus, population levels of 56 weed species were lower or essentially the same during the four-year period (data not shown). Of these 12 species, three are perennials [bigroot morningglory (*Ipomoea turbinata* Lag.), horsenettle, and trumpetcreeper]; three species are annual grasses; and the remaining six are broadleaf annual weeds. Only carpetweed, a low growing annual, should have little competitive effect on cotton and soybean

Table III. Average Densities for Selected Grass Weed Populations at Deep Hollow Mississippi Delta Management Systems Evaluation Area (1996-1999).

		Weed density (standard error)			
Crop	*Tillage*	*1996*	*1997*	*1998*	*1999*
		No./ha			
		Barnyardgrass			
Soybean	Reduced	70	0	290	0
		(70)		(110)	
Cotton	Reduced	0	0	60	0
				(60)	
Cotton	Conventional	0	0	0	0
		Broadleaf signalgrass			
Soybean	Reduced	0	0	3600	0
				(1020)	
Cotton	Reduced	0	0	110	40
				(700	(40)
Cotton	Conventional	0	0	0	0
		Crabgrass			
Soybean	Reduced	59,760	7,120	13,850	510
		(12,800)	(1,130)	(2,800)	(360)
Cotton	Reduced	1,380	660	90	210
		(570)	(320)	(40)	(150)
Cotton	Conventional	0	0	0	0
		Goosegrass			
Soybean	Reduced	350	150	130	440
		(350)	(60)	(110)	(310)
Cotton	Reduced	0	30	430	1,140
			(300	(150)	(810)
Cotton	Conventional	0	0	50	0
				50	

growth and yield. Populations of a few species fluctuated over years and were greater as a result of environmental conditions, including seasonal rainfall [e.g. riceflatsedge (*Cyperus iria* L.) and yellow nutsedge (*Cyperus esculentus* L.)] and cooler or warmer than normal temperatures {e.g. cutleaf geranium, henbit (*Lamiun amplexicaule* L.), shephard's-purse [*Capsella bursa-pastoris* (L.) Medicus], and sibara}(data not shown).

The reductions in weed populations over time in the reduced-tillage cotton and soybeans may be due to the use of the hooded sprayer or glyphosate-resistant soybean and bromoxynil-resistant cotton. In addition, lower overall

Table IV. Average Densities for Selected Broadleaf Weed Populations at Deep Hollow Mississippi Delta Management Systems Evaluation Area (1996-1999).

		Weed density (standard error)			
Crop	*Tillage*	*1996*	*1997*	*1998*	*1999*
		No./ha			
		Honeyvine milkweed			
Soybean	Reduced	830	30	0	0
		(580)	(20)		
Cotton	Reduced	1,420	910	540	40
		(610)	(550)	(360)	(40)
Cotton	Conventional	0	0	450	0
				(450)	
		Palmleaf Morningglory			
Soybean	Reduced	0	180	230	30
			(100)	(200)	(30)
Cotton	Reduced	0	0	0	0
Cotton	Conventional	0	0	0	0
		Pigweed			
Soybean	Reduced	0	1,610	1,490	0
			(710)	(700)	
Cotton	Reduced	40	80	90	1,560
		(40)	(50)	(50)	(860)
Cotton	Conventional	0	190	0	50
			(190)		(50)
		Trumpetcreeper			
Soybean	Reduced	0	360	400	0
			(170)	(190)	
Cotton	Reduced	4,250	1,510	1,260	390
		(1,390)	(490)	(460)	(180)
Cotton	Conventional	0	50	720	90
			(50)	(590)	(90)

weed populations in the conventional and conservation production systems might be due to environmental conditions. In the evaluation period (1996-1999), summers were increasingly drier each year (data not shown). However, these results are encouraging for farmers because tillage operations typically associated with preplant, incorporated herbicide application and cultivations were not required to effectively control most weed species. Additional data is needed to determine if several of the woody species (e.g. bigroot morningglory, horsenettle, etc.) populations will increase in the reduced-tillage cotton and soybean areas regardless of the use of the level of reduced tillage or the use of hooded sprayer management technologies over a longer period of time in cotton and soybeans.

Table V. Weeds with Population Increases at Deep Hollow, Mississippi Delta Management Systems Evaluation Area Over a Four Year Period (1996-1999)

Common name	*Scientific Name*	*Crop*[1]
Bigroot morningglory	*Ipomoea turbinata* Lag.	SR
Broadleaf signalgrass	*Brachiaria platyphylla* (Link.) A.S. Hitchc.	CR
Carpetweed	*Mollugo verticillata* L.	CR
Cutleaf eveningprimrose	*Oenothera laciniata* Hill	SR
Goosegrass	*Eleucine indica* (L.) Gaertn.	CR
Horsenettle	*Solanum carolinense* L.	CR
Ivyleaf morningglory	*Ipomoea hederacea* (L.) Jacq.	CR; SR
Palmleaf morningglory	*Ipomoea wrightii* Gray)	SR
Pigweed	*Amaranthus* spp.	CC; CR
Spurges (4 species)	*Euphorbia* ssp.	CR; SR
Trumpetcreeper	*Campsis radicans* (L.) Seem. ex Bureau	CC

Crop[1] CC - Conventional-tillage Cotton; CR - Reduced-tillage Cotton; SR - Reduced-tillage Soybean.

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Chapter 16

A Watershed Based Bioeconomic Model of Best Management Practices in Mississippi

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This chapter presents an analysis that combines biophysical simulation models with economic optimization models to find the optimal combination of agricultural best management practices. The study investigates potential environmental impacts of alternative cultural practices within a small watershed over long periods of time, and proposes the best crop-management practices that can be achieved under different environmental standards.

Introduction

The purpose of this chapter is to demonstrate the use of simulation models to estimate the impacts that agricultural best management practices (BMPs) have in watersheds where they are introduced. The study examined potential effects of BMPs on both environmental quality and on profitability, which can be used to establish policies that promote BMP adoption. Although producers with a sense of environmental stewardship will adopt certain levels of BMPs,

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acceptance and optimal implementation of BMPs will ultimately depend on the effect of alternative cultural and structural practices on farm profitability. Weather conditions and other sources of uncertainty can make onsite experimentation using BMPs costly for individual farmers. To fully assess impacts on environmental quality and on profitability in terms of input costs and yields requires knowledge of how systems will perform under BMPs in the long run.

To evaluate the full scope of the economic effects of BMPs, impacts to agriculture at both the farm level and watershed level must be addressed. At the farm level, BMPs allow farmers to reduce soil loss and accompanying nutrient and chemical losses, providing benefits in the form of increased soil productivity. However, farmers may perceive that cultural and structural practices that prevent soil erosion would also result in reduced crop yields and/or increased costs. Thus, benefits from avoided soil loss might be countered by potential profit reductions, rendering BMPs unattractive to individual farmers. At the watershed level, societal benefits may accrue from reducing runoff that can degrade offsite water quality and ecosystems. It must be recognized, however, that BMP implementation in a watershed will require cooperative effort among farmers since the method will only be maximally effective if all producers participate. As with any economic activity that requires a coordinated effort to be successful, proper incentives for participation—such as maintenance of profit—must be considered.

Watershed and farm level economic impacts must be evaluated to understand the magnitude of gains and losses to individual farmers through use of BMPs. In this chapter, development of a bio-economic model is discussed to demonstrate novel ways in which farmers can use crop management practices to optimize profits as well as contribute to improvements in environmental quality. Because actual experience with BMP implementation will be correlated with exogenous factors, such as weather, a number of years' experience are needed to demonstrate the expected outcome on farm profits and environmental quality. By using simulation models, it is possible to generate a number of expected economic and environmental outcomes under various assumptions about BMP implementation.

Background

The three experimental watersheds in the Mississippi Delta Management Sytems Evaluation Area (MDMSEA) will ultimately provide a laboratory for developing bio-economic models that combine bio-physical models of soil erosion and water quality within various agricultural systems with economic optimization models. The MDMSEA watersheds surround oxbow lakes in heavily agricultural areas of the Mississippi Delta. This analysis focused on the Deep Hollow Lake watershed, located in LeFlore County, MS. The watershed is approximately 400 acres, surrounding a 20-acre lake, with nearly 250 acres under row crop cultivation. Both structural and cultural BMPs, as well as conventional practices, have been used in the farming system, and the primary crops are cotton and soybeans. It should be noted that the entire watershed is under the management of only one producer so that the individual farm model coincides with the watershed model.

A bio-economic small watershed model was used to calculate the impacts of alternative management systems. The model merged physical data and biological data to analyze various management decisions and to simultaneously determine optimal management in terms of profit and environmental quality. Site information such as cropping practices, soil types, topography and meteorological data were collected over a number of years in the project, but this paper focuses on the years 1998 and 1999 as the basis for the analyses, because full data on practices and weather were readily available for these years. In 1998 and 1999, crop BMPs such as no tillage or reduced tillage were used in this watershed.

Traditional farm models assume that a farmer's production decisions are constrained by various factors such as amount of land, cost of labor and other available inputs. An extension of the traditional model used in the analysis is a bio-economic model. In the bio-economic model developed, environmental quality becomes an additional consideration, and BMPs are included as inputs into the production process. The model was developed for the Deep Hollow watershed, and the model results were extrapolated over a 25-year time period; this time period was chosen in order to examine long-run impacts of practices under a wide variety of weather conditions. The underlying physical simulation model incorporates local weather conditions in the watershed, nutrient uptake and the timing of planting and harvesting of crops, as well as existing and potential cultural and structural BMPs.

The bio-economic model used the Agricultural Policy Environmental Extender, or APEX *(1, 2)*, which was developed as an extension of the EPIC (Erosion-Productivity Impact Calculator) model to small watershed level by the US Department of Agriculture's Agricultural Research Service (ARS), Soil Conservation Service (SCS), and Economic Research Service (ERS) in the early 1980's *(3, 4)*. APEX is designed to simulate bio-physical processes and the interaction of cropping systems with management practices, soils and climates over long time periods. APEX captures times of planting and harvesting and the use of cultural BMPs, and produces environmental parameters where water flows through small watersheds as surface, channelized and subsurface flow. APEX has flexibility in allowing for model calibration with existing data. In this study, our model was calibrated to correspond with onsite empirical measures of environmental parameters.

APEX is a relatively recent extension to EPIC, and has been demonstrated as a tool for predicting changes in NPP from global warming *(5)*. Although few studies exist using APEX, there is a wide body of literature using EPIC to measure edge of field environmental and economic impacts. For example, Smith et al *(6)* used EPIC to demonstrate the reductions of edge of field runoff of nutrients and sediment and the expected changes in profit under conventional and no-till practices, and Forster et al *(7)* compared edge of field predictions from EPIC with actual water quality in two Lake Erie watersheds. Chapman *(8)* uses data from the Ohio MSEA site near Piketon, Ohio and EPIC to demonstrate the impact of nitrogen taxes on the economic well being of farmers.

Analytical Approach

The analytical approach used a two-part process. In the first stage of analysis, the bio-physical model, using APEX to estimate runoff and yields under a number of scenarios was developed, and included combinations of crops and tillage practices. The outputs of interest from this model were expected crop yields and expected runoff of nitrogen, phosphorous and sediment. In addition, scenarios were developed in which filter strip practices were examined. In the second stage of analysis d the Generalized Algebraic Modeling System (GAMS) *(9)* was used, along with information on yields, crop prices, production costs and environmental parameters derived from APEX to estimate optimal cropping systems with and without environmental constraints. Optimality of the system was determined by maximizing profit across the entire watershed.

Watershed Level Physical Model

The watershed level model used data inputs that replicated physical, meteorological and agricultural characteristics of the Deep Hollow Watershed. The watershed consists of ten fields in which the primary crops grown have been cotton and soybeans. Within the watershed, there are six different soil types: Alligator, Arents, Arkabutla, Dubbs, Dundee and Tensas. In each field is a combination consisting of two to three soil types resulting in 22 subfields of unique soils (see Figure 1 and Table I for details).

Approximately 20 inputs into the APEX model were needed for each subfield in order to perform simulations from which to obtain expected yields and nutrient and sediment runoff. The inputs included weather, soil type, soil erodibility factors, topography (as measured by average slope length and steepness), distance from fields to watercourses, relative geographic location of fields within the watershed, crop rotation, tillage practices and fertilizer and chemical use. As part of the MDMSEA project, the soils and topography of these fields have been measured to a high degree of accuracy, and onsite meteorological monitoring

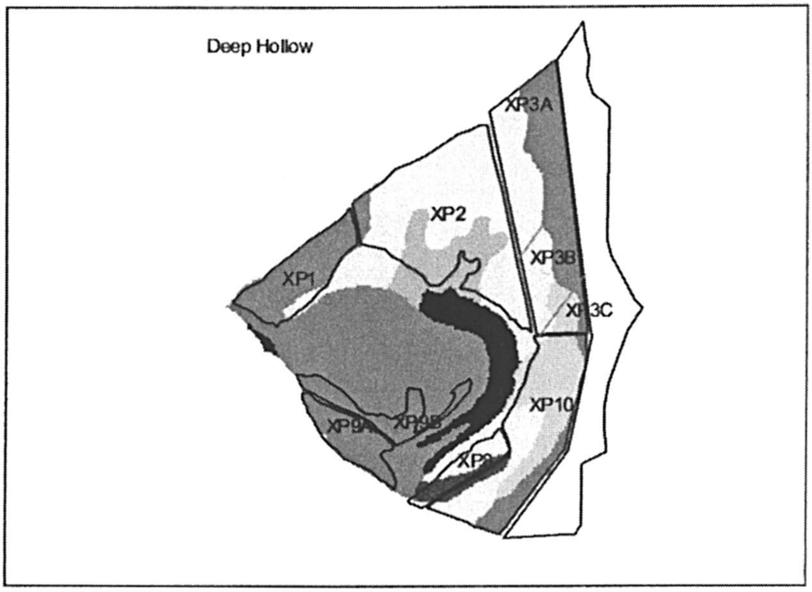

Figure 1. Soil map and fields—Deep Hollow watershed

Table I. Composition of Subfields in Deep Hollow Watershed, MS

Field ID	*Acres*	*Soil*	*% Soil*
XP3A	24.8	Dubbs	7.75
XP3A		Tensas	3.11
XP3B	12.0	Dubbs	2.25
XP3B		Tensas	1.55
XP3B		Dundee	1.04
XP3C	12.4	Dubbs	0.66
XP3C		Dundee	1.04
XP10	37.1	Tensas	6.99
XP10		Dundee	8.30
XP10		Dubbs	1.80
XP1	17.2	Arkabutla	12.27
XP2W	29.5	Tensas	14.09
XP2W		Alligator	3.18
XP2W		Arkabutla	1.24
XP2E	29.5	Tensas	14.50
XP2E		Alligator	3.28
XP2E		Arkabutla	1.24
XP8	9.0	Alligator	2.36
XP9A	12.6	Arkabutla	6.04
XP9A		Arents	2.10
XP9B	10.6	Arents	1.57
XP9B		Arkabutla	3.64

provided weather data for several years *(10)*. In addition, as part of the project, onsite monitoring of runoff of nitrogen and sediment provided some limited historical data that were used to calibrate the APEX model.

Using the Deep Hollow watershed as the study area, scenarios were simulated under a number of assumptions in order to find out how cultural practices and BMPs might affect yields and environmental outputs over a 25-year time period. The specific scenarios included crop-tillage combinations under conventional tillage, conservation tillage and no-till. The crops considered were continuous cotton, continuous soybeans, and a cotton/soybean rotation. Using runoff data obtained through the MDMSEA study, the model was calibrated to reflect actual conditions onsite. That is, known runoff levels, cultural practices and weather obtained through the physical study were used to develop a simulation model that had the same characteristics in terms of runoff and practices as the actual watershed. After calibrating the model to the known watershed parameters, model simulations were run using different crop combinations, cultural practices and filter strips in order to obtain estimates of long-run annual environmental impacts and crop yields. These outputs were generated from the APEX model in order to use them as inputs to the economic optimization model described in the next section.

Watershed Level Economic Model

To investigate the impact of various practices in the watershed on profit and environmental quality, a series of mathematical models were developed in which the maximum watershed profit was determined under a number of constraints. MDMSEA personnel have collected 5 years of budget and operations data (1996-2000) for the watershed, and these data provided important inputs for the economic model. That is, from the budget and operation data, it was possible to derive input and output prices, labor and machinery costs, and so on. The model was run using a number of different constraints, including acreage, labor and, in some cases, environmental standards. This model was used to investigate economic and environmental impacts under decreasing levels of restriction on cropping and increasing levels of restrictions on nonpoint pollution. For example, three cases in which continuous cotton was the sole crop were examined, and the cultural practices were varied to include conventional till, conservation till and no till. In a different scenario, the model was optimized over combinations of continuous cotton, continuous soybeans and a cotton/soybean rotation, while imposing constraints upon the amount of N or sediment allowed as runoff.

The outputs of the economic optimization model included total expected watershed profit, optimal cropping (i.e. crop acreage and practices to be used in each subfield), and gross expected nitrogen (N), phosphours (P) and sediment (S) runoff in the watershed. Thus the model could predict, for a given scenario, which crops should be planted in which field under which practice in order to obtain the maximum profit while still achieving a certain environmental goal.

Results

The results of the bio-economic model reported are broken out by the APEX, or bio-physical, model and by the GAMS, or the economic optimization model.

The Bio-Physical Model

The APEX model was run for a 25-year period based on each type of crop grown on each subfield, and the output reported in the tables includes expected annual yields, expected annual runoff of nitrogen, phosphorous and sediment under different crop/practice combinations. There are nine different scenarios comprised of three practices (conventional, conservation and no till) for each of continuous cotton, continuous soybeans and a cotton/soybean rotation.

The APEX model was run for each of the 22 subfields in the watershed for each of the nine scenarios outlined above. Outputs obtained were expected crop yields and environmental outcomes. Table II provides yield simulation data obtained for each of the 22 subfields, as defined by soil type within a field. Yields reported in Table II represent averages over the simulation time horizon. The mean runoff values for nitrogen, phosphorous and sediment under different tillage practices can be found in Table III. Table III specifically reports the 25-year expected nutrient and sediment runoff for each scenario. As can be seen, runoff parameters associated with sediment loss decreased with decreased tillage intensity, while nitrogen runoff tended to increase with decreased tillage due to reduced topsoil permeability. It should be noted that measurements in Table III are in lb per acre and net tons.

Obviously, in terms of environmental outcomes, there are trade-offs among the various tillage practices. Soybean cultivation may provide a way to mitigate nitrogen runoff, as compared to cotton. Cotton/soybean rotations might also result in lowering of runoff in some cases.

The Economic Model

If the goal were to reduce the runoff in a watershed, it would be a fairly simple task to find combinations of tillages and crops to make environmental improvements. However, producer profits are an important consideration, and thus, considerations of the profitability of the various scenarios come into play. In a simple model of profitability, one can calculate the average profitability of the various scenarios by multiplying bushels per acre of output of each crop by acreage and price, and then subtract costs associated with each practice. However, such a model cannot be used to optimize profits for the complete watershed, simultaneously taking into account the contribution of each subfield to profit and runoff, as does the model used in this analysis.

The economic model used is one in which profit is maximized to find the optimum amount of land to plant in different tillage/practice combinations. A

Table II. Expected Yields for Subfields in the Watershed

Field and Soil Type		*Continuous Cotton*	*Continuous Soybean*	*Cotton/Soybean Rotation*	
XP3A	Dubbs	1118.65	24.01	1176.83	24.30
XP3A	Tensas	1107.94	24.17	1168.27	24.42
XP3B	Dubbs	1121.15	24.01	1176.83	24.28
XP3B	Tensas	1107.94	24.15	1168.62	24.43
XP3B	Dundee	1126.86	23.93	1181.83	24.20
XP3C	DuObbs	1122.58	24.03	1177.55	24.28
XP3C	Dundee	1129.71	23.93	1182.90	24.19
XP10	Tensas	1108.30	24.17	1168.98	24.46
XP10	Dundee	1127.93	23.93	1182.19	24.19
XP10	Dubbs	1122.58	24.03	1177.55	24.30
XP1	Arkabutla	1110.44	24.36	1170.05	24.39
XP2W	Tensas	1108.30	24.41	1167.20	24.43
XP2W	Alligator	1106.87	24.43	1165.05	24.46
XP2W	Arkabutla	1111.16	24.39	1170.05	24.41
XP2E	Tensas	1109.01	24.17	1167.55	24.43
XP2E	Alligator	1106.87	24.19	1165.77	24.44
XP2E	Arkabutla	1110.44	24.15	1169.34	24.41
XP8	Alligator	1105.80	24.19	1167.20	24.44
XP9A	Arkabutla	1110.80	24.12	1169.69	24.41
XP9A	Arents	1149.35	23.52	1202.18	23.82
XP9B	Arents	1148.28	23.45	1202.89	23.71
XP9B	Arkabutla	1110.44	24.07	1170.41	24.31

simplified version of the basic model is given by:

$$\text{Max}\ (PY-C)^{*}X_{f,t,c} \qquad (1)$$
$$\text{Subject to}\ X \leq L$$

In this case, P represents a vector of crop prices, and Y represents a vector of acres per bushel, X is the planted acreage, and L is total available land. The subscripts on X represent subfield, tillage practice and crop practice. The model given by Equation 1 maximizes profit subject to the constraint on land.

Table III. Expected Runoff under Different Tillage Practices and Crops for Nitrogen (N), Phosphorus (P) and Sediment (S)

Tillage Practice	*Cotton*		
	N lb/acre	*P lb/acre*	*S ton/acre*
Conventional	5.6000	0.2018	0.3277
Conservation	5.9296	0.1990	0.3153
No Till	5.8610	0.0306	0.1192

Tillage Practice	*Soybean*		
	N lb/acre	*P lb/acre*	*S ton/acre*
Conventional	2.0686	0.1143	0.3962
Conservation	2.0723	0.1138	0.3731
No Till	1.8203	0.0345	0.1241

Tillage Practice	*Cotton/Soybean*		
	N lb/acre	*P lb/acre*	*S ton/acre*
Conventional	3.2795	0.1234	0.3658
Conservation	3.3438	0.1192	0.3424
No Till	3.0810	0.0339	0.1202

The model was used to estimate three base-case scenarios (see Tables IV and V), one each for conventional, conservation and no till practices. The model outputs for each scenario included the total watershed profits, expected total watershed environmental parameters, and an optimal allocation of fields to various crops. In addition, the model was used to generate similar outputs for the watershed under the practices that were in place in 1999 (see Table VI). Inputs to the model were the environmental and yield parameters obtained from the APEX runs and economic data collected at the site as part of the MDMSEA

Table IV. Optimization Model Base Case Scenarios—No Environmental Constraint (Conventional and Conservation Tillage)

Conventional Tillage			*Conservation Till*		
Field No.	*Planted Acreage—Continuous Cotton*	*Returns Per Field*	*Planted Acreage—Continuous Cotton*	*Planted Acreage—Cotton/ Soybean Rotation*	*Returns Per Field*
XP3A	21.144	$2,118.941	21.144		$1,833.208
XP3B	9.423	917.745	6.406	3.017	788.802
XP3C	3.310	329.819	3.310		285.299
XP10	33.274	3,130.174	19.665	13.609	2,662.361
XP1	23.890	2,192.799	23.890		1,863.921
XP2W	36.039	3,287.423	36.039		2,801.324
XP2E	37.032	3,356.545	37.032		2,875.648
XP8	4.595	455.570	4.595		392.314
XP9A	15.849	1,656.176	15.849		1,441.213
XP9B	10.144	1,084.011	10.144		948.932
Total Watershed Profit $18,529.203			Total Watershed Profit $15,893.022		
Environmental Outcomes			*Environmental Outcomes*		
Nitrogen Runoff (lbs/acre)		1,090.328	Nitrogen Runoff (lbs/acre)		1109.643
Phosphorous Runoff (lbs/acre)		39.287	Phosphorous Runoff (lbs/acre)		37.298
Sediment Loss (net tons)		63.811	Sediment Loss (net tons)		62.151

Table V. Optimization Model Base Case Scenarios—No Environmental Constraint (No Till)

No-Till			
Field No.	*Planted Acreage—Continuous Cotton*	*Planted Acreage—Cotton/Soybean*	*Returns Per Field*
XP3A	21.144		$1,499.364
XP3B	6.406	3.017	643.257
XP3C	3.310		236.302
XP10	19.665	13.609	2,131.880
XP1		23.890	1,513.603
XP2W	36.039		2,280.243
XP2E	37.032		2,327.147
XP8	4.595		326.844
XP9A	15.849		1,203.519
XP9B	10.144		785.883
Total Watershed Profit			$12,948.042
	Environmental Outcomes		
Nitrogen Runoff (lbs)			1,027.466
Phosphorous Runoff (lbs)			6.072
Sediment Loss (net tons)			22.879

project. The economic data include costs of all inputs and outputs. It should be noted that units of measurement are in lbs/acre and English tons in this analysis.

Comparing the results of the model, as under the 1999 practices and under the various optimal scenarios, it can be seen that 1999 practices are suboptimal in terms of profit. By allocating the fields among continuous cotton and a cotton/soybean rotation, significant increases in profit can be made with less runoff. The three baseline scenarios have gross profits ranging from a low of $12,948.04 for no till to a high of $18,529.20 for conventional tillage.

Conventional tillage had a 6.1% higher level of N runoff and almost 179% higher level of sediment runoff than no-till for the watershed as a whole.

After running the baseline model, which constrained operations to one type of cultivation practice, the model was allowed to choose optimal combinations of

Table VI: 25-year Simulation Results Using Actual 1999 Practices

Actual Practice—All Conservation Tillage

Field Number	*Planted Acreage—Continuous Cotton*	*Planted Acreage—Continuous Soybean*	*Returns Per Field*
XP3A	21.144		$2,118.941
XP3B	9.423		917.745
XP3C	3.310		329.891
XP10	33.274		3,130.174
XP1		23.890	1,357.412
XP2W		36.039	1,799.645
XP2E		37.032	1,418.709
XP8		4.595	262.829
XP9A		15.849	915.997
XP9B		10.144	601.724
Total Watershed Profit			$12,853.067
		Environmental Outcomes	
Nitrogen Runoff (lbs)			633.504
Phosphorous Runoff (lbs)			29.206
Sediment Loss (net tons)			74.092

both tillage and crops, but to incorporate constraints on the amount of runoff that was allowed. There were two assumptions for environmental constraints, the first being a 20% reduction in nitrogen runoff, and the second being a 20% reduction in sediment runoff. The general form for the nitrogen-constrained model is given in Equation 2.

$$\text{Max}\ (PY\text{-}C) \bullet X_{f,t,c} \qquad (2)$$
$$\text{Subject to: } X \leq L, \text{ and } \eta \bullet X \leq \textit{Base N Runoff} \bullet (1\text{-}0.20).$$

This model differed from that of Equation 1 by the inclusion of an additional constraint for a 20% N reduction, where η is the nitrogen runoff obtained from APEX that is associated with each field activity. The sediment-constrained model follows the same form as the nitrogen-constrained model and is given by Equation 3.

$$\text{Max}\ (PY\text{-}C) \bullet X_{f,t,c} \qquad (3)$$
$$\text{Subject to: } X \leq L, \text{ and } \sigma \bullet X \leq \textit{Base Sediment Runoff} \bullet (1\text{-}0.20).$$

Table VII: Optimization Model with Environmental Constraint—N-Standard

20% N-Reduction Regulation

Field No.	*Planted Acreage—Continuous Cotton*	*Planted Acreage—Cotton/Soybean*	*Conventional Tillage Acreage*	*No-Till Acreage*	*Returns Per Field*
XP3A	21.44		15.089	3.028	$2,093.184
XP3B	9.423		4.381	2.521	902.706
XP3C	3.310			1.655	311.225
XP10	27.222	6.053	3.505	14.885	2,808.109
XP1	23.890			11.945	2,164.926
XP2W	36.039		33.625	1.207	3,275.003
XP2E	37.032		18.611	9.210	3,188.682
XP8	4.595		4.595		455.570
XP9A	15.849		15.849		1,656.176
XP9B	10.144		10.144		1,084.011
Total Watershed Profit				$17,939.592	

Environmental Outcomes

Nitrogen Runoff (lbs)	872.262
Phosphorus Runoff (lbs)	31.148
Sediment Loss (net tons)	63.811

Table VIII Optimization Model with Environmental Constraint-S-Standard

20% S-Reduction Regulation

Field #	*Planted Acreage— Continuous Cotton*	*Planted Acreage— Cotton/ Soybean*	*Conventional Tillage Acreage*	*No-Till Acreage*	*Returns per Field*
XP3A	21.144		21.144		$2,118.941
XP3B	6.406	3.018	6.406	1.509	835.246
XP3C		3.310	3.310		236.302
XP10	33.274		33.274		3,130.174
XP1	3.672	20.218	3.672	10.109	1,617.991
XP2W	33.625	2.414	36.039		3,219.787
XP2E	8.800	28.231	37.032		2,576.664
XP8	4.595		4.595		455.570
XP9A	15.849		15.849		1,656.176
XP9B	10.144		10.144		1,084.011

Total Watershed Profit	$16,930.862

Environmental Outcomes

Nitrogen Runoff	1,043.82
Phosphorus Runoff	29.377
Sediment Loss (net ton)	51.049

In this case, σ is the sediment runoff obtained from APEX.

The results of the models (Tables VII through VIII) show that a policy of nitrogen reduction to 80% of its baseline level may be significantly less costly to producers than a policy that restricts sediment to 80% of the baseline (Table IV, conventional till). That is, producer profits might be increased by nearly 6% if sediments rather than nitrogen are constrained. It is notable that the sediment constrained model profit is 40% higher than the actual practices model, yet sediment levels are only 86% of the actual practices model, N levels in the constrained model are 37% higher. Since sediment is a more serious problem than nitrogen runoff in the Mississippi Delta, these results suggest that a tradeoff of more nitrogen runoff for less sediment runoff might be optimal.

An interesting feature of the constrained maximization models is that they provide shadow costs for the type of runoff that is under constraint. The shadow price can be interpreted as being the amount of tax that would have to be placed on a polluter in order to make it economically optimal for the polluter to reduce pollution by a certain amount. In the case of the nitrogen-constrained model, the shadow price per pound of nitrogen runoff reduction is $3.25. That is, if the producer were to be charged this amount for every pound of nitrogen running into the watershed, then his optimal profit would occur at the point where nitrogen runoff is reduced by 20% (i.e. 872.262 lbs for the watershed in one year). Likewise, in the sediment-constrained model, the shadow price was $125.799 per English ton. Thus, a farmer would maximize profits at the point where total annual sediments for the watershed are 51.049 tons.

Conclusion

This analysis has significant implications for control of non-point pollution at the watershed level. First, it found that both in terms of profit and taxes (as measured by the shadow price), a nitrogen standard might be a much cheaper policy to institute in the case of the Deep Hollow watershed. In this example, given a sediment standard (20% reduction from baseline), total watershed profits would be $16,930.862, but the total tax on sediment would be $6,421.91, if collected. The profits for the nitrogen standard would be $17,939.59 for the watershed, while total taxes would be just $207.19.

Another policy implication that arises from the nitrogen and sediment constrained models is that for constraint of nitrogen, certain acreage might be taken out of production entirely. The model can potentially aid in identifying marginal land that might be put into Conservation Reserve Programs (CRP), or similar programs. Such programs might insure that environmental goals are met, while still allowing the producer to make a profit. In addition, the analysis may be extended to incorporate filter strips. Allowing filter strips in the model should result in quite different results in terms of optimal cultivation practices.

A final caution in interpreting the results of this analysis is in order; that is, the economic model is extremely sensitive to the results of the APEX model. Therefore, it is essential to obtain good quality on-site data to calibrate the bio-physical model. Once such on-site calibration can be achieved, the model may predict significantly different results than those found here. However, the model shows promise for helping to determine optimal watershed policies as well as to guide producers' cropping decisions.

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Chapter 17

Herbicide and Nitrate in Surface and Ground Water: Results from the Iowa Management Systems Evaluation Area

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The Management System Evaluation Area (MSEA) program sponsored multidisciplinary research at plot, field and watershed scales. Like the Mississippi Delta MSEA, water quality research in the Iowa MSEA targeted herbicide and nitrate transport and fate in different hydrogeologic settings. In central and northeast Iowa, herbicides were transported from fields in runoff and in subsurface drainage water. Herbicides leached to groundwater, but concentrations generally remained below the maximum contamination level (MCL). Relative losses of different herbicides were related to their persistence patterns in soil and soil permeability. In contrast to herbicides, nitrate concentrations in stream water often exceeded the MCL and losses were controlled by subsurface drainage. Nitrate losses are affected by fertilization, mineralization of soil nitrogen, and timing of spring rainfall. Tillage affects nitrate loss indirectly, through changes in water infiltration. The MSEA program established knowledge about the routes of contaminant entry into surface waters, contaminant sources and effects of selected practices.

In Water Quality Assessments in the Mississippi Delta; Nett, M., et al.;
ACS Symposium Series; American Chemical Society: Washington, DC, 2004.

Farming systems in the upper portion of the Mississippi River drainage basin have a significant influence on water quality in small and large stream systems. The sediment, nitrate, phosphorus and pesticides leaving agricultural lands impact local streams and lakes, groundwater, and large bodies of water, such as the Great Lakes and the Gulf of Mexico. The purpose of this chapter are to review other research conducted under the auspices of the USDA Water Quality Initiative, the Iowa MSEA program in particular, to provide a comparative reference for findings of the Mississippi Delta MSEA (MDMSEA). These results illustrate the soil, hydrology and management factors that influence movement of herbicides and nitrate into water resources.

The Management Systems Research Areas were initially established in the states of Iowa, Minnesota, Missouri, Nebraska and Ohio to determine the effects of production systems on water quality. The MSEA program was initiated in response to previous studies indicating that pesticides were widespread in both surface water and groundwater at levels that possibly were significant to public health (*2, 3*). Several MSEA programs included multiple sites and the Minnesota MSEA included sites in South Dakota, North Dakota and Wisconsin. The experiments performed at the sites were not standardized, but did share the common focus of evaluating the patterns and quantities of nutrient and pesticide movement into surface waters and groundwater under existing farming systems (*1*). The scale of experimentation ranged from the plot scale to the watershed scale. The Mississippi Delta MSEA was established later with the same general purpose. This paper reviews and summarizes the findings of the Iowa MSEA program, compares some water quality responses found in the Iowa MSEA to those found in the Mississippi Delta MSEA, and examines the impact of the Iowa MSEA on post-MSEA water quality research.

The Iowa MSEA program was carried out at three principal sites by a combination of researchers from the USDA-ARS, Iowa State University, and the US Geological Survey starting in 1991. The sites included:

1. small field-scale watersheds in loess hills area of southwest Iowa, near Treynor, IA
2. plot, field and watershed-scale studies conducted on the glaciated, rolling topography of central Iowa near Ames; and
3. the large plot-scale studies on the glaciated topography near Nashua in northeast Iowa.

Farming Practices

The farming practices in the area represented by the Iowa MSEA, and to a large extent by the other MSEA programs in Midwestern states, revolve around a fairly limited number of cropping systems that are practiced by the majority of farmers in the region. These systems tend to utilize corn and soybeans as the principal crops, with forage crops and small grains present in smaller quantities. Figure 1 illustrates the distribution of corn in Iowa and surrounding states and

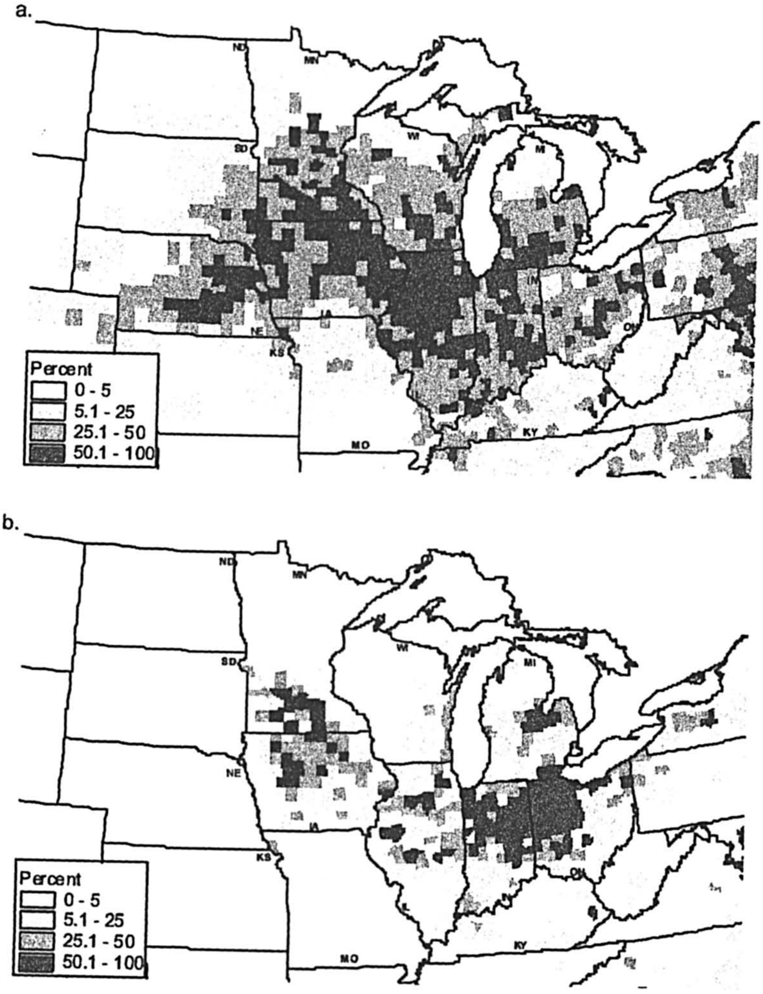

Figure 1. Distribution (percent of cropland) of corn (a) and land with subsurface drainage (b) in Iowa and other midwestern states. The Figure was produced using data from the 1992 Natural Resource Inventory (USDA).

also presents the distribution of land with subsurface drainage. Animals may also be present in these farming systems. The crop rotations, fertilizer inputs, tillage methods, and pest control vary, but are also fairly limited in many respects.

The Iowa MSEA sites utilized two principal crop rotations, continuous corn (Nashua and Treynor sites) and rotated corn and soybeans (Nashua and Walnut Creek sites). The tillage systems in these comparisons included moldboard plowing, disk tillage, ridge-tillage, and no-till, although not all the tillage systems were utilized in all experiments or at all sites. Emphasis was placed on nitrate and the following herbicides at all sites: atrazine [6-chloro-*N*-ethyl-*N*′-(1-methylethyl)-1,3,5-triazine-2,4-diamine], alachlor [2-chloro-*N*-(2,6-diethyl phenyl)-*N*-(methoxymethyl)acetamide], cyanazine {2-[[4-chloro-6-(ethylamino)-1,3,5-triazin-2-yl]amino]-2-methylpropenenitrile}, metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide] and metribuzin [4-amino-6-(1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5-(4*H*)-one] in water monitoring studies and other experiments. The use of these herbicides in Iowa during 1994 on corn (percent of treated acreage) was 66% for atrazine (7.47 million lb), 13% for alachlor (4.11 million lb.), 38% for metolachlor (10.66 million lb.), and 2% for metribuzin (21, 000 lb.). The use of these herbicides in soybeans was 4% for metribuzin (107,000 lb.), and 2% for alachlor (392,000 lb.) in 1994 (*4*). These state-wide herbicide usage patterns were similar to those observed in one of the Iowa MSEA sites, the Walnut Creek watershed, where atrazine was used on 59 to 67% of the land area during the years 1991 to 1994 (*5*). Metolachlor was used on 54 to 73% of the land, including uses on both corn and soybean, and alachlor use was only 2 to 13%. Other herbicides that had significant usage in Walnut Creek watershed were trifluralin and pendimethalin, which are soil-applied, and the postemergence herbicides acifluorfen, bromoxynil, bentazon, imazethapyr and glyphosate. Nitrogen (N) applications in Walnut Creek watershed generally ranged between 90 and 140 kg N ha^{-1}, which are fairly similar to statewide N usage.

Landscape and Hydrology

The Walnut Creek watershed and nearby study sites in central Iowa (near Ames and Kelly, IA) are situated on fields that have a rolling topography with short gentle slopes which often drain into shallow, closed depressions. The dominant Clarion, Nicollet, and Webster soil association (Typic and Aquic Haploudolls and Typic Endoaquolls) has developed on till of the Dows formation deposited during the Wisconsinan glaciation period, 14,000 to 12,500 years before present (*6*). The Clarion soil tends to occur on the hill tops and side slopes which transition into Nicollet and Webster soils lower in the landscape. The soils in the depressions and lower side slopes tend to have greater organic carbon (C) contents and more alkaline pH than the soils on the upper side slopes and hill tops (*7*). These soils are relatively rich in organic C and N and are able to mineralize substantial amounts of N under favorable conditions of temperature and moisture.

The key hydrologic features in this landscape are the lack of a well developed surface drainage network (the pothole topography) and the relatively low hydraulic conductivity of the deeper till, which leads to poor drainage. Groundwater age at the base of the oxidized till ranges from 3 months to 2.1 years (*6*). The poor natural drainage has been alleviated by an extensive subsurface (tile) drain system that intercepts about 95% of the groundwater recharge (*5*). The subsurface drainage network accounts for a substantial fraction of the water flow in Walnut Creek. Walnut Creek flows into the South Skunk River, which in turn flows in a southeastern direction emptying into the Mississippi River south of Burlington, IA.

The Northeast Research Farm of Iowa State University, near Nashua, was used to evaluate the effect of farming practices on 0.4 ha plots on Aquic and Typic Haploudolls (Floyd-Kenyon, Readlyn soil association). Each plot featured a central subsurface drain with a system for collecting subsurface drainage water and for measurement of water discharging from each plot (*8, 9*). A factorial design with crop rotation and tillage treatments was established on replicated plots, with both phases of the corn and soybean rotation present in each year of the experiment.

Three field-scale watersheds ranging from 30 to 60 ha in the loess hills of southwest Iowa, near Treynor, were monitored for a variety of agronomic and water quality parameters. Two watersheds were cropped to continuous corn with disk tillage and the third was cropped to continuous corn with ridge tillage. Median slopes exceeding 4% within the watersheds have led to significant runoff events (*10*). However the soils are relatively permeable and groundwater recharge has been estimated at approximately 20 cm annually (*11*). The soils are classified as the Monona, Dow, Ida, and Kennebec series (Typic Haploudolls, Typic Udorthents, and Cumulic Hapludolls) which overlie Wisconsinan loess.

Herbicides in Surface Water and Groundwater

Herbicides in Walnut Creek were measured using a network of eight monitoring sites that sampled water from hydrologically isolated field drains, aggregated field drains, and surface water. Sampling and analysis procedures are described by Jaynes et. al (*12*) and Hatfield et. al. (*5*). Atrazine and metolachlor were commonly detected in stream water sampled at the base of the watershed over the period from 1990 through 1995. Median concentrations of these herbicides in stream water were generally below 1 μg L^{-1}, but concentrations in individual samples exceeded 10 μg L^{-1} (*12*). Atrazine concentrations exceeding the MCL were found most frequently in the months of

May, June and July, but even in these months the frequency of exceedence was 10% or less. Metribuzin and alachlor were detected much less frequently, which was probably due to their lower use in the watershed and their shorter persistence in soils and subsoils. At one site in the watershed, surface runoff and subsurface drainage were directly compared and runoff was found to be a minor component to the total herbicide load leaving the field, although surface runoff was a major component of some monthly totals (*12*). However, mean atrazine concentrations (1992 to 1995) at two subsurface drainage water sampling sites were 0.10 and 0.15 μg L^{-1}, compared to mean concentrations ranging from 0.44 to 0.67 μg L^{-1} in three stream water stations (*12*). Assuming that runoff accounts for the difference in concentrations between subsurface drains and the streams, these data indicate the magnitude of the surface runoff contribution. Both subsurface drains and stream hydrographs show responses to storm events and the greatest concentrations of herbicides in stream water are associated with storm events.

Herbicide losses in subsurface drains were addressed in several different MSEA studies. At the Nashua site, replicated plots with individual subsurface drains examined the effects of tillage on herbicide loss, which ranged from 0.002 to 7.3 g ha^{-1}. The losses of atrazine in the continuous corn rotation were greatest in the ridge-till and no-till systems and least in the moldboard plow system and reached the greatest concentrations within the first month after application. Similar results were obtained for cyanazine applied to corn rotated with soybeans. The mass losses of triazine herbicides tended to parallel the drainage of water in these different tillage systems; moldboard plow had the least drainage, with the chisel and ridge intermediate in drainage, and no-till with the greatest (*9*). The largest annual average concentrations for the crop rotation treatments (excluding non-detects) were 2.5 μg L^{-1} for alachlor in 1992, 5.7 μg L^{-1} for atrazine in 1991 and 4.3 μg L^{-1} for cyanazine in 1991 (*13*). Within individual tillage systems, alachlor losses (g ha^{-1}) from the soybean phase of the rotation were nearly equivalent to the losses of triazine herbicides from corn. The magnitude and temporal pattern of atrazine losses from this study was similar to losses at sites near Ames in central Iowa and other Midwestern USA cropping systems (12, 13, 14, 15). Runoff was not a significant route of water movement at the Nashua site.

Later studies at the Nashua site showed that losses of atrazine in tile drainage were reduced by banding the herbicide, which effectively reduces the rate of application by 66% (*13*). However, in the same study metolochlor leaching was not statistically reduced by banding.

Herbicide leaching to groundwater was evaluated in several ways. In the Walnut Creek watershed a diffuse network of piezometers was installed to sample shallow groundwater at the margins of farmer's fields (designated as watershed in Table I). A production field cropped to corn and soybeans in alternate years was used to monitor groundwater using piezometers installed within the field (*16*). In the production field (Table I), the application rate of metribuzin was 82% (420 g ha^{-1}) of the average atrazine application (510 g ha^{-1}) at the field site). The average concentration and detection frequency of metribuzin in groundwater were half that of atrazine over four years of monitoring (Table I). Atrazine and metribuzin were detected less frequently in samples from the network of edge of field wells than in the production field (Table I). This result is likely due to differences in the frequency of atrazine and metribuzin use in the fields next to the wells and placement of these wells at the edges of fields. In addition, deep groundwater beneath another production field was monitored for these same herbicides with similar results (*6*). These extensive studies of herbicide mobility in soil profiles developed on glacial till show that herbicides do leach into shallow groundwater, but much of the percolating groundwater enters the subsurface drainage system, eventually entering the local stream system. The diversion of groundwater into the subsurface drainage network protects deeper groundwater.

Table I. Detection of Atrazine and Metribuzin in Groundwater Beneath a Single Production Field Within the Watershed and Groundwater from Wells Positioned at the Edge of Field.

	Field (2.6 m)[a]	*Watershed*[b] *(1.5-3.0 m)*	*Watershed*[b] *(> 4.6 m)*
Atrazine			
Mean Concentration (μg L^{-1})	0.21	0.16	0.06
Detection Frequency (%)	26	15	4
Freq. Exceeding MCL (%)	1.4	< 1.0	< 1.0
No. Observations	837	901	636
Metribuzin			
Mean Concentration (μg L^{-1})	0.11	0.01	0.01
Detection Frequency (%)[c]	13	2	2
No. Observations	842	901	636

[a] Depth of sampling from wells located within a production field with atrazine applied for two years and metribuzin applied for two years.

[b] Depth of sampling from wells positioned adjacent to fields postioned at various points within the watershed.

[c] No MCL is established for metribuzin.

Source: Reference 16, © 1999, American Society of Agronomy.

Soil herbicide interactions appear to affect the movement of herbicides to groundwater. The greater frequency of atrazine detection in groundwater compared to metribuzin (as described in Table I) appears to be due to greater persistence of atrazine in soils and subsoils (*8, 16, 18*). In the production field described in Table I, atrazine was detected in 2 to 15% of soil samples below 45 cm depth, including the two years when atrazine was not applied applied. However, metribuzin was detected in soil only rarely below 30 cm and only in years when it was applied (*16*).

The pothole topography limits surface runoff to streams, instead routing runoff water to the depressions (potholes), which are the most extensive artificially drained areas of the field. Mitigating these hydrologic factors is the high organic C content of the pothole soils that adsorbs atrazine to a greater extent than the sideslope soils adjacent to the pothole (*7*). This greater adsorption tends to retard leaching. However, where surface inlets to the drainage line have been installed, runoff is transmitted directly through the drainage line to surface waters. Deep leaching of atrazine past the drainage lines is further retarded by strong atrazine sorption in deeper, permanently saturated, unoxidized till materials (*17*).

In addition to the extensive research on glaciated landscapes, the Iowa MSEA investigated herbicide movement in two other landscapes. At the confluence of Walnut Creek and the South Skunk River, the creek crosses the alluvial floodplain of the river. At this site, a sandy alluvial aquifer is present beneath the silty floodplain soils. A monitoring study of groundwater at this site found atrazine in 14% of the samples (*19*). Studies using small diameter piezometers showed that Walnut Creek supplied water to the alluvial aquifer. Concentrations of atrazine, cyanazine, metolachlor and the degradation products deethylatrazine (DEA), deisopropylatrazine (DIA), and the ethanesulfonic acid of alachlor (metabolite ESA) were found in the groundwater at concentrations below 1 $\mu g\ L^{-1}$ (*20*). Based on the water flux through the streambed and the herbicide concentrations, it was estimated that these herbicides were transported in greater quantities in stream-fed recharge than would be expected from leaching through soil.

The loess hills of southwest Iowa are relatively permeable and atrazine and metolachlor were detected in both the unsaturated zone and in groundwater over a three year period (*21*). Atrazine was detected in 30% of the groundwater samples and metolachlor in 17%. Atrazine concentrations were generally below the MCL and the median concentrations for both herbicides were less than 1 μg L^{-1}. The atrazine metabolites DEA and DIA were also detected, but less frequently than atrazine.

Nitrate in Surface Water and Groundwater

In contrast to the relatively low concentrations of herbicides in stream water, the yearly median nitrate-N concentration exceeded the MCL of 10 mg

NO_3-N L^{-1} for three of the six years in Walnut Creek during the period from 1992 to 1995 (*12*). NO_3-N concentrations in stream water were greatest in the months of May and June. This incidence of NO_3-N concentrations exceeding the 10 mg L^{-1} standard is similar to that found on the Des Moines River during the period from 1980 through 1990 (22). The NO_3-N concentrations were not greatly affected by storm events, that suggests that overland runoff was not contributing substantial amounts of NO_3-N. Nitrate-N loads measured from large drain outlets show that the vast majority of the NO_3-N was delivered to Walnut Creek through the subsurface drainage network (*12*). Losses from the watershed (averaged over the drainage basin) ranged from 4 to 66 kg N ha^{-1}. Burkart and James (*23*) used an estimated nitrogen balance approach to estimate residual N available for leaching over the entire Mississippi Basin. Their analysis suggested that the upper Mississippi Valley, including central Iowa, southern Minnesota, and western Illinois, was the hydrologic basin producing the largest amounts of residual N (>56 kg ha^{-1}). While residual N does not necessarily move to stream water or groundwater, their estimates suggested that even modest improvements in N management were likely to have positive impacts. At the watershed scale, the nitrate concentration in stream water was positively correlated with the fraction of land in row crops (*24*).

Nitrate in tile drainage water results from two immediate sources: nitrate resulting from the mineralization and nitrification of organic N in the soil and the nitrification of ammonia fertilizer. Several lines of evidence suggest that both processes contribute to the nitrate leaching below the root zone. The NO_3-N losses in subsurface drainage are similar when fields were cropped to either corn or soybean, even though no N fertilizer is applied to soybean crops (*25, 26*). Studies with ^{15}N-labeled fertilizer showed that a larger fraction of fertilizer N enters the organic N pool in the soil than is lost (leached, volatilized, or denitrified) from the system (*27*), but this organic N can become mineralized in subsequent growing seasons. Nitrate losses were greatest in the Walnut Creek watershed in the period from November to May, when plants were not present (26). Fall application of anhydrous ammonia was the predominant fertilizer application method for corn production.

Concentrations of nitrate in groundwater tended to decline with increased depth below the watertable surface. Mean NO_3-N concentrations (1992-1996) in groundwater at the production field in Walnut Creek ranged from 10.3 mg L^{-1} from the 1.5 to 3 m depth to 1.8 mg L^{-1} in wells deeper than 4.6 m depth. Denitrification in deeper, unoxidized till appears to account for this trend (*26*). Unoxidized till has greater quantities of organic C, which supports elevated rates of microbial denitrification and methanogenesis relative to the oxidized till above it (*28, 29*). The particulate carbon driving these microbial processes was apparently incorporated into the till during the last glaciation.

Tillage and rotations affected the loss of nitrate in subsurface drainage from the large plot studies at the Nashua site (*9, 25*). In a study of four tillage systems cropped with continuous corn, rotated corn, and rotated soybeans, both phases of the rotation (corn or soybeans) were present during the three-year period. The nitrate concentration (annual rotation x tillage treatment means) in drainage water ranged from 0.86 to 65 mg L^{-1} (*25*). The mass of NO_3-N lost in drainage water ranged from 0.89 to 107 kg N ha^{-1}. Losses of NO_3-N from the continuous corn were consistently greater than losses from the corn-soybean rotation regardless of the tillage system. The effect of tillage on losses of NO_3-N from the rotated corn and soybeans were relatively minor (Figure 2).

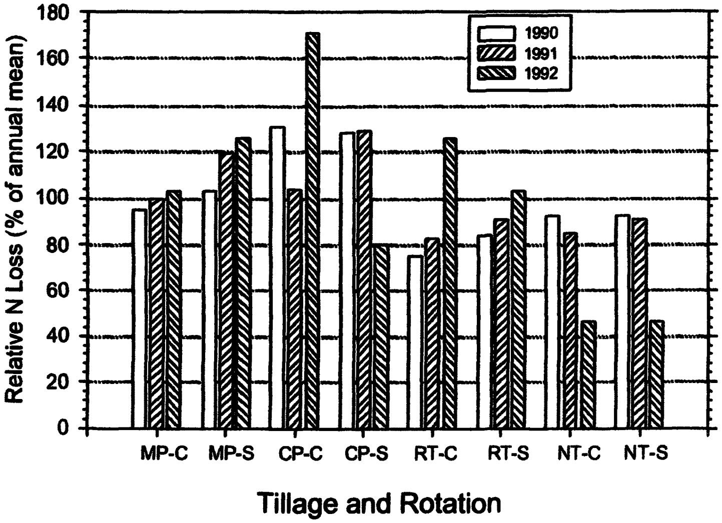

Figure 2. Relative loss of NO_3-N from moldboard plow (MP), chisel plow (CP), ridge-till (RT) and no-till (NT) cropped to rotated corn (-C) or soybean (-S). Relative loss for each treatment is expressed as a percentage of the mean annual NO_3-N loss for all treatments (crop-tillage combinations). Mean annual losses were 40.2 kg N ha^{-1} in 1990, 35.7 kg N ha^{-1} in 1991, and 9.8 kg N ha^{-1} in 1992. (Adapted from Reference 9. Copyright 1997, American Society of Agronomy.)

To eliminate the year-to-year differences in NO_3-N losses, which were largely driven by precipitation patterns, the data in Figure 2 show the NO_3-N losses from the individual crop-tillage treatments expressed as a percentage of NO_3-N masses lost in tile drainage averaged across all treatments for that year. Thus, crop-tillage treatments that have greater than average losses exceed 100% while treatments with less than average losses are below 100%. Nitrate-N loss was slightly greater from the moldboard plow and chisel plow tillage than from the ridge-till and no-till systems and losses were similar from both the corn and soybean phases of the rotation.

As in Walnut Creek, significant amounts of NO_3-N were exported in drainage water from the Nashua plots at times when plant uptake is absent or minimal, principally late fall through spring (*30*). The magnitude of these seasonal losses were highly dependent upon precipitation and temperature variations, particularly in the late fall, winter and spring seasons. This variability was illustrated in a later study at the Nashua site, where soil profile mineral nitrogen (residual N) tended to increase over winter, from 4.7 to 13 kg N ha^{-1} following corn, compared to changes ranging from an 8.5 kg N ha^{-1} loss to a 6.5 kg ha^{-1} increase in N following soybean (*31*).

Nitrate-N balance and movement was also evaluated in ridge-till and disk tilled continuous corn at the Iowa MSEA site in southwest Iowa. In this topography, water that infiltrates through the hill-top and side-slope soils emerges later as stream baseflow at the foot of the watershed. Nitrate was often present in baseflow concentrations exceeding 10 mg L^{-1} in the watershed managed with ridge-tillage which was monitored extensively (*32, 33, 34*). This was consistent with the measurement of high nitrate concentrations in both the vadose zone and the saturated zone, with some concentrations exceeding 50 mg N L^{-1} in the same ridge-tilled watershed (*33, 34*). In the ridge-till watershed, NO_3-N leaching loss accounted for 16% of the cumulative fertilizer N input from 1968 to 1991, with NO_3-N and NH_4-N loss in surface runoff accounting for only 1% of the fertilizer N input (*33*). In comparison, grain removal accounted for 50% of the fertilizer N input to the system and 31% of the N was either in the soil or was lost through volatilization or denitrification. Clearly, the magnitude of NO_3-N leaching (approximately 2.5 to 20 kg N ha^{-1} annually) was partly due to excessive fertilizer N application (170 to 230 kg N ha^{-1}) in relation to crop removal (*32, 35*). Residual soil NO_3-N in the root zone after harvest accounted for between 117 and 246 kg N ha^{-1} in both tillage systems. Nitrate concentrations in stream base flow averaged two to three times more in the ridge-till watershed than in the conventional tillage watershed, despite similar N fertilizer applications (*32*). This combined with greater base flow from the ridge-till watershed results in greater NO_3-N loss from this system, but with much less sediment loss (*11, 32*).

Conclusions, Current Research, and Outlook

The Iowa MSEA project examined the impact of current farming systems on the quality of surface water and groundwater. The research shows that the environmental impact was a product of the climate, soils, geology and farming practices. The glaciated parts of Iowa that have extensive subsurface drainage are represented by research at the sites near Ames and Nashua and the results from these sites were reasonably consistent. The combination of subsurface drainage, thick till deposits and the slow flux of water through these sediments resulted in little actual or potential contamination of deep groundwater. Herbicide retention (sorption) and degradation processes are sufficient to prevent more extensive contamination. Shallow groundwater is contaminated with herbicides and nitrate which are carried in subsurface drainage to the stream network. Surface waters carried measurable herbicide residues, but the concentrations only occasionally exceeded MCL levels, usually in response to runoff events. The development of newer, low application rate herbicides is changing the spectrum of chemical usage. Although these chemicals were detectable in surface water and groundwater, concentrations were well below health advisory levels (*36*).

Nitrate concentrations in stream waters regularly exceed the MCL and contribute to N concentrations in the Mississippi River. Excess nitrate in the Des Moines and Raccoon Rivers caused the city of Des Moines to construct and operate a large and expensive nitrate removal plant (*37*). Both soil and fertilizer N contribute to the N load in surface water, as do both soybean and corn crops. Significant amounts of fertilizer N enter the soil organic matter pool through decomposition of plant residues and microbial immobilization processes. The release of soil organic N through the N mineralization process was highly dependent upon seasonal weather, which can lead to significant N losses during the non-growing season.

The Iowa MSEA results clearly identified nitrate transport from individual fields and agricultural watersheds as the greatest water quality issue. The impact of the Iowa MSEA research was most immediate in the development of follow-up projects designed to mitigate the nitrate problem of excessive nitrate loss. These approaches to reducing nitrate losses on tile-drained lands include the timing and rates of fertilizer application, cover crops, crop rotations, riparian buffers and wetlands (*38, 39*). Clearly, accurate and timely prediction of nitrogen mineralized from soil would allow fertilizer N applications to be adjusted to account for soil N. In addition, seasonal weather patterns also affect crop demand for nitrogen. Research performed subsequent to the MSEA shows that split applications of fertilizer N with soil testing (LSNT, late spring nitrate test) can impact water quality at the stream scale (*40*). In this study LSNT-guided application of fertilizer N to one sub-basin of Walnut Creek appears to have started a trend towards lower NO_3-N concentrations in stream water. After two years without effect, the LSNT management has resulted in a 30% reduction in NO_3-N concentration in the third year. A similar result has been also obtained in the fourth year (D. Dinnes, personal communication).

Other post-MSEA research has examined the use of cover crops, such as oats (*Avena sativa* L.) or rye (*Secale cereale* L.) planted into the maturing corn or soybean crop provides active plant uptake of nitrate over a greater period in fall and spring. In large lysimeters, cover crops were able to reduce nitrate leaching losses from soil (*41*). Similar field studies show that cover crops can be established under Midwestern conditions and that they reduce nitrate leaching (*42*). Adoption of cover crops by producers may be limited by seed costs and by the difficulty in establishing a stand following a corn crop, which tends to be harvested later in the year than the soybean crop.

The Iowa MSEA research was a component of the larger multi-state MSEA program. Different impacts on water quality in were observed in different regions that were related to soils, hydrogeology, and agricultural management for both herbicides and nitrogen (*38*). For instance, there is considerable similarity between the findings of the Mississippi Delta MSEA (described elsewhere in these symposium proceedings) and results from the Iowa and other parts of the Midwest concerning the importance of surface runoff in the transport of pesticides to surface waters. Best management practices (BMP) such as riparian buffers, erosion control practices and cover crops appear to be effective throughout the Mississippi River drainage basin. In contrast, the dynamics of nitrate pollution are substantially different in the Mississippi Delta than in Iowa. While the upper Mississippi River basin streams have nitrate seasonal nitrate concentrations well in excess of 10 mg NO_3-N L^{-1}, the local surface waters of the Mississippi Delta rarely reached that level (*43, 44*). Smith et al. (*45*) speculated that riparian zone denitrification was a primary cause of low nitrate concentrations in surface water. Fewer subsurface drains in the Mississippi Delta may also contribute to this difference.

While the effect of soils, climate and geology on contamination of surface water and groundwater were not entirely unexpected, study of the interaction of these factors with agricultural management reveals the complexity of agricultural water quality issues. Certainly, the importance of understanding the factors that control pollutant movement at field and watershed scales was demonstrated. While research has demonstrated that over application of nutrients will lead to water quality problems, the inability to predict plant nutrient demand in concert with accurate, timely assessment of soil nutrient supply limits our ability to make precise fertilizer application recommendations. In addition to the practices described above, off-site N management practices that are currently receiving extensive evaluations include, reconstructed wetlands, tile-line denitrification walls, and riparian buffers. The implementation of the in-field and off-site practices are likely to be driven by economic and regulatory forces. The linkage of Midwestern agricultural pollution with the hypoxia condition in the Gulf of Mexico, with advancing eutrophic conditions in streams and reservoirs, and antibiotics from animal feeding operations (*46*) underscore the importance of developing production systems that are more efficient in retention of nutrients and organic chemicals.

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Chapter 18

National Needs, Regional Solutions: The Development of Site-Specific Assessments of Pesticides in Water Resources

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Pesticide risk assessment and registration are currently in a state of flux because of the efforts of the regulatory, environmental and agricultural communites to come to terms with the Clean Water Act and the Food Quality Protection Act. Rulemaking, attempts at compliance, and measuring and remediating pollution all require new science to be developed, gaps in monitoring data to be recognized, and model prediction and extrapolation to be pushed up to and sometimes beyond the models' inherent limits. In this context, this symposium has shown by example how much more can be accomplished, and how much more credible the outcome, when the uniqueness of specific regional nonpoint pollution dynamics is recognized at the outset. There is more to do, however: regional approaches must be folded into a national structure because, while ecosystem risk must be regulated regionally or even locally; human risk is national and even global in nature. The tools to do this are emerging.

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Introduction: The Regulatory Context

This conference has provided clues to the future of water quality assessment and remediation , and the tools needed for scientifically defensible water quality planning are coming together. The two most important legislative tools being used to preserve or recover water quality in the United States (US) are the Clean Water Act (CWA) (*1*) and the Food Quality Protection Act (FQPA) (*2*). These acts are the basis of legal pressure from environmental interests, and the resulting court settlements in some 38 states have forced timelines for assessment and implementation. These deadlines mean that implementation of remediation measures will have to be accomplished before much of the science needed to defend such measures can be done. Litigation is likely to continue.

Both the CWA and the FQPA define goals and approaches which sound imminently practical and reasonable. The CWA requires that the uses for each water resource in the US be designated and the resource assessed as to its capacity to receive pollutants without impairing its designated use. Thus, a pristine glacial lake supporting endangered species will be held to a different standard than a coastal waterway supporting commercial traffic. FQPA focuses on human exposure to pesticides and treats drinking water as one source to be included in a total maximum daily intake limit from all sources. Thus FQPA requires a measurement, or a reliable estimate, of concentrations of pesticides in community water supply systems.

How will these relatively seemingly straightforward approaches be implemented? Again, the current conceptions of how the calculations are to be done sound reasonable.

For the CWA, individual states and tribes assess water resources (typically surface waters only) for actual or potential uses, and estimate the level of pollutants that the waters may receive without "impairing" those uses. For example, a stream reach may have "fishing" as a use; therefore, this defines potential problem pollutants (e.g., mercury for fish consumption) and the maximum level of each pollutant that may not be exceeded. These maximum levels are usually defined in terms of *concentrations* because most water quality standards relate impacts to concentrations. If regulation of point sources is not sufficient to return pollutant concentrations back below the established exceedance levels, the CWA requires states and tribes to establish the Total Maximum Daily Load (TMDL) of pollutants (from both point and non-point sources) that a stream may receive and still meet its designated use criteria. Because all individual sources within a watershed may not easily be quantified as a concentration, the TMDL represents the total sum load of pollutant that may be received by the water body in a given period of time. Although implied in the name, this does not necessarily have to be load integrated over a full day. It may be appropriate (for example, in the case of toxicity to a specific life stage of a sensitive species) to set the TMDL as the continuous duration of a set concentration for a specific time period. Once a TMDL has been set, states and tribes are also required to develop TMDL Implementation Plans that describe the approach and targeted timeline that will be used to return the water body to compliance. The plans may address point sources, non-point sources, or both and may include response options ranging from specific pollutant reduction levels to implementation of named remediation technologies to implementation of improved land management practices. States and tribes are also required to follow-up with monitoring to confirm improvement. Margins of safety and "accounting for temporal variability" are required.

Over 20,000 impaired water resources have been identified in the US (*3*). EPA Regional offices are overseeing the process, while the states have been given the responsibility of implementing cleanups. The pressure is on nonpoint pollution, simply because point sources have been largely controlled. Agriculture and forestry, as holders of much of the land and thus generators of much of the nonpoint nutrient, pesticide and sediment pollution, and urban areas because of industrial and homeowner-generated pollution, are facing a significant portion of the allocation of load reduction.

The FQPA is concerned with human exposure to food contaminants. The Act defines "food" to include drinking water. The Environmental Fate and Effects Division or EFED, of EPA's Office of Pesticides has been tasked with calculating the concentrations of all pesticides in every drinking water source in the country serving more than 25 people. Driven by a very short deadline for the organophosphate cumulative assessment, EFED used USDA-Economic Research Service food production regions and the PRZM/EXAMS environmental concentration prediction model to estimate concentrations in high-risk watersheds within each region and compared the results with the limited monitoring data available. The results appear quite defensible, principally because pesticide runoff into impoundments was calculated using crop area percentages and pesticide application percentages; the results indicated that drinking water would contribute no more than 1% to 10% of the levels of exposure that would be obtained from foods (*4,5,6*).

EFED is also working with the US Geological Survey (USGS) to extend and apply the WARP (Watershed Regression for Pesticides) model (previously known as the Gilliom-Larson model (*7*), to estimate pesticide concentrations in some 7000 surface drinking water intakes. WARP is a regression equation developed by the US Geological Survey from their hydrologic "Study Areas," which are watersheds typically hundreds to thousands of square miles in size. The model predicts pesticide concentrations in streams at the outlets of such study areas using parameters for pesticide use and the hydrologic characteristics for the watershed. It appears to provide reliable order-of-magnitude estimates for the probability distribution function of pesticide concentrations in streams, at least for streams where some historic data is available for calibration.

The Difficulty: Nonpoint Pollution is Site-Specific

The CWA recognizes that nonpoint pollution depends on region, and state and local governments are being tasked to deal with the specific water quality problems that lead to a stream reach being listed. FQPA, however, is being implemented at a national level by EPA and national modeling approaches are being used--the best that can be done given the time lines under which the Agency is working. It is not certain at this time whether, e.g., WARP basin-scale regression equations, which are determined by the data sets available (mostly USGS monitoring data) may be extrapolated with confidence to other basins, climates, and pesticides, but a USGS/EPA/USDA/industry work group and project is examining this. Every watershed has a unique combination of climate, crops and/or pest control needs, soils, and pesticide usage. Urban watersheds (especially, but indeed all watersheds) present special problems for determining pesticide usage. It is likely that current approaches will be most useful for determining which drinking water resources should be targeted for actual monitoring.

Once a water resource has been determined to contain a pollutant at concentrations which exceed some standard, whether a DWLOC (drinking water level of concern) or ecological or recreational use standard, what is to be done about it? The answer in part is, ***remediation approaches are just as site-specific as impairments***. A Best Management Practice or BMP that works for atrazine in a Corn-Belt reservoir may not be the right answer (or of course, may not be needed at all) in the Coastal Plain.

In summary, the solution to water pollution is local assessment, local source allocation, and local remediation solutions. There are tools, including models and monitoring approaches, that are applicable everywhere. But their use in every case will be directed by local conditions.

Regional Estimation Of Pesticide Impacts On Water Quality

The impact of pesticides on surface water ecosystems or human drinking water resources will be a function of both the sensitivity of species or of humans to a given pesticide, and the capacity of the whole watershed ecosystem to reduce that sensitivity through conversion, degradation, or sequestration. While a thorough assessment of risk from pesticides should include detailed consideration of both concerns, current risk assessment approaches essentially compare only worst-case exposure estimates to most-sensitive-species no-effect concentrations. This methodology is rapidly undergoing improvement, especially in the use of more detailed models and probabilistic presentations of results. But we still do not do an adequate job of evaluating the capacity of ecosystems to ameliorate impacts of pesticides. This is in part due to a lack of information on specific pesticides' fate, and in part to the inherent difficulties associated with predicting pesticide fate in complex systems.

Typically, site-specific or even region-specific pesticide environmental parameters are not available. A specific example: the "standard" half-life of the cotton defoliant tribufos used by the USEPA in its risk assessment is 745 days, based on a single registrant study (*8,9*). However, actual in-field half lives as measured in the Georgia coastal plain range from a few days to two weeks (*9*). Such large discrepancies in information point to the need for a much more site-specific approach to pesticide risk assessment and to how risk management is implemented.

Once site specific-analyses are done they must still be integrated to national or global scales for many purposes including risk management. We propose that, because the fate of any pesticide will depend upon the unique interactions of ecosystem components such as climate, topography, geology, biology, and ecosystem management, the appropriate development of risk indices should follow a protocol similar to that proposed by Hunsaker et. al (*10*) and Strickland et. al (*11*) for atmospheric pollutants. The approach identifies six specific steps that should be taken to extrapolate narrow or site-specific research results to population-based projections of response: 1) water resource identification and characterization; 2) identification of regions and/or functional subregions; 3) characterization of pesticide use patterns and use amounts in a given area; 4) definition of end-points i.e., impact probability distribution functions; 5) selection and application of appropriate models for projection; and 6) spatial presentation of projected responses. A brief set of example issues to be considered at each step is presented below for the pesticide case. For a more detailed implementation example (sulfate deposition and stream acidification), see Holdren et. al (*12*).

1. Resource Identification and Characterization

The first step attempts to bound the issue of concern. This step requires an explicit consideration of: 1) the types, quantities, and timing of pesticides in use; 2) the sinks and sink types (soil, sediment, DOC, POC) where the pesticide is known to reside in the environment; 3) the type of effects expected from exposure (chronic, episodic, life stage, etc.); 4) and the extent of sensitive ecosystem components at risk from exposure. The output from this step is a map that spatially defines the anticipated type and magnitude of concern that stem from pesticide use patterns.

2. Identification of Regions and/or Functional Subregions

As indicated above, because different classes of compounds are rendered harmless via a wide range of interactions between the particular compound and environmental factors, it is essential to define regions or subregions that are expected to exhibit relatively homogeneous response characteristics with respect to pesticide removal. As a first approximation, it may be appropriate to define broad regions via spatial overlays of use patterns (amounts and timing), pesticide chemical/physical properties (key controls on rate of transport to surface waters), and climate (frequency and intensity of rainfall also impacts loss rate, and moisture and temperature are key controls on degradation rate).

Aggregating the local results into distinct physiographic units (i.e., regionalization of the results) can be a much more powerful means to enhance the potential for effective application of remediation approaches such as label changes or regional use approvals. For such analyses, population weights are an attractive alternative that allows the assessor to scale model results to a target population of stream reaches in the region.

Extrapolations of model estimates to regional scales carry implicit or explicit assessments of how the resource is characterized and what level of damage to the resource is economically and/or socially acceptable. The approaches used to summarize outputs at the regional level can have a significant influence on how the results are perceived and interpreted. There are two primary issues associated with regionalization that will affect interpretation: spatial aggregation of the individual systems, and the selection of population-based end points. Spatial aggregation allows the user to group resources into biogeographically distinct areas that can be grouped according to interactions of physiography, land use, geology, and climate. We propose that pesticide fate will be particularly sensitive to these parameters because of the high level of biological/ecological control associated with their degradation.

3. Characterization of Application

One of the most significant weaknesses in efforts to assess risk from pesticide usage is obtaining accurate information on actual use rates and timing of applications. At the large scale, general averages can be developed that are useful for coarse considerations. However, in order to protect the privacy of individuals, such data are generally only available as aggregated information at the state, or sometimes county, level. The USDA-National Agricultural Statistics Service is beginning to develop some useful new products in this area (*13*). This issue can be finessed by linking detailed information collected at a few locations to equally detailed information on land use (and rates of change in land use over time) that is collected at fine resolution (< 30 m pixels) over large areas. Such correlative approaches provide surrogates for intensive data collection efforts that might otherwise invade privacy or be prohibitively expensive. Information collected in this manner should be warehoused into an integrated and consistent geographically-linked information system presenting estimated pesticide use within unique pixels.

4. Definition of Endpoints

End-points define the level of socially-acceptable impact. One approach to selecting end points is to use the most sensitive criterion to define the acceptable concentration for the stream or for a region as a whole. This is likely an appropriate option in the case of human health and DWLOCs. When direct impacts to human health are not a concern, an alternative to the most sensitive criterion is to select, for example, a percentage of reaches above which you would consider significant degradation of the natural resource to have occurred. The exact level used for such an approach is a sociopolitical issue, but the approach allows the development of benefit-cost ratios that society can use to select its tolerance level. Regardless of the approach used, the process of selecting regional end points on which to base the selection criteria does have a subjective, value-based component.

5. Selection and Application of Appropriate Models for Projection

Changes in pesticide use sufficient to cause a decrease in surface water concentration below a DWLOC in any stream having drinking water as a designated use, or below the LD_{50} for stream biota in more than 10% of the stream reaches, can be significant. Therefore, if the projected concentration difference between two different model outputs is less than the difference required to take a surface water above these criteria, then the results from the two models might be considered comparable. If the model results differ by more than this, there is indication that one or more of the models is incorrectly representing processes affecting pesticide fate at the scale of examination, thereby constituting an inappropriate set of tools for predicting response. These ecological limits are arbitrary, but they do offer realistic starting points from which to make comparisons.

At this step in the process there are several questions that should be considered in deciding the best model (or models) to use in projections of impacts. Explicitly addressing these questions results in making a conscious decision about acceptable levels of accuracy and precision regarding pesticide fate within a given area/region (field, watershed, basin, region). Three questions that are key for this process include: 1) Are the differences between model projections statistically and environmentally significant; 2) What is the magnitude of variation within and between locations evaluated; and 3) What are the model components that contribute the most sensitivity to variation in precision of output? The answers to these questions tell us whether there is a problem, the magnitude of the problem, and whether or not there is anything that can be done to reduce the problem.

It is imperative for the model user to carefully match the capabilities of the model(s) being employed with the predictive needs. There can be substantial differences among models in terms of their performances for projecting responses to management practices or changes in pesticides applied or their rates or application methods. In general, process-based models such as RZWQM (*14*) do a better job of projecting responses, but at a cost of increased data and computational resource requirements. Conversely, more spatially-averaged models such as PRZM-EXAMS (*15*) do a good job of using minimal data input to describe an average condition, but are of little value in selecting an effective mitigation scenario for a specific locale.

In conducting studies of this type, it is essential to have benchmarks for comparison. Response models use different assumptions, have different structures, and, as a consequence, may yield somewhat different results. When multiple models are available for use, but their suitability for application in new regions is unknown, the user must also determine the desired (or acceptable) level of accuracy and precision in forecasts. Stated more directly, "What range of uncertainty (model comparability) is appropriate to use for standard setting?" In the case of pesticides, model comparability might be based on the predictions of responsiveness of surface water pesticide contents to changes in use and land management. If surface waters, and especially waters that initially have pesticide values exceeding DWLOCs, exhibit large responses to a unit change in management, then the potential economic impact for a single region may be substantial and models need to agree closely to consider their outputs' justification for regulatory action or label changes.

6. Spatial Presentation of Projected Responses and Establishing Comparability Criteria

As a last step, it is important to evaluate the consistency (or difference) in projections of response behaviors among ecosystems and regions exhibiting differing combinations of environmental conditions, pesticide loads, and ecosystem use (management) criteria. The purpose in this step is to evaluate the suitability of the conceptual model(s) used to delineate the "homogeneous" response regions, thus enhancing confidence in the models selected, the critical end points of concern that were chosen, and the utility of establishing regional regulatory or labeling criteria. This can be accomplished by considering each modeled pixel as an individual member of a population of locations.

Model outputs should be presented as plots aggregating individual pixel responses at multiple hierarchies (e.g., national, southeast, state, large basin, small basin). Statistical comparisons of model output (sensitivities) can then be made describing:

- the differences in outputs from different models run on the same system;
- the range of differences in outputs for populations of pixels or polygons aggregated at various hierarchical levels;
- the range of differences in the shapes of the cumulative frequency distribution curves generated for each level of aggregation.

Comparison of differences within and between each of these levels will provide "an estimate" of whether and how much different groupings of ecosystems vary in their capacity for pesticide degradation. Comparing this range of variability with the range of stream pesticide concentrations considered to be "within the margin of safety" should provide a relatively clear picture of whether the accuracy and precision of the overall assessment approach is sensitive enough to use as a policy setting tool. The same approach can also be used to complete a post hoc delineation of "bioregional response areas" where the responses to management action can be placed in a context of "population type" response statistics for any given pesticide.

As a final step, the regional extrapolations of modeled outcomes should be compared to real data wherever possible. Where such data are available, coarse maps developed from actual sample data should be compared to the modeled frequency distributions at larger scales (e.g., national, southeast) to evaluate whether the modeled response regions compare well to actual data. These comparisons can be used to develop estimates of uncertainty in the overall approach and can provide an additional boundary criterion to qualify regulatory/labeling decisions. Uncertainty estimates thus produced can be incorporated into socio-economic evaluations to make estimates of the impacts that differences would cause to social infrastructure if any individual approach or combination of approaches were chosen.

Even failed comparisons have substantial value. They provide information allowing estimates to be made regarding the number of actual sampled pixels that are necessary to obtain a desired level of comparability between approaches, and thus provide information allowing a cost-benefit analysis on the feasability of establishing additional research and monitoring locations to use as extrapolation points. The differences in output between models supposedly depicting the same environmental processes also provide valuable keys in designing research to better explain ecosystem behavior at the large scale and long-term time frame.

The Corn Belt MSEA Versus The Mississippi Delta MSEA: Region-Specific Experimental Approaches For Agriculture

An example of the approach for addressing national water quality issues on a regional scale is the Management Systems Evaluation Area or MSEA. The MSEA program was designed from the outset to provide regional-based assessments and evaluations of BMPs for remediation of nonpoint water quality impairments. The MSEA program was begun in 1990 in response to the Presidential Initiative on Water Quality. Major goals of the program were to develop water quality programs that protect water resources from contamination and develop management practices that reduce contamination of water resources. The MSEA program was primarily driven by USDA-ARS in cooperation with various Federal and state agencies, including other USDA agencies, USGS, and USEPA. More details of the history and background of the MSEA program can be found in other chapters in this volume (Locke; Romkens).

The scope of the MSEA program was originally confined to the Midwest "Corn Belt" region of the U.S., and five states were selected as participants: Iowa, Minnesota, Missouri, Nebraska, and Ohio. Groundwater pollution issues, particularly nutrients such as nitrate were a driving force force for the Midwestern phase of the MSEA project. Although crops grown in the subregions of the Midwest MSEA projects were similar, i.e., corn, soybeans, it was recognized that each subregion possessed distinct features such as topography, soil characteristics, and climate that precluded extrapolating results across the entire region.

As the first five-year phase of research in the Midwest was concluding, other regions were studied as potential sites for expanding the MSEA program. The Mississippi Delta region was selected as one of the sites for MSEA expansion. Establishment of a MSEA in the Mississippi Delta--the MSEA which is the focus of the present symposium--was a result of several important factors. The Delta region is a major agricultural region, extending from southern Missouri to the Gulf Coast of Mississippi, so from a geographic standpoint, it is the southern extension of where the Midwest MSEA left off. It has a more humid climate and a longer crop growing season than the Midwest, that provides a favorable environment for production of crops such as cotton, soybean, and corn. Although corn and soybeans were part of the cropping systems evaluated in the Midwest, including cotton management as a system component was unique to the Mississippi Delta MSEA (MDMSEA) program.

In contrast to the gently rolling landscape of several of the Midwest MSEA subregions, the Delta topography is relatively flat, and an extensive ditch drainage system is in place to divert excess surface water runoff during periods of heavy precipitation. By the time that the MDMSEA was initiated, surface water quality issues had supplanted groundwater quality as the focal interest. Evaluating the potential for removal of sediment and agrichemicals in surface runoff and developing ways to minimize these losses therefore were major factors in establishing the need for water quality research in the Delta.

Like the Midwest MSEAs, research effort was a collaboration among many entities. MDMSEA scientists proposed a framework for water quality research that took advantage of a natural and common feature in the Mississippi Delta landscape: oxbow lakes. Utilizing oxbow lakes provided relatively closed systems wherein all surface water runoff within the confines of the watersheds drained into the lake. The relatively small size of the watersheds allowed consideration of a number of management practices. The establishment of compact, closed watersheds as the centerpiece of research was another factor that distinguished the MDMSEA progam from the earlier MSEA research where the watersheds along streams and rivers were the focus of research.

Like the Midwest MSEA projects, both system and individual BMP approaches were used for assessing the MDMSEA lake watersheds. In system assessments, the focus for the MDMSEA was on how lake water chemistry, physical characteristics, and biology responded to the combination of BMPs imposed on that watershed. Changes in the ecology of the lake and associated riparian areas were also part of the evaluations. The strong ecological component in the MDMSEA is another distinction from the Midwest MSEA research. Composition and health of fish and other vertebrate populations were monitored. Socio-economic analysis and modeling studies were also part of the MDMSEA evaluations.

The use of watersheds along streams and rivers in the Midwest projects resulted in a large number and diversity of farms and farm practices, making it difficult to discern and isolate factors contributing to quality of the water bodies. Comparisons from one watershed to another therefore were complicated. In the MDMSEA, three oxbow lake watersheds were selected for comparisons of BMP effects on lake water quality. A hierarchy of best management practices was established among the watersheds that ranged from no improvements in one, only edge-of-field practices in another, and a combination of edge-of-field and agronomic practices in the third. Edge-of-field practices included vegetative buffer strips, vegetative turn rows, and slotted board risers.

Comparisons among the regional approaches used for the various MSEA projects provide a useful background for assessing water quality on a regional scale rather than a "one size fits all" approach. Although improving water quality was the driving force for the MSEA program, each MSEA project had its own unique objectives and each subregion its own mix of agricultural commodities, agrichemicals, landscapes, and climate. Each individual MSEA project had its own strengths and weaknesses, and none stood out as distinctly superior in approach used. In summary, each MSEA project was established for and catered to the needs of that particular subregion.

Summary: Bringing Together Regional Monitoring and Modeling, and Scaling Up for National Needs

"Think globally, act locally", the creed of conservationists, recognizes that risk management must be based on global (read: national for regulatory agencies) concerns, but remediation must be based on local knowledge. The tools available for modeling and risk mapping allow integration of regional knowledge into national programs. Regional monitoring and research projects like the MDMSEA provide a reality check, and provide verified remediation solutions for both TMDL and BMP implementation. This combination provides increased protection of resources with decreased disruption of local agriculture and other human activities. Because the knowledge gained is site-specific, the protective measures implemented are more certain and realistic. They are also typically less draconian because uncertainties, and therefore safety margins are smaller. Everyone wins.

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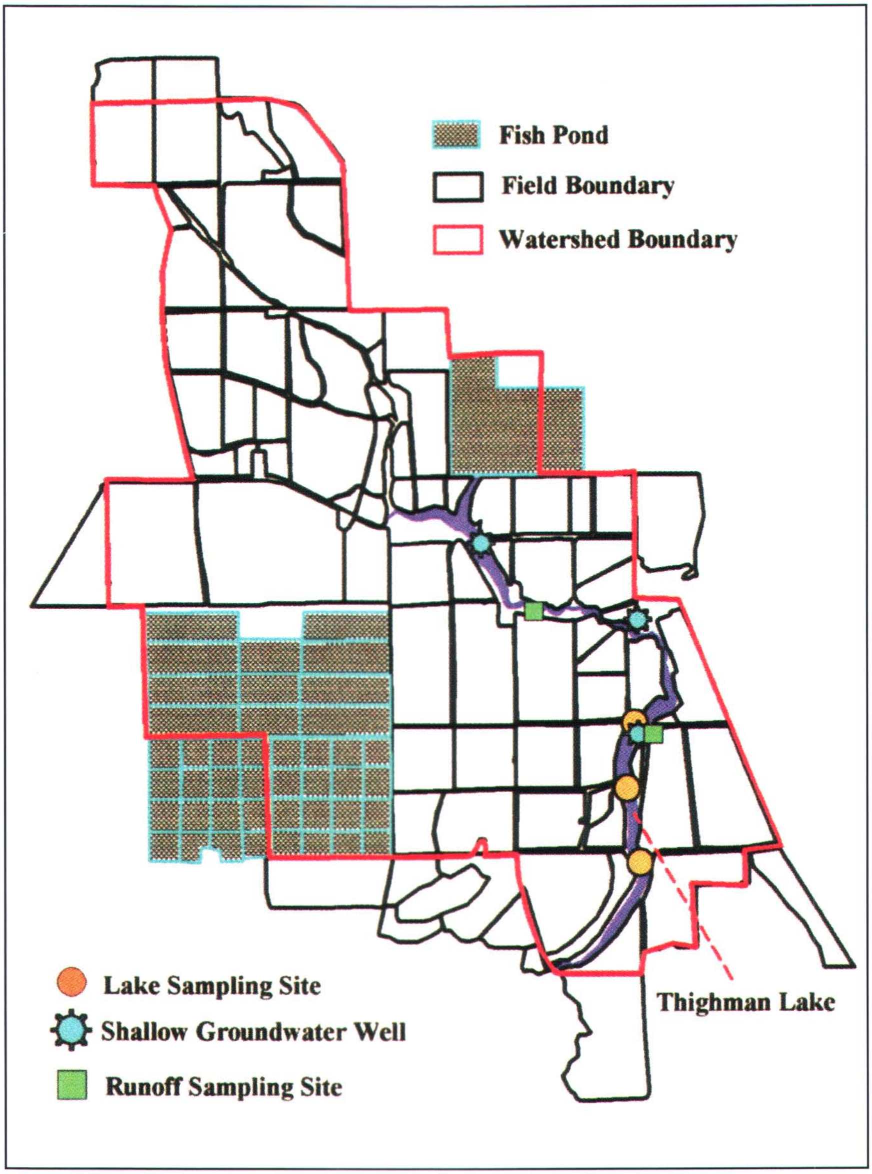

Figure 3. Map of the Thighman Lake watershed.

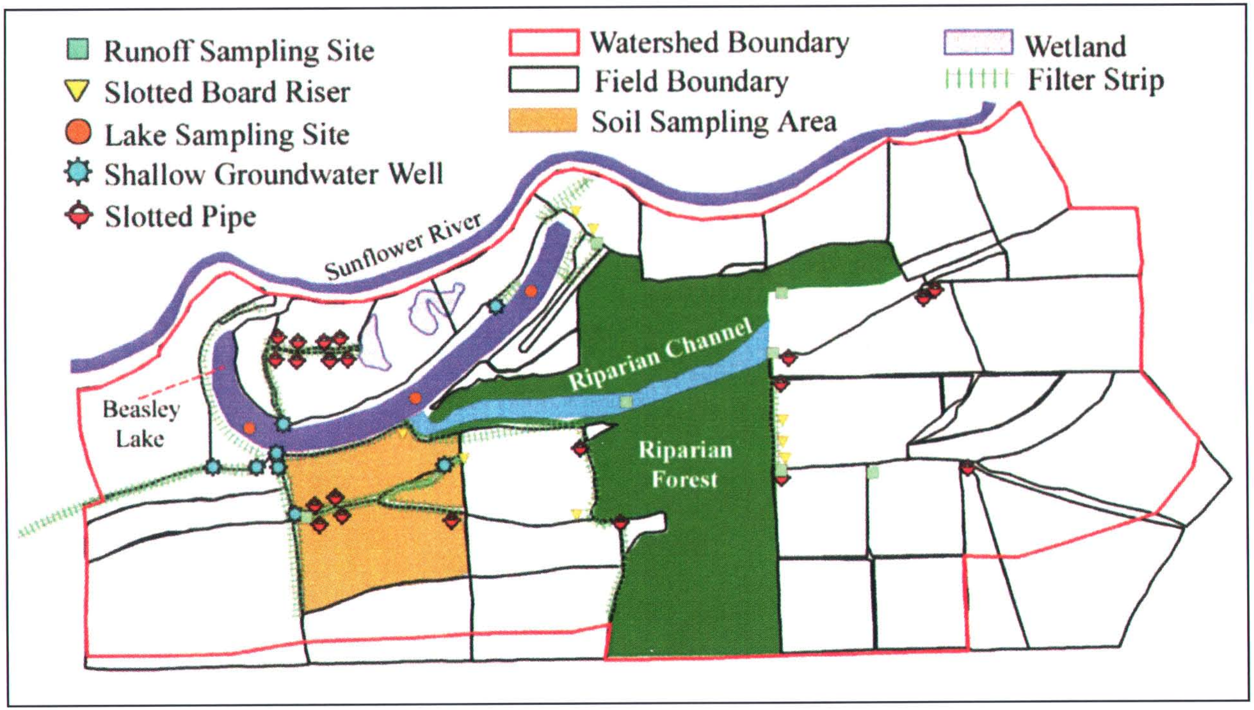

Figure 4. Map of the Beasley Lake watershed.

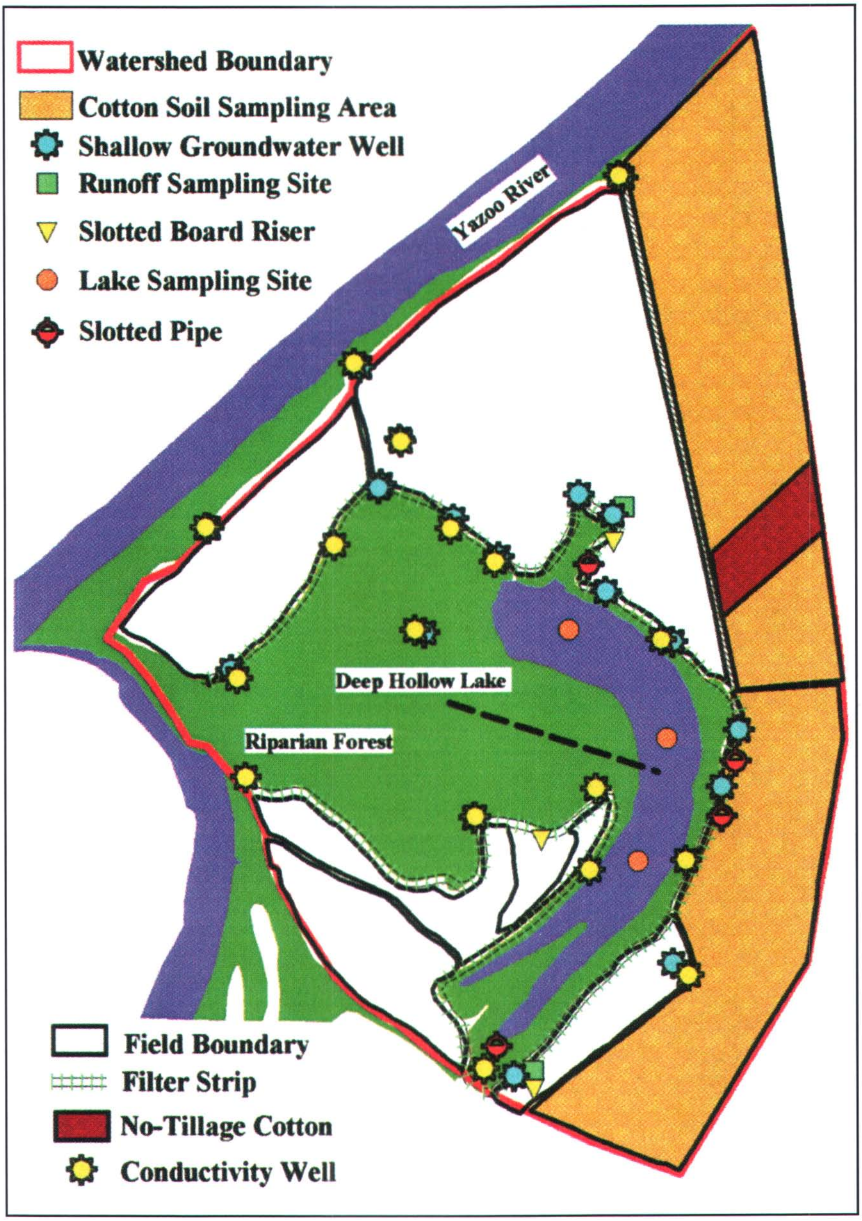

Figure 5. Map of the Deep Hollow Lake watershed.

Author Index

In Water Quality Assessments in the Mississippi Delta; Nett, M., et al.;
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Subject Index

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