Water Resources Research Institute of the University of North Carolina

Annual Technical Report

FY 2000

Introduction

SUMMARY

The North Carolina Water Resources Research Institute program for 2000-2001 (Federal Fiscal Year 2000) continued to focus on three broad areas of concern: surface waters, groundwater, and urban water management. The Institute program also emphasized technology transfer in the form of publications, conferences, workshops, forums, seminars and newsletters. Support from the U.S. Geological Survey through the State Water Resources Institute Program (SWRIP) was supplemented by State Appropriations, Urban Water Consortium, American Water Works Association Research Foundation, and various divisions of the North Carolina Department of Environment and Natural Resources. Fifty-five research projects were supported with these combined resources. The research program focused on seven water quality related projects. These projects involved studies in groundwater, nutrients, swine wastes, pesticides, wetlands, and sediment. Funds for these projects were obtained under the Section 104 RCGP Award.

The technology transfer program for the Institute focused on disseminating the results of the Institute's research program; on gathering and disseminating information on emerging water issues, laws, regulations, and problems; and on transferring regulatory and technical information to facilitate changes in North Carolina's water quality related programs. The following strategies were used: (1) reviewed and published 5 reports as part of the Institute report series; (2) evaluated all research projects with research investigators and users to assess progress; (3) developed separate brochures describing each of the current research projects and listing Institute publications; (4) published a bi-monthly newsletter summarizing research results, new state and federal water laws, regulations and program changes, and announcements of conferences, workshops, forums and seminars; and (5) organized and co-sponsored eight seminars, four forums, six workshops, and one conference on key water issues. The year two thousand continued to bring into focus the need for better scientific information to support and guide policy decisions and regulatory activities regarding water quality and water resource management in North Carolina.

The problem is not just one of increasing magnitude. New technology spawns new kinds of potential threats to public health and the environment, and advances in science are making those threats more apparent. Moreover, the mix of agricultural, industrial, and urban activities are affecting the state's water resources in ways that have not been sufficiently explored.

Just as the state faces unprecedented demand for water use, it also enjoys unprecedented public support for regulations, arrangements, and technologies to protect that resource. North Carolina's legislature as well as the press continue to devote much attention to water-related environmental issues. Among those issues that have drawn the most attention during the year are: 1) protecting water resources from effects of urban growth; 2) water supply and interbasin transfers of water; 3) management of stressed aquifers; and 4) basinwide nonpoint source pollution management.

Research Program

Basic Information

Title:	An Assessment of the North Carolina Water Reuse Regulations
Project Number:	B-02
Start Date:	3/1/2000
End Date:	2/28/2001
Research Category:	Water Quality
Focus Category:	Waste Water, Irrigation, Conservation
Descriptors:	Water Reuse, Law, Wastewater Irrigation
Lead Institute:	Water Resources Research Institute of the University of North Carolina
Principal Investigators:	Helene A Hilger, Mark D Sobsey

Publication

Problem and Research Objectives

North Carolina promulgated water reuse regulations in 1996 in response to growing municipal interest in water reuse. Although the regulations were drafted by an expert committee that sought to integrate the best features of existing state reuse regulations and federal guidelines for reclaimed wastewater, they were written without benefit of any North Carolina pilot or demonstration project data, since none were available.

In 1999, two full-scale municipal water reclamation facilities were proposed and designed. The planning, permitting, and initiation of the projects gave rise to a number of regulatory concerns. The first and most frequently cited was that North Carolina coliform limits are higher than those in states such as California and Florida, where there is a long history of water reuse practice and research. A second concern stemmed from a recognition that fecal coliform monitoring alone may not be adequate to detect the possible presence of viral and parasite pathogens. Some studies have shown that viruses and parasites are more resistant to treatment and more persistent in the environment. Third, municipalities in the process of developing water reclamation projects have questioned whether the existing set back distance requirements are sensible and achieve the desired outcome.

The objective of this research was to examine state water reuse regulations with respect to their ability to (1) stipulate water quality standards that will safeguard public health; (2) permit sensible facility design and operation plans; and (3) stimulate confidence in municipal water reuse options. Some of the research questions posed included:

· *How consistently does the quality of reclaimed water at the point of discharge from the treatment plant meet state regulations?*

· *Does compliance with existing fecal coliform limits insure minimal exposure to virus or parasite pathogens?*

· *Is the quality of reclaimed water at the point of distribution adequate if the water meets state regulations at the treatment plant?*

· *Does the application of reclaimed water to grass in areas of unrestricted public access result in microbiological contaminant loadings that would increase health risks due to contact or ingestion?*

· *How do the microbiological limits in the current regulations compare to findings reported in the most recent pertinent literature and in the most recently revised regulations from other states?*

· *Are the regulations that address design and operation at the treatment facility and distribution site those that optimize public health safeguards without being overly restrictive?*

Methodology

The experimental plan included four main categories of tasks: (1) reviewing of plant monitoring records; (2) testing of reclaimed water collected at the plant and at the delivery sites; (3) modeling of runoff from the delivery site to assess the likely impact of

different buffer widths on receiving water quality; and (4) conducting a literature review to assess the latest findings on microbiological contaminant risks.

The yearlong review of plant monitoring records was to be conducted at each of the two municipal water reclamation facilities that were about to go on-line early in 2000. These plans were amended when the plant start-ups were delayed. The Neuse River WWTP system (Raleigh, NC) is still not delivering water because their customer, the River Ridge Golf Course, has not yet complied with all permitting requirements. The second plant, the Mallard Creek Water Reclamation Facility (MCWRF)(Charlotte, NC), began delivering water to Tradition Golf Course three months into the funding period (June 2000), but operational problems quickly required a shut-down, and service did not resume until September 2000. Therefore, we have extended our monitoring past the end of the grant funding period in order to collect a more complete and useful set of data.

We are also conducting our own tests on water collected from a sampling port on the plant distribution pipe and from irrigation headers and grass at each of three sites at the point of delivery on the golf course. The parameters measured include 5-day biochemical oxygen demand (BOD_5), total suspended solids (TSS), fecal coliforms, NH_4-N, NO_3-N, total dissolved solids (TDS), chloride, chlorine residual, and turbidity. All sampling is done in triplicate and tests are performed within the acceptable time intervals prescribed in Standard Methods for the Examination of Water and Wastewater. Testing is conducted in the UNC-Charlotte environmental engineering laboratories, except for the coliphage assays, which are performed in the UNC-Chapel Hill microbiology laboratories.

For predicting the coliform loading that would result from storm water scouring of plant and soil surfaces, SCS type II rainfall hyetographs for the Charlotte, NC region were developed for rain events that varied in duration (1, 2, 6, and 24 h) and return period (2, 10, and 50 yr). Runoff estimates were calculated using the SCS-TR55 method, and it was assumed that the first flush (1/2") of rain would be sufficient to remove fecal material from the golf course surface. For a worst case analysis, stream flow will be set using the 7-yr low stream flow with a 10 yr return period (7Q10), however, the model will evaluate other possible scenarios as well. For modeling the coliform loading that could result from irrigation water entering the stream, a "25^{th}-day" over-watering with maximum daily load concentration each day will be modeled as the flushing event with and without the attenuating benefit of a vegetative filter strip.

Results

Plant monitoring. Plant monitoring was conducted to help assess how consistently and reliably the treatment plant was meeting the permit criteria. Sample collection began in September, when the system resumed continuous service after a brief start and shut-down in June. Sampling continued in October and November but was discontinued from December through March when irrigation demand was negligible. Sampling resumed in April 2001 and will continue through August 2001.

The MCWRF is rated at 8 mgd and is being expanded to 12 mgd. They are permitted to deliver up to 3 mgd to the golf course, which is approximately 30,000 feet from the treatment plant. The golf course demands up to 1000 gpm, and the treatment plant has two 100-gpm jockey pumps and four 700-gpm pumps that can operate as adjustable frequency drive or constant speed pumps. The pumping system is automated and can deliver a wide range of flows from a wet well to the suction side of an irrigation system

booster pump. A flow-paced sodium hypochlorite feed system provides disinfection. Fecal coliform limits require that the geometric monthly mean be less than 14 cfu/100 mL and that the daily maximum not exceed 25 cfu/100 mL. The golf course is also served by municipal potable water from (1) the Franklin Water Treatment Plant and (2) an 8-inch potable water line from the MCWRF pump station. The 8-inch line allows the pumping system at the WWTP to automatically switch from plant effluent to potable water when the plant effluent turbidity approaches 9 NTU; likewise, it can switch the golf course back to reclaimed water when the water turbidity falls below permit limits (10 NTU). The system also has an alarm that sounds when the reclaimed water turbidity reaches 8 NTU.

The plant has struggled with consistency and reliability, which is probably due in large part to the ongoing construction at the site. The early shut-down soon after start-up was due to high turbidity problems, and there were numerous incidents that required a shift to potable water for weeks at a time. Because there were multiple sources of potable water to the irrigation headers at the golf course (golf course manual shift to potable water; MCWRF pump system shift to potable water; and MCWRF manual shift to potable water), and because there is no standardized protocol for one facility to notify the other when changes are made, the operators at both facilities are often unable to state the current status of the system. There were frequent instances when both the treatment plant and the golf course reported that they were delivering reuse water when, in fact, potable water was sprayed. Our inquiries reveal that the decision at MCWRF to make manual switches to potable water were related to construction.

Water and Grass Sample Testing: Tests for bacterial and viral pathogens during the months of September, October and November 2000 indicated that although fecal coliform limits were consistently met in reuse water leaving the treatment plant, our grab samples in October contained 550 and 1000 pfu/100 mL of F^+ coliphage and somatic coliphage, respectively. In samples taken on the same day from three golf course irrigation headers, samples from two of the headers had more than 400 pfu/100 mL F^+ coliphage, and all of the headers had more than 500 pfu/100 mL somatic coliphage. In September, when samples from the grassed buffer region that received no reuse water had coliphage counts of 1000 pfu/100 mL, grass samples from beneath the irrigation headers had F^+ coliphage counts exceeding 42,000 pfu/100 mL and somatic coliphage counts exceeding 47,000 pfu/100 mL. Chlorine residuals in grab samples from the treatment plant averaged 3.5, 0.04, and 1.9 mg/L in September, October and November, respectively.

Modeling Results: We expect to have the modeling results completed within the next few weeks. We are in the process of developing coefficients that (1) represent the retention of coliforms on grass and soil after spray irrigation and (2) that represent the ease with which coliforms adsorbed to the grass will be scoured off by storm water runoff. Preliminary trials in Dr. Sobsey's laboratory indicate that fecal coliforms are not readily removed when eluted in water. When completed, the modeling runs will show how much fecal contamination carried by storm water or irrigation runoff is likely to be prevented from entering a receiving stream if a buffer region is provided where reuse water irrigation is prohibited. The modeling will evaluate worst case and more intermediate weather and stream flow conditions and a variety of buffer widths.

Principal Findings and Significance

There is already a great deal of interest in municipal wastewater reclamation projects in North Carolina, and this interest has fueled a curiosity about how the first few systems are performing. The results of our monitoring and a complete summary of the successful features as well as some of the operational problems we identified will help to make urban water reuse a proven concept within the state. It will also provide useful information to practitioners as new conceptual designs are developed. The microbiological testing demonstrates that although fecal coliform limits are met, there are substantial numbers of viable coliphage that are not killed in the treatment process. The significance of these counts and whether there is a need to reduce coliphage levels in reuse water sprayed in areas of public access must be evaluated by scientists, municipal personnel and ultimately policy-makers. The modeling results addressing buffer requirements, our review of state regulations nationally, and our literature review of microbiological concerns will offer guidance as North Carolina water reuse regulations are applied and reviewed.

Basic Information

Title:	Assessment of Changing Land-Use Practices on Basin Sediment Yields and Provenance in Western North Carolina Using Multivariate Finger Printing Techniques
Project Number:	B-03
Start Date:	3/1/2000
End Date:	2/28/2001
Research Category:	Climate and Hydrologic Processes
Focus Category:	Sediments, Surface Water, None
Descriptors:	Sedimentation, Geomorphology, Water Quality, Reservoir Siltation, Fingerprinting
Lead Institute:	Water Resources Research Institute of the University of North Carolina
Principal Investigators:	Jerry R. Miller

Publication

Problem and Research Objective**:**

The ecological and financial impacts of sediment on streams and rivers of the southern Appalachians has become a significant issue in the past decade. It is generally assumed that most of this sediment is the result of land-use alterations, particularly those associated with development activities. In fact, federal, state, and local agencies have stated that anthropogenically derived sediment (i.e., sediment resulting from human activities) is the most serious non-point source pollutant in the mountainous terrain of western North Carolina. Unfortunately, however, there have been few attempts to actually quantify the impacts of land-use alterations on upland erosion in the southern Appalachians. This investigation examines the use of physical and geochemical fingerprinting techniques and sediment mixing models within the Fairfield Lake basin to determine if they can be effectively utilized in the steep terrain of western North Carolina. More specifically, the study attempts to determine the relative contributions of sediment, at any given time, to Fairfield Lake from specific geologic units and delineated land-cover types (e.g., forests, roads, lawns, etc.). To our knowledge, this is the first attempt to apply these procedures in the southern Appalachians.

Methodology:

The utilized multivariate fingerprinting techniques required the collection of sediment samples from upland areas as well as the bed of Fairfield Lake. Upland soil samples were collected over two rock units (the Whiteside Granite and the Tallulah Falls Formation) in both pristine (forested) and developed areas. In order to minimize sampling biases, the upland sampling sites were selected by overlaying a numbered grid on a base map of the Fairfield Lake basin. The procedure used for sample collection involved the removal of the organic-rich O-Horizon and the collection of the upper 5 cm of mineral matter. Four samples were generally collected within a 10-meter circle and subsequently composited for each grid. Samples adjacent to streams were collected in the upper 5 cm of the bank sediment. Care was taken to insure that sediment contamination between sites did not occur. All of the collected samples were transported to Sediment/Soils Laboratory at Western Carolina University where they were analyzed for selected physical and mineralogical properties. Subsamples were also sent to the Nevada Bureau of Mines and Geology for selected geochemical analysis under the direction of Dr. Paul Lechler using an Inductively Coupled Plasma Mass Spectrometer (ICP-MS). Quality of the data were assured through analysis and monitoring of blanks, replicates, controls, and standard reference materials (e.g., USGS, NIST, and in-house and international SRMs).

It was critical to collect cores of the lacustrine sediments from depositional zones within the reservoir that were representative of the sediment flux to the lake as a whole. In order to identify such sites, the bathymetry of the lake was determined and spot samples of the lakebed sediment were collected using a grab sampler. Core samples were subsequently collected to determine the stratigraphy of the lake bed sediments in addition to being sampled for chemical analysis. Core locations were chosen based upon the bathymetry, and the watershed bedrock geology, geomorphology, land use patterns, and stream positions. Cores were obtained using a Wright-Livingston coring device at a total of 16 locations in water depths ranging from 1.4 m to 6.6 m. The

sedimentology of the cores was then described in the Soils and Sedimentology Laboratory at WCU. Once described, the data were used to identify spatial variations in depositional patterns within the lake and the total thickness of the lake bed sediments. These interpretations ultimately led to the selection of three cores for further study including the analysis of the deposits for ^{210}Pb and ^{137}Cs (for age dating purposes) and a suite of 24 other elements (and isotopes) for the purpose of multivariate fingerprinting. The Pb and Cs samples were analyzed by Flett Research Ltd. in Winnipeg, Canada.

Principal Findings and Significance**:**

Sedimentation within Fairfield Lake has been limited since dam closure in 1890. Most of the sediment that enters the lake is deposited near the mouth of tributaries creating deposits on the order of 50 to 100 cm in thickness. Deep-water areas located along the axis of the reservoir, and which are removed from the direct influx of tributary sediment, have received only a limited amount of debris (generally <30 cm).

^{210}Pb data clearly indicate that sedimentation rates have significantly increased during the past few decades. The most significant increases occur in the mid-1980s and the late 1990s, both of which correspond to periods of development documented by the comparison of aerial photographs obtained in 1963, 1975, 1988, and 2000. The more recent sedimentation rates are several fold greater than the rates observed during the first half of the 1900s. If the current rates of sedimentation continue into the future, sediment accumulation will likely lead to ecological impacts within the lacustrine system and cause problems for those utilizing the lake for recreational activities.

The statistical treatment of geochemical data from sediments overlying the Whiteside Granite and the Tallulah Falls Formation suggest that the soils associated with these lithologies can be delineated on the bases of Cu, Mn, Sn, U, and Zn. That is, the bedrock units exhibit a unique geochemical fingerprint defined by these five parameters. Similarly, materials from differing sediment sources within the Whiteside Granite, including forests, roads, lawns, and alluvial deposits along upland streams can be defined on the basis of Ag, Bi, Cr, Mn, Mo, Ni, Sb, Sn, and Zn. Thus, the results from the linear discriminant analysis suggest that it is possible to use sediment mixing models to determine the quantity of material derived from differing lithologies or land-cover types.

In light of the above, a separate sediment mixing model was developed using the parameters defined in the discriminant analysis to (1) assess the relative contributions of sediment derived from the different bedrock units that underlie the watershed, and (2) define the contributions of materials to the lake from the four different upland sediment sources. With respect to differentiating between bedrock sources, the model worked reasonably well. However, it appears to have been unable to distinguish between sediment derived from the Tallulah Falls Formation and sediment from a micaeous, more mafic-rich unit of the Whiteside Granite. These two units apparently have a similar geochemical fingerprint. This problem may be addressed by using one of two different approaches. First, the micaeous unit of the Whiteside Granite can be treated as a separate sediment source. Thus, in this study, the mixing models would examine the contributions of material from three lithologic units. For small watersheds, such as the Fairfield Lake basin, this approach may work well. However, for larger watersheds, the approach may lead to an unmanageable number of different sediment sources. An

alternative approach is to define sediment sources according to the gross mineralogical composition of the rocks. In this case, sediments from the Tallulah Falls Formation and the micaeous unit of the Whiteside Granite would be treated as a single source type. There is some merit to this approach in that previous studies have shown that rock units of similar composition also function similarly in terms of their erodibility. Model output may then lead to a conclusion that sediment from a particular lithologic (mineralogic) group tends to produce most of the sediment in an area and, therefore, these rock units should be treated differently (perhaps more stringently) in terms of management practices.

The modeling of the relative contributions of sediment from forests, lawns, roads, and upland alluvium also shows promise in that the model was able to define systematic changes in core geochemistry that are related to changing sediment sources documented on aerial photography. However, it appears that the geochemical signal of lawns, roads, and forests may be muted by geochemical processes as the sediments are transported through upland streams to depositional sites within the lake. Thus, the approach will require modification before it can be effectively used in western North Carolina. Specific modifications should focus on (1) the use of elemental ratios as geochemical fingerprints, and (2) the use of weighting factors based on the ratios of more soluble to less soluble constituents (e.g., Ti) to reduce the effects of elemental loss on the mixing model results.

Basic Information

Title:	Technical and Economic Evaluation of Alternatives for Animal Waste Management
Project Number:	B-04
Start Date:	3/1/2000
End Date:	2/28/2001
Research Category:	Engineering
Focus Category:	Treatment, Nutrients, None
Descriptors:	Animal Waste, Nutrients
Lead Institute:	Water Resources Research Institute of the University of North Carolina
Principal Investigators:	Michael Overcash, Mitch Renkow

Publication

Problem and Research Objectives:

The overall goal of this proposal is to provide more complete information on the full environmental impact and the broad economic consequences of changing the waste management technologies for livestock production industry. We seek to accomplish this through tools that provide an "apples-to-apples" comparison of current and developing waste management technologies. The comparisons will be for

a) all environmental emissions and
b) the broader economic costs.

Specific goals are,

1) to tailor a life cycle framework and an economic framework to the unique challenges of evaluating technologies for waste management in the livestock industry of North Carolina. The specific rules, assumptions, and ultimate data will assure that a reasonable apples-to-apples comparison can be made of each current and new technology. Developing these frameworks will streamline future work and direct research to areas of inadequate understanding.

2) to conduct life cycle comparison of technologies currently being evaluated in direct economic terms by DEHNR as potential candidates for change .

3) to utilize analogous literature information to expand the economic analyses currently undertaken at DEHNR in order to begin to move from direct costs (on-site) to the significant total systems economics that will be influenced by proposed waste management technology changes at livestock facilities. This will improve the cost/benefit analyses (on-going at DEHNR), but will not be able (during this one year project) to represent the complete economic analysis. Thus only certain economic modules will be developed.

4) to provide environmental and economic information to decision-makers as a means of better understanding the complex system of livestock waste management. These individuals include agribusiness, government, and communities. The results of this project will lead to help in making more informed decisions about future waste management alternatives and hence better decisions.

Methodology:

Life cycle and economic frameworks were developed to meet the needs of this research project. For this study, the research method focuses on both the direct comparisons of new alternative livestock waste management technologies to the conventional anaerobic/land application systems, but also on understanding the general magnitude of the indirect or off-site components versus the on-site environmental emissions. This allows one to begin generalizing the results to future alternative technologies or to locations elsewhere in North Carolina or the U.S.

Principal Findings and Significance:

Three animal waste management technologies were completed in this study, the conventional anaerobic lagoon with irrigation of effluent, the biological filter process and the covered lagoon. The covered lagoon has the highest nitrogen contents in both the lagoon effluent the lagoon sludge among other technologies. The biological filtered

process is followed by the covered lagoon in the preservation of nitrogen. The anaerobic lagoon has the highest loss ratio of nitrogen due to the vaporization of ammonia in the lagoon.

For the total energy use, the covered lagoon has the highest avoided energy because of the utilization of biogas, methane, from the lagoon. The biological lagoon requires the electricity for the aeration. The total energy in the biological filtered process ranges from -9.66×10^3 to 3.79×10^3 because of the data sources: from municipal wastewater data or from aerated lagoon data. The resources like coal, crude oil and natural gas, follow the profile of the total energy. It shows that the energy is a major factor influencing the use of resources, not feedstock.

Except the biological filtered process, where carbon dioxide is released from the lagoon, the anaerobic lagoon and the covered lagoon release methane, but the covered lagoon utilizes methane gas to generate electricity and to heat water. Therefore, the anaerobic lagoon has the highest methane emission. The avoided methane emission due to saving the inorganic fertilizer is relatively small. All the three technologies release carbon dioxide from the lagoon. The biological filtered process has the highest carbon dioxide emission. The covered lagoon has the lowest carbon dioxide emission. Though there are avoided energies due to the utilization of methane, the amount of carbon dioxide emission excluding the avoided emission from the inorganic fertilizer is still positive because carbon dioxide is included in the biogas.

Nitrogen oxide is released from the land application; the largest nitrogen applied in the land causes the highest nitrogen oxide emission. Therefore, the covered lagoon has the highest nitrogen oxide emission. Ammonia is also released during the land application. However, the ammonia emission shows different profile from nitrogen oxide because the anaerobic lagoon loses nitrogen through the vaporization of ammonia in the lagoon. The anerobic lagoon has the highest ammonia emission among other technologies.

For NOx emission, the biological filtered process has the highest NOx emission because nitrogen is oxidized and converted into NOx during the aeration. Other emissions show the same emission profile as the total energy.

The comparison between three technologies shows that the covered lagoon is superior to the other two technologies in most of the environmental loadings except N_2O and NH_3 emission. In the covered lagoon the biogas from anaerobic digestion is utilized to generate electricity and to heat water, and there is no nitrogen loss so that the avoided inorganic nitrogen fertilizer is maximized.

Table 2 presents the data on variable (operating) costs, capital costs and, where applicable, credits for by-products. For ease of comparison, we present all data on a cost-per-hog-basis. Beginning with variable (i.e., operating) costs, these are highest for the upflow biofilter system, ranging from $3.14 - $4.33 per animal. Operating costs are also relatively high for the constructed wetlands system ($2.14 per animal). Operating costs are much lower from the SBR system, and are much more sensitive to facility size than any of the other systems – an indication that economies of scale are the greatest for this system. Finally, the cost data indicate that the covered lagoon systems are the least expensive to operate – particularly the systems in which methane is flared off. In all cases, the CL systems cost less than one dollar per animal to operate.

As with variable costs, capital costs are generally lowest for the covered lagoon systems, and are highest for the upflow biofilter and (especially) the constructed wetlands system. Capital costs of covered lagoon systems with electrical generation are roughly double those of covered lagoon systems in which methane is flared off. However, this additional capital cost is more than made up for by the value of electricity that is generated. As was the case for variable costs, unit costs for the sequencing batch reactor systems emerge as most sensitive to scale of operation – again, an indication of significant scale economies in construction for the SBR technology.

The cost estimates include offsetting credits for potentially useful by-products created by two types of systems: biosolids for UB system and electricity sales for CLG system. With respect to biosolids, it is important to recognize that whether or not these can be sold by a user of the UB technology will depend on whether or not a market for those by-products exists. It is beyond the scope of this research project to make such an assessment. However, we would point out that the potential usefulness of a nitrogen rich by-product is only one of several necessary conditions for such markets to come into being. Other important pre-requisites include the ready accessibility of potential users of the product, steadiness of the supply of bio-solids, and reliability of the chemical composition of the by-product for quality assurance/quality control purposes. We would further note that consumer resistance to waste-based products has been observed in a variety of contexts (Renkow and Rubin, 1998).

Use of the recovered methane to generate electricity represents a potentially important offset to the cost of the covered lagoon system. We would point out in passing that there is some question as to the ease with which small-scale generators of electricity are able to sell that electricity back to power companies. For this reason, we discount the value of surplus electricity generated by the CLG systems (over and above what is needed to run the waste treatment technology) from 6¢ per kWH to 3.5¢ per kWH.

Table 2. Costs per hog of alternative swine waste management systems

System	Facility size[a] (hogs per turn)	Variable cost per hog	Capital cost per hog
Upflow Biofilter	4,000	$4.33	$2.92
	8,000	$3.14	$2.06
Sequencing Batch Reactor (clay liner)	2,500	$1.60	$1.76
	7,500	$0.88	$0.82
Sequencing Batch Reactor (synthetic liner)	2,500	$1.64	$2.22
	7,500	$0.90	$1.09
Covered Lagoon with flare off (clay liner)	2,500	$0.30	$0.74
	7,500	$0.21	$0.56
Covered Lagoon with flare off (synthetic liner)	2,500	$0.32	$0.98
	7,500	$0.23	$0.74
Covered Lagoon with generator (clay liner)	2,500	$0.69	$1.39
	7,500	$0.40	$1.03
Covered Lagoon with generator (synthetic liner)	2,500	$0.72	$1.63
	7,500	$0.42	$1.21
Constructed Wetland	3,520	$2.14	$4.58

a. All systems assume 2.8 turns per year, except for the constructed wetlands (which assumes 2.5 turns per year).

Basic Information

Title:	Environmental and Human Health Impacts of Swine Waste Management Practices
Project Number:	C-08
Start Date:	9/1/1998
End Date:	2/28/2001
Research Category:	Water Quality
Focus Category:	Nutrients, Agriculture, None
Descriptors:	nitrogen, waste treatment, agriculture, animal waste, denitrification, fertilizers, nutrients, soil chemistry, public health, pathogens
Lead Institute:	Water Resources Research Institute of the University of North Carolina
Principal Investigators:	Stephen C. Whalen, Mark D Sobsey

Publication

1. Hill, V.R.; and M.D. Sobsey, 1998, Microbial indicator reductions in alternative treatment systems for swine wastewater. Water Science and Technology, 38(12), 119-122.
2. Hill, V.R.; 2001, Investigation of Constructed Wetlands, Lagoons and Other Treatment Systems for Reducing Salmonella and Enteric Microbial Indicators in Swine Waste, Ph.D. Dissertation, University of North Carolina, Chapel Hill, NC.

Problem and Research Objectives:

The swine industry is an increasingly important sector in North Carolina agriculture and is thus a potential contributor to non-point source water pollution. This unprecedented growth presents problems in determining the impact of potential pathogens and the disposal of swine manure.

Little is known about the concentrations of pathogens and other enteric microbes in swine waste and swine farm waste management systems. Without some understanding of the presence and fate of pathogens and other microbes in swine waste treatment systems, it is difficult to evaluate the public health risks posed by current swine waste management techniques.

Nutrient management plans for large-scale swine producing facilities involve waste storage in anaerobic lagoons and land application of lagoonal contents as fertilizer at no more than the agronomic nutrient (in this case N) requirement for the host crop. Improper management will encourage offsite transport, leading to enhanced N loading in adjoining ecosystems, particularly rivers, estuaries and coastal waterways. Excessive N loading in North Carolina coastal waters has led to the recurring development of nuisance algal blooms, summer fish kills, and a growing propensity for bottom water hypoxia and anoxia in major coastal rivers and estuaries. Rapid contemporary growth of the swine industry has been implicated as a source of accelerated nutrient loading to coastal environments. Various aspects of the fate of N in land-applied liquid lagoonal swine effluent have been individually analyzed in detail, including efficiency of plant utilization, long-term soil accumulation, NH_3 loss to volatilization during application and export to groundwater. Considerably less research effort has focused on microbial N transformations in spray field soils. Comprehensive studies that encompass all aspects of N cycling dynamics in spray fields, including simultaneous analysis of changes in pool sizes and rates of microbial N transformations are lacking. Information of this nature at all scales is critical to evaluate the efficacy of present Best Management Practices for waste disposal at large-scale swine production facilities and to determine the extent to which offsite N transport may influence adjoining terrestrial and aquatic ecosystems.

This project has a two-fold objective. First, to develop a nitrogen mass balance for field plots experimentally fertilized with liquid lagoonal swine effluent at a representative large scale swine production facility in the North Carolina Hog Belt. The magnitude of nitrogenous nutrient pools and rates of transformation among pools in waste-amended plots for two weeks post-fertilization period are being evaluated at two typical loading rates. Second, to determine the concentrations of *Salmonella* and microbial indicators of fecal contamination in flushed swine waste prior to treatment, during lagoon treatment, and in alternative waste treatment systems.

Methodology: Whalen

The study site is a farrow to half-finish facility that is centrally located in North Carolina's "Hog Belt." Waste management practices are representative of the industry. Swine waste is stored in anaerobic lagoons and land-applied throughout the growing season via a set sprinkler system to a summer crop of coastal bermudagrass (*Cynodon* sp.) and a winter crop of tall fescue (*Festuca* sp.). Both crops are fertilized with liquid lagoon waste at the rates that meet the agronomic N requirement which is similar for both species, 20 to 22 kg $(\text{dry tonne})^{-1}$ (Zublena et al. 1993).

For each sampling session, seven 1.5 m x 1.5 m experimental plots are established on a spray field. The grass cover is cut to a uniform 15 cm height and cores are taken for initial plant and microbial biomass as well as soil nutrient content. One plot serves as a control (no fertilization) and the remainder are amended with liquid swine effluent at volumes corresponding to 1.25 or 2.5 cm additions (3 plots each volume). The control plot and duplicate plots for each amendment are instrumented with integrating soil moisture and temperature probes and output is continuously sent to a data logger. These 5 plots are also each fitted with 2 permanent soil anchors for measuring rates of N_2O and NH_3 exchange between the soil and atmosphere. A rain gauge is deployed adjacent to the plots to measure precipitation during the two-week experiment. Immediately following fertilizer addition, NH_3 volatilization is measured from the control and fertilized plots using a dynamic chamber approach. In addition, N_2O flux is measured using static chambers. Thereafter, NH_3 volatilization and N_2O flux are measured at 3 h intervals to 24 h, daily to 72h and at days 5, 7, 10 and 14. Duplicate cores are collected from each plot for determination of rates of denitrification immediately after fertilization, at 6, 12 and 24 h, daily to 72 h and at days 5, 7, 10 and 14. Soils from these cores are analyzed for nutrient content as well to determine rates of net nitrification. Additional soil cores are collected at days 3, 7 and 14 to determine the change in microbial biomass-N. On day 14 soil cores are collected to 50 cm to determine transport of nutrients below the surface, microbially active layer of 20 cm. This essentially represents transport to shallow groundwater. Finally, cores are also taken to assess the increase of plant biomass-N from fertilization. Soil cores from the non-experimental, fertilized companion plots are used to replace the soils removed from the experimental plots during each destructive sampling to minimize disturbance that results from sampling.

Methodology: Sobsey

All samples were collected from swine farms in North Carolina and analyzed for *Salmonella* (by an enrichment broth Most Probable Number method), bacterial indicators (fecal coliforms, *E. coli*, enterococci and *C. perfringens* spores) by membrane filtration, and viral indicators (somatic and male-specific coliphages) by agar pour plate methods.

Flushed waste and lagoon liquid samples were collected on an approximately monthly basis at four swine farms between December 1998 and May 2000. Two of these farms had single-stage lagoon systems, and the other two farms had lagoon systems consisting of two-stage lagoon systems with two lagoons in-series.

Flushed waste and effluent samples from an in-ground, ambient-temperature anaerobic digester were also collected approximately monthly (December 1998 to May 2000), at a commercial, farrow-wean swine farm operating at North Carolina State University's research swine farm. Eleven sets of samples were collected from the biofilter system between June 1998 and January 2000. Wastewater from the biofilter system was also used to investigate the effectiveness of UV irradiation for reducing enteric microbe concentrations in swine wastewater. Bench-scale, collimated-beam UV disinfection experiments were preformed in our UNC laboratory.

Flushed waste, treated wastewater, and recovered swine waste biosolids were collected from commercially operated, multi-stage biological treatment systems designed to recover marketable biosolids at two swine farms. The wastewater samples were analyzed to determine enteric microbe reductions in the liquid stream of the treatment

systems. The biosolids were analyzed for *Salmonella*, fecal coliforms and other enteric microbes to evaluate the ability of the treatment systems to produce biosolids meeting federal (US EPA) Class A microbiological standards for biosolids reuse.

Three treatment systems were investigated in parallel at a commercial swine nursery. These systems (constructed wetlands, overland flow and marl-gravel media filtration) received liquid from the farm's anaerobic lagoon. Nineteen sets of samples were collected from the constructed wetland system between March 1997 and May 2000. Eight sets of influent and effluent samples were collected from the media between March 1997 and June 1998. Six sets of influent and effluent samples were collected from the overland flow system between March and October 1997.

Principal Findings and Significance: Whalen

This project has been slow to get off the ground for a number of reasons. The first two experimental plots were abandoned due to a hurricane in September of 1999 and an unprecedented winter snowfall in January 2000. Subsequently, we discovered that the initial design of the NH3 flux chambers was inefficient at trapping volatilized gas. We expended considerable effort testing and redesigning traps before settling on a new protocol. We were able to occupy field sites successfully for two-week periods in August, 2000 and in January and April of 2001. We intend to conduct additional experiments in July and September of 2001. Samples have been analyzed for all flux measurements and changes in pool size. Data are largely in a raw form. Accordingly, the following comments with regard to results are general in nature. More than 90% of the NH3 volatilized from land-applied swine waste was emitted within 24 h of application in all experiments. Little waste-N (<1%) is lost to denitrification as N_2 or N_2O. These losses occur largely within 24 h of fertilization. However, these losses occur sporadically throughout the experiment, especially for N_2. This reflects the high spatial variability for this microbial process. As we collect cores throughout the experiment, we sometimes encounter "hotspots" of activity. Nitrification occurs steadily throughout the experimental period, as evidenced by the accumulation of NO3 in the soil. Qualitatively, it appears that little applied N is assimilated into microbial or plant biomass during the measurment period. Further, no N migrates below the acitve 20 cm surface soil zone. Even these qualitative results should be viewed with caution, as soils were uncharacteristically dry and weather was unseasonably hot during each experiment.

Principal findings and significance: Sobsey

In untreated swine waste lagoon influent, average concentrations of *Salmonella* spp. were approximately 2000 MPN/100 mL. *Salmonella* were reduced by 83-98% in primary lagoons and by further 94-96% in secondary lagoons. In general, fecal coliforms, *E. coli* and enterococci were reduced to a similar, but slightly greater, extent than *Salmonella* (~97-98%) in each lagoon cell provided. *C. perfringens* spores were less efficiently reduced in lagoons than the other enteric bacteria studied, being reduced by approximately 75% in primary lagoons and a further 92% in secondary lagoons. Somatic and F-specific coliphages were reduced to a similar extent as measured for fecal coliforms, *E. coli*, and enterococci (~97% in primary lagoons and a further 94-96% in seconary lagoons). *Salmonella* and enteric microbe reductions in the in-ground anaerobic digester were similar to those measured in anaerobic lagoons, with the exception that reductions of enterococci and *C. perfringens* spores were significantly higher in the digester than the lagoons.

In surface flow constructed wetland treating lagoon liquid, fecal coliform, *E. coli*, and enterococci were reduced by 98,99 and 87%, respectively. In the same system, *Salmonella* spp. were reduced by 96% and *C. perfringens* spores, somatic coliphages and F-specific coliphages by 97, 99 and 98% respectively. In gravel media filter and overland flow field systems investigated in parallel with the surface flow constructed wetland, reductions of enteric microbial indicators were, in general, far lower than achieved in the constructed wetland (typically ≤90%). In the aerobic biofilter field system, reductions of fecal coliforms, *E. coli*, and enterococci were 97, 97 and 96%, respectively. *Salmonella* spp. were reduced by 94% and *C. perfringens* spores, somatic coliphages and F+ coliphages by 84, 95 and 97%, respectively.

In the biosolid recovery biological treatment systems investigated at two farms, reductions of fecal coliform, *E. coli* and enterococci were approximately 99.3, 99.3 and 99.5%, respectively, within the closed-loop portion of the treatment systems. In this portion of the systems, *Salmonella* were reduced by 99.4% and *C. perfringens* spores, somatic coliphages and F-specific coliphages by 81, 99.5 and 99.8% respectively. In the "temporary storage areas" at the two farms (i.e., the former waste lagoons retrofitted to hold excess water from the aerated solids recovery biological treatment systems), concentrations of microbial indicators (except *C. perfringens* spores) and *Salmonella* were, in general, over 4 orders of magnitude lower than in the untreated, flushed swine waste. This indicates that lagoons replaced by alternative swine waste treatment systems can be utilized for additional reduction of enteric microbe concentrations in the liquid subsequently applied to sprayfields. In addition, biosolids data from these systems indicate that this treatment technique is capable of generating biosolids of sufficient microbiological quality to meet federal Class A standards for unrestricted use of sludge.

Overall, the data from this study show that high concentrations of *Salmonella* and other enteric microbes can be found in untreated and lagoon-treated swine waste. The results of this study demonstrate that alternative biological treatment systems can be effective for achieving similar or even much higher enteric microbe reductions compared to single-stage lagoon systems, thereby reducing risks to human health and environmental resources.

Basic Information

Title:	Soil Processes Impacting Groundwater Quality in North Carolina Piedmont: Contamination by Organic Agrochemicals
Project Number:	B-III
Start Date:	3/1/1999
End Date:	6/1/2000
Research Category:	Ground-water Flow and Transport
Focus Category:	Groundwater, Hydrogeochemistry, Solute Transport
Descriptors:	Sorption, Desorption, Soil Chemistry, Soil Iron Oxides, Pesticides, Herbicides, Organic Compounds, Water Chemistry
Lead Institute:	Water Resources Research Institute of the University of North Carolina
Principal Investigators:	Dharni Vasudevan

Publication

1. Vasudevan, D.; and E.M. Cooper, 2000, Retention of polar/ionogenic pesticides in iron-oxide rich soils, in Abstracts of Papers of The American Chemical Society, Division of Envrionmental Chemistry, 40(2), 156-158.

Problem and Research Objectives:

The NC Piedmont is dominated by heavy-textured ultisols ("red clay soils"), acidic soils that have low organic matter, high iron (Fe), and high content of low-activity clays (e.g., kaolinite), particularly in the subsoil horizons. These and other attributes, including the soil's potential for possessing variable charge, make Piedmont red clay soils physically and chemically distinct from many of the soils of the coastal plain. As a result of the extremely small size of clay and Fe oxide particles and the reactivity of the electron-deficient surface-bound Fe atoms, subsurface horizons of the red clay soils are the seat of important physical-chemical activity. Systems and guidelines for evaluating pesticide/herbicide fate developed from information based on the more commonly studied temperate soils have been successful for the coastal plain, however, additional research on other soil types will help determine how we can best adapt these and other systems for the evaluation of pesticide/herbicide fate in the NC Piedmont.

This research explores abiotic interfacial (surficial) processes that contribute to the attenuation and mobilization of three polar/ionogenic herbicides in two common soils of the NC Piedmont. More specifically, we have examined the potential for sorption, desorption, and surface assisted transformation of 2,4-dichlorophenoxy-acetic acid (2,4-D), norflurazon, and quinmerac in Appling and Georgeville soils as a function of (1) the mineralogy, composition, and physical-chemical properties of the soil, and (2) the molecular structure and physical-chemical properties of the herbicide.

Methodology

Samples of Appling and Georgeville soils were obtained from sites in the Duke forest at gates 12 and 11, respectively. Samples were taken at five depths between 0-200 cm to represent all prominent soil horizons as determined by visual and physical changes in the soil profile. Each soil sample was characterized for several parameters including total elemental composition, texture, pH, effective cation exchange capacity, saturated paste conductivity, N_2BET surface area, extractable aluminum (Al) and iron (Fe) oxide content, and maximum capacity for phosphate sorption. Well-controlled laboratory batch and continuous flow stirred tank reactors (CFSTR) were used to evaluate the nature and extent of herbicide sorption, desorption, and transformation at soil pH in the various soil samples. Statistical tools including linear regressions and principal component analysis (PCA) were used to evaluate the relatedness of soil properties and influence of soil properties on herbicide-soil interactions.

Principle Findings and Significance

Soil Composition and Physical-Chemical Properties
The upper horizons (0-70cm) of the Appling soils can be categorized as sandy loams and the lower horizons evaluated (70-170cm) as clay soils. In the case of the Georgeville soils, the uppermost (0-30cm) and the lowermost (150-200cm) horizons evaluated are silt loams and the intermediate horizons (40-150cm) are clay soils. Both soils are relatively acidic, with pH values between 4.5-5.4. Trends with respect to surface area, total and extractable Al and Fe content, and phosphate sorption capacity as a function of soil depth are closely related to soil texture, with the clay soils possessing higher values of these measured parameters than the sandy and silt loams. Total carbon is highest in the uppermost horizons of the two soils, and the nitrogen and phosphorus content is low in all soil horizons.

Batch studies of herbicide-soil interactions
We find that the extent of loss from soil solution of the two *ionic* herbicides, *2,4-D and quinmerac*, as a function of soil depth differs considerably from the non-ionic norflurazon. In all cases, loss from solution is believed to be primarily due to sorption onto the soil matrix. Additionally, the behavior and extent of loss from solution for all herbicides differs between Appling and Georgeville soils and appears to be related to differences in soil properties. Correlations between the extent of herbicide loss and soil properties reveal that 2,4-D and quinmerac loss are strongly correlated with surface area, clay content, total aluminum, total iron, and free (or crystalline) iron oxide content, while norflurazon loss can only be correlated to total soil carbon. Batch studies with pure phase minerals, hematite, goethite, -aluminum oxide, and kaolinite, confirmed that iron and aluminum oxides are important sorptive surfaces for 2,4-D and quinmerac. These minerals, however, do not have a capacity for norflurazon sorption.

Soil iron and aluminum oxides are expected to have a net positive charge at the measured soil pH (4.5-5.4). Hence, we speculate that the high retention of 2,4-D (negatively charged at soil pH) and quinmerac (neutral to negatively charged) in iron-rich mineral horizons is due to favorable electrostatic interactions with the soil surface. In addition, simultaneous complexation of the carboxylic acid groups with surface-bound electron deficient iron centers, via ligand exchange with surface bound –OH and H_2O, is also likely. In the absence of an ionizable group such as the carboxylic group, as is the case for norflurazon, interaction with soil minerals is less likely and hydrophobic interactions with soil bound organic matter is the dominant process for herbicide retention.

CFSTR studies of sorption-desorption phenomena
Evidence of partial or complete desorption using deionized water in the CFSTR experiments confirms that the observed loss from soil solution in the batch studies is primarily due to sorption. Furthermore, for 2,4-D and quinmerac, desorption is initially more rapid than sorption; this indicates that H_2O and/or OH^- can competitively desorb 2,4-D, and quinmerac. It also provides additional evidence that the herbicide mass involved in reversible sorption is bound to the soil surface via favorable electrostatic interactions and/or weak surface complexation (ligand exchange). Irreversible retention of 2,4-D and quinmerac likely results from strong surface complexation or entrapment within soil aggregates or particle micropores. For norflurazon, sorption and desorption appear to occur at the same rate; this provides further evidence that nature of norflurazon-soil interactions are distinct from 2,4-D and quinmerac interactions with Appling and Georgeville soils. These findings demonstrate that CFSTR studies conducted in conjunction with batch studies allow for improved evaluation of sorption/desorption phenomena at the soil-water interface.

Statistical Analyses
Our findings based on batch and CFSTR laboratory experiments are substantiated by principal component analysis conducted to establish the inter-relatedness of soil parameters and the influence of soil parameters on the nature and extent of herbicide retention. The analysis confirms that crystalline iron oxide content, non-crystalline aluminum oxide content, total iron and aluminum content, and surface area play the most important role in the retention of ionogenic herbicides (2,4-D and quinmerac) and that these soil properties are more influential than pH and organic matter content. The analysis also shows the expected dependence of norflurazon retention on soil carbon.

Conclusions

Our study clearly demonstrates that in ultisols (or red clay soils) of NC Piedmont, herbicide properties other than hydrophobicity, and soil properties other than organic matter, texture, and acidity should be considered when evaluating ionogenic herbicide fate and transport. Polar ionogenic compounds possessing ligand donor groups (such as –COOH) can be retained in the mineral horizons of the ultisols via favorable electrostatic interactions and surface complexation with soil Al and Fe oxides. In the absence of ligand groups (non-ionic herbicides), partitioning to organic matter is expected to dominate.

For the soil types examined, it appears that in the absence of rapid microbial degradation 2,4-D and quinmerac are less likely to be retained in the uppermost soil horizon as compared with the lower horizons, while the opposite may be expected for norflurazon. Our results also suggest that norflurazon that migrates below the uppermost soil horizon is less likely to be attenuated in the subsoil and is hence more susceptible to leaching and groundwater transport. Furthermore, the nature of the herbicide-soil interaction is relatively weak for a significant mass of the herbicide attenuated by the soil matrix (sorbed on the soil), hence, precipitation or irrigation can easily transport (or leach) the "reversibly" retained fraction through the soil profile and potentially into groundwater. However, the mass that is entrapped within the soil matrix will likely prove more recalcitrant with respect to the susceptibility for leaching into groundwater. Additionally, herbicides that are transported to lower soil horizons where microbial activity is typically low may persist in the environment longer than expected. Therefore, a significant fraction of herbicide mass remaining in the uppermost soil horizon has a high susceptibility to leach into groundwater under intensive rainfall and irrigation.

Basic Information

Title:	Impact of Sediment Processes on Water Quality in the Neuse River Estuary
Project Number:	B-II
Start Date:	3/1/1999
End Date:	2/28/2001
Research Category:	Water Quality
Focus Category:	Nutrients, Sediments, Water Quality
Descriptors:	Sediment processes, Estuaries, Nitrogen, Geochemistry, Model Studies
Lead Institute:	Water Resources Research Institute of the University of North Carolina
Principal Investigators:	Marc J. Alperin

Publication

1. Clesceri, E.J.; M.H. Krief, Alperin, M.J., and B.J. Ream, 2001, Sedimentary recycling efficiency of primary production in the Neuse River Estuary, N.C., in 2001 North Carolina Water Resources Research Conference Abstracts, p. 32.
2. Ream, B; M.J. Alperin, 2001, Impacts of organic matter reactivity, bottom current, and bottom water oxygen concentrations on estuarine sediment oxygen demand, in 2001 North Carolina Water Resources Research Conference, p 53.
3. Nie, Y.; M. Alperin, and J. Fear; 2001, Denitrification in the Neuse River Estuary: Isotope pairing technique and numerical modeling, in 2001, North Carolina Water Resources Research Conference, p. 54.
4. Alperin, M.; Bowen, J., D. Herrington and D. Stotts, 2001, A coupled water column-sediment biogeochemistry model for the Neuse River Estuary, in 2001 North Carolina Water Resources Research Conference, p. 59.
5. Ream, B.J.; and M.J. Alperin, 2000, Controls on estuarine sediment oxygen demand: Impacts of bottom current and organic matter reactivity, EOS 81: F493.
6. Schlenker, J.C. and M.J. Alperin, 2000, Sulfate reduction rates in the mesohaline portion of the Neuse River estuary during the summer. EOS 81:F494.

Problem and Research Objectives: Numerous studies of estuaries clearly demonstrate that sediment-water exchange plays an important role in regulating water column oxygen and nutrient concentrations. Although most detrital organic matter that becomes incorporated into sediments is eventually remineralized, the sediment oxygen demand and net flux of nitrogen across the sediment-water interface is controlled by both biogeochemical and physical (hydrodynamic) processes. Because these processes interact in a complex, nonlinear way, the magnitude of benthic fluxes are difficult to predict. The goal of this project was to quantify the contribution of bottom sediments to oxygen demand and nutrient loads in the Neuse River estuary. Our specific objectives were to: (1) conduct a detailed field study of sediment carbon and nitrogen cycling at four stations in the mesohaline section of the Neuse River estuary; (2) develop a process-level diagenetic model capable of predicting benthic fluxes of oxygen, nitrate, and ammonium; (3) investigate the decomposition kinetics of sedimentary organic matter to evaluate the lifetime of the sediment oxygen demand and benthic nitrogen pool; and (4) extend the diagenetic model throughout the estuary by linking it to an existing water quality model.

Methodology:

(1) Benthic flux measurements. We used two complementary approaches to quantify rates of sediment-water exchange: (a) direct measurements of benthic flux with sediment chambers, and (b) calculations of benthic flux using measured porewater concentration gradients. Sediment chambers were made from 25-cm long by 14-cm diameter PVC tubing capped with a Plexiglas lid (O-ring seal) equipped with inlet and outlet ports and magnetic stirring bar. Since benthic fluxes can be extremely sensitive to flow conditions inside the chamber, we calibrated the stirring rate (alabaster plate method) so that natural hydrodynamic conditions near the floor of the estuary could be simulated. Triplicate sediment cores for the benthic chambers were collected by diver by gently inserting the chamber barrels into the sediment and sealing with a base plate. The chambers were placed in a water bath at *in situ* temperature; water samples were collected at regular intervals and analyzed for oxygen (micro-Winkler titration), total CO_2 (flow injection analysis), and nutrients (ammonium, nitrate, and phosphate; Lachet automated ion analyzer). Bottom-water oxygen demand was measured to provide a control. For calculated fluxes, porewater was collected from sediment gravity cores. Triplicate cores were sliced at high resolution (0.5 cm) to provide the best possible estimate of concentration gradients near the sediment-water interface. Porewater was extracted by centrifugation, filtered, and analyzed for total CO_2 and nutrients as described above. High resolution oxygen concentration gradients were calculated by microelectrode (Clark-type) profiling of sediment in the benthic chambers after completion of the flux experiment. Fluxes were calculated from Fick's First Law after correcting diffusion coefficients for porosity.

(2) Sediment concentration profiles. Triplicate gravity cores were sectioned at 0.5-cm intervals (0-2 cm) or 3-cm intervals (0-40 cm). Porewater was extracted by centrifugation, filtered, and analyzed for total CO_2, nutrients, sulfate and chloride (ion

chromatraphy), and total H_2S (colorimetry). Whole sediment was analyzed for methane by headspace extraction/gas chromatography. The solid sediment was lyophilized and analyzed for porosity and TOC, C:N, ^{13}C-TOC, and ^{15}N-TN (elemental analyzer interfaced to isotope ratio mass spectrometer).

(3) Rate Measurements. All rate measurements were conducted at *in situ* temperature using triplicate gravity cores. Sulfate reduction rates were measured by the ^{35}S-SO_4^{2-} technique. Whole sediment in glass incubation syringes was injected with microliter quantities of radio-sulfate and incubated for 24 hours. The incubation was terminated by freezing the sample and radiosulfide was collected by acidic Cr-distillation and quantified by liquid scintillation counting. Ammonium, total CO_2, and methane production rates were measured by the tube incubation technique in custom-built, headspace-free incubators that allow for periodic, gentle sediment mixing. Five sediment aliquots were sampled from the incubators at 1-day intervals and analyzed for ammonium, total CO_2, and methane as described above. Ammonium production rates were corrected for adsorption using K_D values measured by the potassium displacement method. Denitrification rates were measured by the isotope pairing technique. Intact subcores are incubated with $^{15}NO_3^-$ in the overlying water for 30 min to 3 hr to generate a 4-point time-series. At the end of the incubation, dissolved gases were extracted, transferred to a nitrogen-free serum vial, and analyzed for $^{14}N^{14}N$, $^{15}N^{14}N$, and $^{15}N^{15}N$ on a GC-mass spectrometer equipped with triple-beam collector.

(4) Diagenetic model. The model used in this project is based on a set of coupled, nonlinear differential equations that describe biological and chemical reactions and diffusive and advective transport in the bottom few centimeters of the water column to a depth of 1-meter in the sediments. The model explicitly links nitrogen, oxygen, and carbon biogeochemical cycles in order to simulate the sequence of diagenetic processes that constitute the sediment microbial food web. The hydrodynamics of the

benthic boundary layer are simulated by intense damping of turbulent diffusion through the viscous sublayer.

(5) Microcosm study. The “lifetime” of the most reactive sedimentary organic matter was evaluated by measuring changes in sediment oxygen demand and nutrient and total CO_2 fluxes (described above) over a 1 year time-series. Sediments in the benthic chambers were stirred and aerated between flux measurements, and overlying water was periodically replaced by fresh estuarine water.

Principal Findings and Significance: In the Neuse Estuary, approximately 50% of the sub-pycnocline oxygen consumption occurs within the sediment column. Thus, organic matter decomposition in both the sediment and bottom water are important in producing the hypoxic and anoxic water that blankets the estuarine floor throughout much of the summer.

(1) Laboratory experiments and the sediment diagenetic model show that sediment oxygen uptake is highly impeded by diffusion through the benthic boundary layer. Thus, estuarine hydrodynamics has a far greater impact on the magnitude of the benthic oxygen flux than changes in the quantity or reactivity of sedimentary organic matter.

(2) Benthic ammonium fluxes are high throughout the summer and provide 20-50% of the nitrogen demand of primary producers.

(3) Denitrification is limited during the summer by low nitrate concentrations in the bottom water combined with restricted nitrification due to limited oxygen penetration into the sediment. However, coupled nitrification-denitrification (0.2 to 3 mmol N m^{-2} d^{-1}) plays a significant role in the nitrogen budget any time that bottom waters become aerated.

(4) Benthic oxygen demand remains high (about 1 g O_2 m^{-2} d^{-1}) in sediments incubated in the lab in stirred chambers for more than one year. Since these sediments have been in the dark and have received no new source of organic matter, the persistence of oxygen demand implies a long lifetime for sedimentary organic matter and/or a substantial reservoir of reduced inorganic compounds in the porewater.

(5) Our multispecies, coupled diagenetic model accurately predicts sediment oxygen demand, denitrification rates, benthic fluxes of ammonium and total CO_2, as well as concentration profiles of total CO_2, ammonium, sulfate, and methane. We have been working with colleagues in the Department of Computer Science at UNC-Chapel Hill to develop a JAVA-based module that will allow us to efficiently couple the sediment diagenetic model to a water column hydrodynamic model. We expect a coupled sediment-water column model to be operating and calibrated by the end of Summer 2001.

Basic Information

Title:	Predicting Long-term Wetland Hydrology Using Hydric Soil Field Indicators
Project Number:	B-IV
Start Date:	3/1/1999
End Date:	2/28/2000
Research Category:	Not Applicable
Focus Category:	Wetlands, Groundwater, Models
Descriptors:	Wetlands, Soil-Water Relationships, Groundwater Modeling, Hydric Soils
Lead Institute:	Water Resources Research Institute of the University of North Carolina
Principal Investigators:	Michael J. Vepraskas

Publication

1. Grimley, D.A. and M.J. Vepraskas; 2000, Magnetic susceptibility for use in delineating hydric soils, Soil Science Society America Journal, 64, 2174-2180.
2. Hayes, Jr., W.A.; and M.J. Vepraskas, 2000, Morphological changes in soil produced when hydrology is altered by ditching, Soil Science Society America Journal, 64, 1893-1904.
3. Vepraskas, M.J. and S.P. Faulker, 2001, Redox chemistry of hydric soils,In J.L. Richardson and M.J. Vepraskas (eds.) Wetland Soils, CRC Press, Boca Raton, Florida, 85-105.
4. Vepraskas, M.J., 2001, Morphological features of seasonally reduced soils, In J.L. Richardson and M.J. Vepraskas(eds.) Wetland Soils, CRC Press, Boca Raton, Florida, 163-182.
5. Hayes, Jr., W.A., 1998, Effect of ditching in soil morphology, saturation and reduction in a catena of Coastal Plain soils, M.S. Thesis, Soil Science Department, NC State University, Raleigh, 116 pgs.
6. Xiaoxia, He, 2000, Estimating historic water table fluctuations in Coastal Plain soils using a hydrologic model and hydric soil indicators, Ph.D. Dissertation, Soil Science Department, N.C. State University, Raleigh, 203 pgs.

Problem and Research Objectives:

Current regulations governing wetland identification make it virtually impossible to identify freshwater wetland routinely using current technology. Jurisdictional wetlands include areas that are saturated within 30 cm of the surface for 5% of the growing season in 5 or more years out of 10. Such information on wetland hydrology can be obtained by long-term monitoring studies that span both wet and dry years. These require long periods of time (5 to 10 years) to complete, and are too expensive to do at most sites where the information is needed. An alternative approach is to use hydrologic models to estimate water table data over long periods at a few benchmark sites. These data can be obtained quickly (in less than 6 months). The hydrologic information can be extrapolated to other soils by calibrating soil indicators of saturation for the specific frequencies and durations of saturation estimated by the model. These indicators (basically seen as gray and red colors) occur in most wetland soils that are chemically reduced and can be easily identified during on-site inspections. By using hydrologic models in combination with hydric soil indicators, we should be able to estimate quickly and economically how long the major soils are saturated in the Coastal Plain region of North Carolina. This information should be of great value to those charged with determining wetland boundaries.

Objectives

1. To estimate the time that the soils along a hillslope were saturated each year for a 40-year period using historic rainfall data and a hydrologic model.

2. To compute probabilities that each soil along the hillslope will be saturated at a given depth during a year, both during and outside the growing season.

3. To correlate the hydric soil features observed in each soil to the probability values determined in objective 2.

Methodology

The study was conducted at two locations in the North Carolina Coastal Plain. At both sites transects of soil plots were established along hillslopes with plots in moderately well, somewhat poorly, poorly, and poorly drained soils. Four transects of plots were used in Pitt County, NC and two transects were used in Bertie County, NC. In each soil plot the water table was monitored daily for three years, and redox potential was monitored weekly. Rainfall was monitored hourly at each location. Pits were dug in each plot to describe the soil colors and identify hydric soil field indicators. Percentages of gray color (redox depletions) and red color or mottles (redox concentrations) were estimated by eye. Saturated hydraulic conductivity and pore size distribution were determined for each major horizon in each soil.

DRAINMOD was calibrated to simulate water table fluctuations in each plot using the daily water table data, rainfall, and soil properties. The calibrated models were then used to compute daily water table levels in each soil plot over a 40-year period using daily rainfall levels obtained from the nearest available weather stations.

DRAINMOD output was used to compute a “saturation index” value which reflected the number of times the soil was saturated for 21 days or longer. Saturation index values were computed for each depth for each of 40 years, and an average saturation index

value was estimated for the 40-year period. The average saturation index values were then correlated with the percentage of redox depletions (gray color) and redox concentrations (red color) observed in each soil for depths of 30, 45, 60, 75, and 90 cm. Data from all soil plots within a site were combined for analysis.

Principal Findings and Significance

DRAINMOD was able to accurately simulate water table levels in all plots of both sites. This is significant because the sites did not contain the network of parallel drains that the model assumes are present. We adjusted the depth and distance of imaginary drains until the model's simulation of water table levels matched the measured values. Average absolute deviations between simulated and measured values were generally 20 cm or less.

At both sites, the percentages of redox depletions and concentrations were significantly correlated with saturation events, and r^2 values were generally between 0.80 and 0.95 for redox depletions and redox concentrations. Higher r^2 values were found during the growing season for all soil depths. Each depth had to be treated separately, because a given saturation index produced fewer redox depletions at 90 cm, than at 40 cm.

Correlations were also obtained by combining data for both sites. The r^2 values for relations between percentage of redox depletions and saturation index were between 0.80 and 0.95 for saturation periods throughout the year.

These results show that percentages of redoximorphic features can be used to estimate saturation frequency in Coastal Plain soils with a high degree of accuracy. Depths at which redox depletions occur are saturated for at least 21 consecutive days, and the more frequent the saturation the greater the percentage of depletions. Graphs of the statistical relationships were developed which will allow wetland delineators to determine when wetland hydrology has been met. Such graphs need additional field testing before distribution.

Information Transfer Program

Basic Information

Title:	The Institute NEWS
Start Date:	3/1/2000
End Date:	2/28/2001
Descriptors:	Newsletter
Lead Institute:	Water Resources Research Institute of the University of North Carolina
Principal Investigators:	Amy (Jeri) B Gray

Publication

The Institute *NEWS*, a 16-page newsletter, was distributed bimonthly to more than 4,200 federal and state agencies, university personnel, multi-county planning regions, city and local officials, and engineers. The *NEWS* regularly covers a wide range of water-related topics from current federal and state activities and new research findings to special announcements and listings of new publications. This newsletter can also be electronically obtained through our homepage on the world wide web (URL=http://www2.ncsu.edu/ ncsu/CIL/WRRI).

Basic Information

Title:	The Sediments News
Start Date:	3/1/2000
End Date:	2/28/2001
Descriptors:	Newsletter
Lead Institute:	Water Resources Research Institute of the University of North Carolina
Principal Investigators:	Amy (Jeri) B Gray

Publication

The *Sediments News*, a 6-page newsletter, is published quarterly and 5,600 distributed by the Institute for the N.C. Sedimentation Control Commission. The newsletter provides information and assistance to the regulated community and facilitates communication among personnel of state and local erosion and sediment control programs.

Basic Information

Title:	Water Resources Research Seminar Series
Start Date:	3/1/2000
End Date:	2/28/2001
Descriptors:	Conferences
Lead Institute:	Water Resources Research Institute of the University of North Carolina
Principal Investigators:	Robert E Holman

Publication

Water Resources Research Seminar Series. WRRI continued a seminar series on current water resource issues and research projects funded by the Institute. The seminars occurred once a month during the year except for the months of June, July, August, and December. The following seminars were given during FY 2000-2001:

Development of a Probability Network Approach for the Neuse River Estuary - Ph. D.Candidate Mark Borsuk - Nicholas School of the Environment, Duke University

The Cost of Watershed Management Policies - Professor David Moreau – Department of City and Regional Planning, University of North Carolina at Chapel Hill

Quantification of Pfiesteria Species - Associate Professor JoAnn Burkholder - Department of Botany, North Carolina State University

Assessment of the North Carolina Water Reuse Regulations - Assistant Professor Helen Hilger - Department of Civil Engineering, University of North Carolina at Charlotte

Effectiveness of Multiple Best Management Practices in Agriculture - Professor Carlyle Franklin - Department of Forestry, North Carolina State University

Assessment of Changing Land-Use Practices on Basin Sediment Yields – Assistant Professor Mark Lord - Department of Geosciences, Western Carolina University

A Comparative Analysis of Compact and Low-Density Development - Associate Professor Philip Berke - Department of City and Regional Planning, University of North Carolina at Chapel Hill

Technical and Economic Evaluation of Alternative Animal Waste Management – Professor Michael Overcash - Department of Chemical Engineering, North Carolina State University

Basic Information

Title:	NCWRA/WRRI Forums
Start Date:	3/1/2000
End Date:	2/28/2001
Descriptors:	Conferences
Lead Institute:	Water Resources Research Institute of the University of North Carolina
Principal Investigators:	Robert E Holman

Publication

Land Use and Watershed Planning. In September, WRRI and the North Carolina Chapter of the American Water Resources Association presented a forum on watershed planning. Professors from N.C State University and University of North Carolina at Chapel Hill, and an individual from the N.C. Wetland Restoration Program provide examples of land use planning and design, compact and sprawl development, and local wetland watershed planning.

Endocrine Disrupting Compounds. In December, WRRI and the North Carolina Chapter of the American Water Resources Association presented a forum on endocrine disruption. A representative from the U.S. Geological Survey discussed the concept of endocrine disruption as being a paradigm shift from increasing the risk of cancer and lethal doses. The occurrence and level of these emerging contaminants in our water resources is not well documented and the environmental and human health significance of these contaminants has generally not been studied.

Water Reuse in North Carolina. In February, WRRI and the North Carolina Chapter of the American Water Resources Association presented a forum on water reuse. The Utility Director for Cary discussed the projects that are being implemented in the Town of Cary to reclaim wastewater and a private consultant discussed the regional reuse system in Brunswick County, North Carolina.

Overuse of Eastern North Carolina Aquifers. In April, WRRI and the North Carolina Chapter of the American Water Resources Association conducted a forum on eastern North Carolina aquifers. A geology professor from East Carolina University discussed the hydrologic solutions to overuse of the Cretaceous aquifers. He indicated that groundwater levels were declining and saltwater intrusion would be occurring in the aquifer systems of the coastal plain.

Basic Information

Title:	Erosion and Sediment Control Design Workshops
Start Date:	3/1/2000
End Date:	2/28/2001
Descriptors:	Conferences
Lead Institute:	Water Resources Research Institute of the University of North Carolina
Principal Investigators:	Robert E Holman

Publication

Erosion and Sediment Control Fall Design Workshops. In September and October, WRRI, the N.C. Sedimentation Control Commission and the North Carolina Department of Environment and Natural Resources (NCDENR), Division of Land Resources, Land Quality Section presented two 2-day workshops in New Bern and Hickory, North Carolina, on erosion and sediment control design. The workshops were held to familiarize design professionals with the erosion and sediment control requirements and design applications. Topics such as sedimentation control rules, soil erosion processes, sediment and erosion control across the U.S., storm water management, pipe design, dissipator design, erosion and sedimentation control certification, plan review, stream restoration, new technologies, and new research topics were discussed.

Erosion and Sediment Control Spring Design Workshops. In February and March, WRRI, the N.C. Sedimentation Control Commission and the NCDENR, Division of Land Resources, Land Quality Section presented two 2-day workshops in Greenville and Hickory, North Carolina, on erosion and sediment control design. The workshops were held to familiarize design professionals with the erosion and sediment control requirements and design applications. Topics such as plan requirements, plan design, group exercise in plan design, sediment basin design, NC Department Environment and Natural Resources one-stop permitting, buffers and wetlands, incorporation of vegetation into design practices, erosion control plan approval, mining permit approval, virtual field trip and site inspection were discussed.

Basic Information

Title:	Erosion and Sediment Control Workshop for Local Programs
Start Date:	3/1/2000
End Date:	2/28/2001
Descriptors:	Conferences
Lead Institute:	Water Resources Research Institute of the University of North Carolina
Principal Investigators:	Robert E Holman

Publication

Erosion and Sediment Control Workshop for Local Programs. In January, WRRI, the N.C. Sedimentation Control Commission and NCDENR, Division of Land Resources, Land Quality Section presented a two-day workshop to allow local programs to get together and exchange ideas and practices utilized at the local level. Topics such as administrative rules and forestry activities, NC Department Environment and Natural Resources one-stop permitting, virtual field trip and site inspection, plan design and review, update of programs in Cabarrus County, Rowan County, City of Greenville and City of High Point, and storm water requirements were discussed.

Basic Information

Title:	New Research Reports
Start Date:	3/1/2000
End Date:	2/28/2001
Descriptors:	Research Publications
Lead Institute:	Water Resources Research Institute of the University of North Carolina
Principal Investigators:	Robert E Holman

Publication

New Research Reports - A strong demand for Institute reports continues. During the year, the Institute published the following reports for distribution to users throughout the state and nation:

WRRI-329	Characterization of Atmospheric Ammonia Emissions from Swine Waste Storage and Treatment Lagoons
WRRI-330	Sampling Strategies for Estimating Status and Cost of Watershed Management Policies
WRRI-331	Data Collection to Support a Simplified Bacterial Regrowth Model for Distribution Systems
WRRI-332	Benefits of Quality Improvements in North Carolina's Water Resources
SRS-22	Benthic Macroinvertebrates as Indicators of the Effectiveness of Urban Best Management Practices: A Literature Review

Basic Information

Title:	2000-2001 Program
Start Date:	3/1/2000
End Date:	2/28/2001
Descriptors:	Annual Publication
Lead Institute:	Water Resources Research Institute of the University of North Carolina
Principal Investigators:	Amy (Jeri) B Gray

Publication

2000-2001 Program - A 16-page publication describing 9 new and 24 continuing research projects being funded by WRRI and other sources has been published. The program defines the other related activities of the Institute such as the Urban Water Consortium, information dissemination and technology transfer.

Basic Information

Title:	Publications Listing
Start Date:	3/1/2000
End Date:	2/28/2001
Descriptors:	Publications Listing
Lead Institute:	Water Resources Research Institute of the University of North Carolina
Principal Investigators:	Robert E Holman

Publication

Publications List - A 28-page listing of all the publications that the Institute has published to date was revised and made available. This includes 389 individual publications.

Basic Information

Title:	Current Issues in Stormwater Regulations, Planning and Design
Start Date:	3/1/2000
End Date:	2/28/2001
Descriptors:	Conference
Lead Institute:	Water Resources Research Institute of the University of North Carolina
Principal Investigators:	Robert E Holman

Publication

Current Issues in Stormwater Regulations, Planning and Design. Also in September, WRRI, the North Carolina Chapter of the American Public Works Association and the North Carolina Cooperative Extension presented a conference on stormwater management. Participants learned more about current regulations and their impact on planning and design issues. Other topics such as biological monitoring, basin planning, flood recovery, and stream corridor design were also discussed.

Basic Information

Title:	Year of the Hurricanes
Start Date:	3/1/2000
End Date:	2/28/2001
Descriptors:	Conferences
Lead Institute:	Water Resources Research Institute of the University of North Carolina
Principal Investigators:	Kenneth H Reckhow

Publication

The Year of the Hurricanes. In March, WRRI hosted its annual conference on current water resources research in North Carolina and the theme was "Year of the Hurricanes." The one-day conference covered six topic including hypoxia, Piedmont issues, groundwater, economic and public participation, hurricanes, and pathogens. There were 31 presentations and 29 individuals providing a poster session.

USGS Summer Intern Program

Student Support

Student Support					
Category	**Section 104 Base Grant**	**Section 104 RCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	0	3	6	4	13
Masters	0	3	2	3	8
Ph.D.	0	0	2	2	4
Post-Doc.	0	3	0	4	7
Total	0	9	10	13	32

Notable Awards and Achievements

Mark D. Sobsey is the 2001 recipient of the American Water Works Association A.P. Black Award for sustained contributions to water research.

Michael J. Vepraskas was elected "Fellow" of the Soil Science Society of America in 2000.

Michael A. Mallin was named an Aldo Leopold Environmental Leadship Fellow for 200 (an Ecological Society of America sponsored program).

Governor James B. Hunt, Jr., has appointed Dr. Kenneth H. Reckhow, Director of the Water Resources Research Institute and Professor, Nicholas School of the Environment at Duke University, as the new chairman of the North Carolina Sedimentation Control Commission. This commission is charged with adopting rules, setting standards, and providing guidance for implementation of the N.C Sedimentation Pollution Control Act. The composition of the Commission is set by statute to encompass a broad range of perspectives and expertise in areas related to construction, industry, government, and natural resource conservation and quality.

Dr. Daniel J. Phaneuf, Assistant Professor, Department of Agricultural and Resource Economics at North Carolina State University, is conducting a project to evaluate the economic benefits of water quality improvement in North Carolina. This project employs revealed preference methods to assess the monetary benefits to recreation users of water quality improvements. Preliminary results indicate that reducing the loading of phosphorus would equate to citizen willingness to pay 42.2 million dollars each year to visit recreational sites with cleaner water. His project was a featured article in the November issue of the U.S. Water News.

Dr. David H. Moreau, Former Director of the Water Resources Research Institute and Professor, Department of City and Regional Planning at the University of North Carolina at Chapel Hill, has been re-appointed as Chairman of the North Carolina Environmental Management Commission (EMC) by Governor James B. Hunt, Jr. The EMC is a 17-member commission appointed by the Governor, the President Pro Tempore of the N.C. Senate and the Speaker of the N.C. House. Under the authority of the North Carolina General Statute, the commission establishes rules and regulations to provide for protection, preservation and enhancement of water and air resources of North Carolina. In addition, Dr. Moreau has completed a valuable report titled "The Cost of Watershed Management Policies " for the Institute. This report develops an improved method of estimating the costs of controlling nonpoint

sources from agricultural operations.

Dr. Kenneth H. Reckhow has been funded for two-years to conduct the Neuse River Modeling and Monitoring Project (ModMon). Components of this effort by six-institutions have been used to develop the nitrogen total maximum daily load (TMDL), that must meet the 40 mg/L chlorophyll a standard for the Neuse River Estuary in North Carolina. The TMDL analysis was presented to EPA in July using nitrogen reduction cases of 15, 30 and 45%. Also, this TMDL will include apportionment of the total nitrogen load among sub-watersheds and major source categories such as point and nonpoint sources. There are five reports from the first year's activities that are now available from the Institute.

Publications from Prior Projects

1.
2.
3. Mallin, M.A., J.M. Burkholder, L.B. Cahoon and M.H. Posey, 2000, North and South Carolina coasts. Marine Pollution Bulletin 41:56-75.
4. Mallin, M.A., 2000, Impacts of industrial-scale swine and poultry production on rivers and estuaries. American Scientist 88:26-37.
5. Mallin, M.A., J.M. Burkholder, L.B. Cahoon and M.H. Posey, 2000, The North and South Carolina Coasts in C. Sheppard (ed) Seas at the Millennium: An Environmental Evaluation. Elsevier Science, New York, 341-361.
6. Mallin, M.A., 2000, Storms, floodplain development, and water pollution in the Cape Fear River. In E. Rickert (ed). In the Eye of the Storm. Coastal Carolina Press, Wilmington, N.C.
7.
8.
9. Mallin, M.A.; M.H. Posey, M.R. McIver, S.H. Ensign, T.D. Alphin, M.S. Williams, M.L. Moser, and J.F. Merritt, 2000, Environmental Assessment of the Lower Cape Fear River System, 1999-2000, CMS Report No. 00-01, Center for the Marine Science, University of North Carolina at Wilmington, Wilmington, N.C.
10. Padgett, D.E.; M.A. Mallin, and L.B. Cahoon, 2000, Evaluating the use of ergosterol as a bioindicator for assessing water quality. Environmental Monitoring and Assessment 65:547-558.
11. Mallin, M.A.; L.B. Cahoon, R.P. Lowe, J.F. Merritt, R.K. Sizemore and K.E. Williams, 2000, Restoration of shellfishing waters in a tidal creek following limited dredging, Journal of Coastal Research 16:40-47.
12. Amatya, D.M.; G.M. Chescheir, G.P. Fernandez, and R.W. Skaggs, 1999, Testing of a Watershed Scale Hydrologic/Water Quality Model for Pooerly Drained Soils; "Advances in Water Quality Modeling", ASAE Int'l Meeting, Toronto, Canada, Papr No. 99-2070.
13. Birgand, F.; G.M. Chescheir, R.W. Skaggs, and J.W. Gilliam, 1999, Quantification and Effects of In-Stream Processes in the Ditches and Canals of the Lower Coastal Plain of North Carolina. ASAE Int'l Meeting, Toronto, Canada, Paper No. 99-2136.
14. Chescheir, G.M.; D.M. Amatya, G.P. Fernandez, J.W. Gilliam, and R.W. Skaggs, 1999, Nutrient Loading from a Lower Coastal Plain Watershed, ASAE Int'l Meeting, Toronto, Canada, Paper No. 99-2201.
15. Haan, P.K.; and R.W. Skaggs, 1999, Effect of Parameter Uncertainty on DRAINMOD Predictions for Hydrology and Water Quality, ASAE Int'l Meeting, Toronto, Canada, Paper No. 99-2163.
16. Skaggs, R.W.; and G.M. Chescheir, 1999, Effects of Subsurface Drain Depth on N Losses to Surface Waters, ASAE Int'l Meeting, Toronto, Canada, Paper No. 99-208
17. Fernandez, G.P.; G.M. Chescheir, D.M. Amatya, and R.W. Skaggs, 1999, GIS Based Lumped Parameter Water Quality Model, Advances in Water Quality Modeling, ASAE Int'l Meeting,

Toronto, Canada, Paper No.99-2136.

18. Fernandez, G.P.; R.W. Skaggs, G.M. Chescheir, D.M. Amatya, and R.W. Skaggs, 1999, GIS Based Lumped Parameter Water Quality Model, In Proc. of the 2nd Intr-regional Conference on Environment, Lausanne, Switzerland, Water 99.