Water Resources Center

Annual Technical Report

FY 1999

Introduction

Research Program

Basic Project Information

Basic Project Information	
Category	**Data**
Title	Economic and Hydrologic Analysis of Integrated Wetland Reservoir and Subirrigated Agricultural Production Systems
Project Number	C-02
Start Date	09/01/1997
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Research Category	Climate and Hydrologic Processes
Focus Category #1	Irrigation
Focus Category #2	Wetlands
Focus Category #3	Agriculture
Lead Institution	Ohio State University

Principal Investigators

Principal Investigators			
Name	**Title During Project Period**	**Affiliated Organization**	**Order**
Larry C. Brown	Associate Professor	Ohio State University	01

Problem and Research Objectives

Problem and research objectives: The Maumee River valley is characterized by flat topography with soils that are predominantly heavy clay - glacial deposits and lakebed sediments. Extensive drainage

projects have permitted the area to be drained, cleared, and farmed, resulting in a very productive farming region, but one which is very dependent on surface and subsurface drainage improvements. Drainage discharge enters the Maumee River and Lake Erie as a result of intensive drainage improvements. Sediment, phosphorus, nitrate, and certain pesticides in agricultural runoff are of great concern in the region. No research has been conducted on hydrologic interactions within the direct linkage of an agricultural production system and a wetland-reservoir ecological system, nor the economics of such a system. An existing demonstration project (funded by USEPA/GLPO and others) demonstrates construction and management of permanent wetland-reservoirs linked directly to subirrigated corn and soybean production systems on field-sized areas. The demonstration project was initiated in 1994 to illustrate how construction and management of wetlands coupled with subirrigation can be economically profitable for farmers. The overall objective of the demonstration project is to stimulate adoption of wetlands, reduce adverse impacts of agricultural runoff, and maintain profitability. The project was built on the need to enhance and properly use wetlands near agricultural land use areas where the success of subirrigation has a high potential. The WRRI project added important economic and hydrologic research components to the existing Maumee River valley demonstration project. This productive farming region is very dependent upon drainage improvements, which discharge to the Maumee River and Lake Erie where sediment, phosphorus, nitrate, certain pesticides in runoff are of concern. Runoff and drainage from prior converted cropland will seasonally feed wetland-reservoirs, which provide water quality and wildlife habitat functions, and supplemental water supply for state-of-the-art subirrigated crop production systems. Construction and management phases for three wetland-reservoir-subirrigation sites were funded and completed (operational for 1996 growing season). Research was needed on hydrologic interactions within the direct linkage of agricultural production systems and wetland-reservoir ecological systems, and the economics of such systems. At the time of the initiation of the overall project, no work of this focus and extent was being conducted elsewhere in the U.S. Research Objectives Objective 1: Characterize, analyze, model hydrologic interactions between integrated subirrigated agricultural production and constructed wetland-reservoir systems, and evaluate the water quality (sediment, pesticide, nitrate and phosphorus transport) impacts and benefits of this integrated system. Objective 2: Examine and determine farm-level economics of integrated subirrigated agricultural production and constructed wetland-reservoir systems. Technology Transfer Objective Objective 3: Develop a technical design and management guide for subirrigated agricultural production and constructed wetland-reservoir systems, and conduct an applications and design workshop to teach agricultural producers and consultants how to use water table management for environmental and economic benefit.

Methodology

Existing Funded Demonstration Project Wetlands were constructed on prior-converted cropland to receive drainage from adjacent cropland, resulting in near zero-discharge from those fields directly to streams. Agricultural runoff and subsurface drainage recharged the constructed wetland seasonally. The wetland-reservoir water recycles through a subirrigation system, thereby providing a supplemental water supply for subirrigating corn and soybean crops in adjacent fields. In a year with average rainfall, the system should produce a near zero-discharge to streams and rivers which will greatly aid in improving water quality, reducing peak flows, and at the same time form permanent pools for increased wildlife habitat areas. Substantial subirrigation research on corn and soybean conducted in Michigan and Ohio suggested a strong potential for northwestern Ohio, but often water supply is a limiting factor. The soils and topography are those that will respond to subsurface drainage improvement, subirrigation, and constructed wetlands. Cropping and management plans for the entire farm include agricultural practices used in accordance with an approved conservation plan as prepared by USDA-NRCS, with a landowner commitment of five years minimum. Each landowner was required to provide information on all inputs

and outputs, and follow the water management plan and the cropping management plan established by the project team (contract established between demonstration project and landowner). The systems were designed using research results and inputs from the USDA-ARS Soil Drainage Research Unit; Michigan State University - Department of Agricultural Engineering; The Ohio State University, Department of Food, Agricultural, and Biological Engineering, Ohio Agricultural Research and Development Center, and Ohio State University Extension; and technical assistance from the USDA-NRCS and the Ohio and Michigan Land Improvement Contractors' associations. The Maumee Valley RC&D coordinates all specific tasks with the main sponsors (USEPA/GLPO; Lake Erie Protection Fund, etc.), and all collaborators. The WRRI funded research focused on all 3 sites: Defiance Agricultural Research Association (DARA) site (near Defiance County airport and weather station); Shininger farm (Fulton County); and March Foundation (Van Wert County near Farm Focus), but the main focus of the intensive monitoring and research is at the DARA site. Each site consisted of a subirrigated area for corn and soybean production, constructed wetland, and constructed upground reservoir (or existing pond or reservoir). Runoff and subsurface discharges from adjacent cropland flow into the constructed wetland. Water flowing from the wetland is pumped to the upground reservoir where it is stored for water supply. During the crop season, water is pumped into the subirrigated cropland, where a water table is established and held at a 14- to 20-inch depth throughout most of the growing season. Each site has numerous locations to measure and sample surface and subsurface flows, subirrigation water use, runoff, etc., with the intent to eventually instrument all three sites so that water flow rates and volumes, and sediment and chemicals concentrations can be measured at the inflow and outflow of each component of this integrated system at each site. We proposed to monitor and evaluate runoff and subsurface discharge during and after all storm events (possibly 10 to 20 storm events annually), and during selected less dynamic times throughout the year. One-liter water samples will be collected during flow events. For two selected storm events per year, more intensive sampling will occur to establish the water and chemical discharge relationship with time for the entire rainfall event. All samples will be analyzed for nitrate+nitrite, soluble phosphorus, and selected pesticide concentrations by the Environmental Water Quality Lab at Ohio State University following USEPA approved QA/QC procedures. All concentration data will be analyzed on a flow-weighted basis. For the recessional limb sampling, the number of samples collected each year will be approximately 90 (up to 20 events per year, at up to six sampling locations). For the full storm duration sampling sequence, approximately 80 samples will be collected per year (20 samples per selected storm event per year for both drainage treatments). Sediment samples will be analyzed locally by gravimetric means. Wetland and reservoir sedimentation will be assessed annually. Inflows and outflows from each flow control point will be measured at time of sampling. In addition to the installation of commercial flow rate and volume measurement devices, the drainage control structures will be modified with a V-notch weir for flow rate estimation at the time of sampling, thus producing a redundant volumetric sampling. Runoff entering the wetland area will be monitored using H-flume and stage recorder systems. Within each field area, simple water table observation wells will be installed between laterals near each outlet to allow monitoring of water table elevations. Rainfall at each site will be measured using manually read rain gauges, and local weather records are available in each county. Daily measurements of water table elevations, flow rates and volumes, etc. will be made by the demonstration project personnel. All management and data collection at all three sites is fully funded through the existing project through the 1999 crop season, and is managed by a team of farmers, state and federal agency personnel, and university faculty. All instrumentation and data collection procedures are being designed by Dr. Brown, in coordination with the demonstration project team. Each site has unique characteristics that allow excellent research opportunities over a range of conditions. Objective 1: Characterize, analyze, model hydrologic interactions between integrated subirrigated agricultural production and constructed wetland-reservoir systems, and evaluate the water quality (sediment, pesticide, nitrate and phosphorus transport) impacts and benefits of this integrated system. Substantial soils, topographic, cropping system, water budget, sediment and chemical data, and engineering design information, will be

generated from the existing demonstration project. Much of this information and data will be used to calibrate existing, state-of-the-art agricultural water management models and design techniques that will be modified to analyze and evaluate hydrologic interactions between these systems (discussed below). Soil characteristics (profile description, textural analysis, hydraulic conductivity, etc.) will be measured at each site. In addition, each field-sized research area were hydraulically characterized before the actual design, construction and implementation of subirrigation. All crop production and land management conditions will be the same on both the subirrigated and non-subirrigated areas. Crop growth and production characteristics (leaf area index, height, canopy, yield, etc.) will be measured during each crop season. Crop yield, crop production management, tillage, and nutrient and pesticide application data will be collected from each cooperator. A water table management scenario will be established at each demonstration site in consultation with the demonstration project technical advisory committee, and based upon recommendations by Cooper and Fausey (1991; 1992). Dr. Brown and the engineering graduate associate will conduct the research that addresses Objective 1 using the agricultural water management simulation models DRAINMOD (Skaggs 1980; Skaggs et al. 1981), ADAPT (Agricultural Drainage and Pesticide Transport) (Chung et al. 1992a; Chung et al. 1992b), and possibly the new USDA erosion model WEPP (Water Erosion Prediction Project). These hydrologic and erosion prediction models will be used to conduct computer simulations using long-term climatic records to evaluate the hydrologic and crop production potential of the soils at all three demonstration sites for subirrigation and drainage collection in the study area. These hydrologic models have the ability to evaluate subirrigation scenarios, and can be used to analyze and evaluate these integrated systems over time using historic climatic records. Both DRAINMOD and ADAPT have the capability to simulate water table elevations, surface and subsurface movement of water on agricultural soils that are not drained, and for water table management conditions with conventional subsurface drainage, controlled drainage, and subirrigation. Long-term subsurface discharge, runoff, evapotranspiration, water use, water table elevation, and other water budget parameter estimates, as well as crop yields, will be statistically evaluated. In addition, sediment, pesticide, nitrate and phosphorus movement from all three sites will be evaluated using the ADAPT model. For use with DRAINMOD and ADAPT, soils data have been obtained at each site, from the state's Soils5 data base (Baumer, 1989), and county soil survey manuals. In addition, hydraulic conductivity and topographic information from each demonstration site has been obtained for our use. Climatic data (hourly precipitation, max/min daily temperatures) with a minimum of 30 years of record (forty year records are being developed) for at least four northwest Ohio locations have been obtained and formatted for DRAINMOD. These records will be modified for input to ADAPT so that each model will use the same soils and climatic data The DRAINMOD and ADAPT models produce similar predictions of water table elevations on agricultural land use areas (Desmond et al. 1994), and both models have been tested on Ohio conditions. DRAINMOD currently does not have the capability to predict water quality impacts (sediment, nitrate, phosphorus, pesticide transport). However, the ADAPT model has the capability to model erosion processes, and based upon algorithms adapted from the GLEAMS model (Knisel et al. 1992), it can model nitrate and phosphorus transformations and transport. ADAPT will be used in this study to assess the hydrologic, erosion, runoff, subsurface drainage, and crop yield potential of water table management practices for the demonstration site soils. Because of its wider acceptance throughout the United States to evaluate the hydrology of agricultural land use areas and wetland hydrology, DRAINMOD predictions will be used simultaneous to ADAPT as a control. For the conditions at each demonstration site, long-term simulations will be used to develop matrices of crop yield, nitrate and phosphorus transport relationships, thus allowing the research team to assess the relationship of the economic and water quality benefits of these integrated subirrigated - constructed wetland-reservoir systems. The USDA erosion model WEPP (Water Erosion Prediction Project) is being evaluated for its application to this project. Objective 2: Examine and determine farm-level economics of integrated subirrigated agricultural production and constructed wetland-reservoir systems. The long-term economic

performance of integrated subirrigated agricultural production and wetland-reservoir systems investments relative to systems with no subirrigation-wetland linkage will be analyzed and evaluated. Net present value techniques will be used to value profitability, and linear programming techniques will be used to compare differences in profitability reflecting differences in farm size under the two production systems. Actual capital investments for design and construction will be obtained from each demonstration site. Estimates of the useful life of each component of the system and maintenance costs will be made, and actual production costs, yields, and returns will be collected for production of each crop at each site. Historical yield and cost data will be gathered for each site for years prior to the wetlands development. These data will be the basis for comparison of economic costs and returns for each site, prior and subsequent to the wetlands-subirrigation investment. In addition, Drs. Fausey and Cooper, and the Michigan State cooperator, respectively, have agreed to provide selected Ohio and Michigan water table management system cost and return economic data. For comparison, we are currently evaluating the subsurface drainage yield response data from two long-term projects in Ohio. Dr. Batte and the agricultural economics graduate associate will assess the economic performance of subirrigation technologies. Enterprise and whole-farm budgeting techniques will be used to examine the impact of the subirrigation investment for typical Ohio commercial farms. Because these investments involve long-time durations, capital budgeting techniques also will be used to reflect differences in timing of receipts and expenditures. Additionally, mathematical programming techniques will be used to compare the economic performance of a representative farm with and without subirrigation improvements. Enterprise and whole-farm budgets will be constructed for representative farms under two scenarios: 1) with a conventional subsurface drainage system designed to be optimal for prevailing soil conditions, and 2) with a subirrigation system, again designed to be optimal given existing soils. Simple budgeting analyses as described above and reported in a number of empirical studies (Evans et al. 1988; Rath and DeBoer 1991; Belcher 1992; and Drouet et al. 1989) do not provide a complete analysis of profitability differences among systems. The reason is that there may be changes in a great number of other aspects of the business resulting from the subirrigation investment. Positive impacts may include farming of larger acreage, incorporation of higher-valued (but previously infeasible) crops into the rotation, greater specialization in the highest-valued crop, or reduced hiring of labor during critical periods for field operations. Negative impacts might include increased competition within the business for scarce capital resources and associated loss of production efficiency or business size. Linear programming models will be constructed for representative farms in northwestern Ohio. At each site, one model will feature crop production on representative soils with conventional subsurface drainage. A second model will consider the addition of a subirrigation system that will provide supplemental subsurface irrigation as well as provide improved drainage. The owned land base and the existing machinery complement will be treated as fixed resources. Decision variables will include farm size (expandable through leased acreage), crop rotation, and other cultural practices. The model will incorporate constraints on capital, labor, and machinery capacity which are functions of both weather and drainage system during several planting and harvesting periods. In order to understand the impact of water quality guidelines imposed on the farm firm, the base model will be modified to incorporate externally imposed constraints (pollution limits) on nitrate and phosphorus discharge. Previous studies have demonstrated that subirrigation systems have the potential to reduce the level of nutrient discharge from subsurface drains (Wright et al. 1992). In order to meet water quality guidelines, farms with conventional subsurface drainage systems will need to make greater changes in the overall organization of their farming system (e.g., reduced fertility rates, change of rotation, and/or adoption of other pollution abatement practices) than will a similar farm with subirrigation. Such alterations may significantly impact profitability. The linear programming model will be constructed in such a way as to allow measurement of the sensitivity of the crop production activities in the optimal solution to prices of key resources, prices of commodities, and restrictions on labor or capital availability. Standard linear programming output provides estimates of the marginal value of additional resources as well as an indication of the amount by which profitability of competing activities must change before those

activities would enter the optimal farm plan. Objective 3: Develop a technical design and management guide for subirrigated agricultural production and constructed wetland-reservoir systems, and conduct an applications and design workshop to teach agricultural producers and consultants how to use water table management for environmental and economic benefit. Technology transfer is a major component of both the existing demonstration project and the proposed project, using tri-state (Ohio, Indiana and Michigan) water management conferences and field days to teach farmers, technical and regulatory agency personnel, and non-agricultural citizens the benefits of interfacing wetlands with modern agricultural production. Research/demonstration results will be the basis for management guide development, with a primary focus on environmental and economic benefits of water table management and constructed wetlands, site identification, water supply, engineering design, construction, and system operation and management. All aspects of the existing demonstration project and proposed project will feed into Dr. Brown's educational activities conducted cooperatively by Ohio State University Extension, the demonstration project and its cooperators and technical advisors, and the Overholt Drainage Education and Research Program at The Ohio State University. The state-of-the-art knowledge of water table management and associated constructed wetlands technologies will be developed into a comprehensive technical and educational guide on the design, operation and management of subirrigation systems that enhance water quality and sustain productivity. Research from across the Cornbelt, Great Lakes, and southeast regions of the U.S., and from Canada will be incorporated into this effort. Computer simulation models (i.e., DRAINMOD, ADAPT), and the subirrigation evaluation/design model SI-DESIGN (Belcher et al. 1993) will be used in the analysis. The results of the analyses performed to address Objectives 1 and 2 will be incorporated into this effort. Dr. Brown will conduct a series of one- to two-day planning sessions to outline the content and production schedule for the guide. The guide content will be produced by the end of year two of the project. Field demonstrations of research is an excellent mechanism through which agricultural producers can be educated. This technology transfer technique actually incorporates complex research systems into field teaching laboratories. Field demonstration days will be organized and conducted at selected demonstration sites each year of the proposed project. Field demonstration days will be conducted in a cooperative effort by the Maumee Valley RC&D, Ohio State University Extension, and Drs. Brown and Fausey. These field demonstration days will be advertised in the Great Lakes Region. Field day participants will witness field-scale and plot-scale subirrigation, constructed wetlands on prior-converted cropland, be exposed to the operational requirements for successful subirrigation and management of a constructed wetland-reservoir, and be presented with data that supports the economic and water quality benefits of water table management by subirrigation integrated with constructed wetland-reservoirs. The project team will conduct one regional workshop in year two of the proposed project. This will be a multi-disciplinary, interagency effort, primarily targeting agricultural producers. However, persons who provide agricultural water management services to producers will be targeted as a secondary audience (technical agency personnel, soil and water conservation contractors, consultants, etc.).

Principal Findings and Significance

The following is a summary of the work completed under this grant and others associated with the three objectives described above. Hereafter, the three sites will be referenced as Shininger (Fulton County), DARA (Defiance County), and Marsh (Van Wert County). The work and accomplishments are presented by WRRI Proposal Objectives, starting with Objective No. 2, then Objectives No. 1 and 3. Introduction Wetland-Reservoir-Subirrigation Systems (WRSIS) have the potential both to improve downstream water quality by reducing discharge to streams, to provide wildlife habitat, to increase wetland acres and vegetation, and to provide a reliable supply of subirrigation water for sustained crop production. In a WRSIS, a wetland is constructed to receive subsurface drainage and runoff from

adjacent cropland. The cropland is subirrigated by a water supply reservoir that is also linked to the constructed wetland. The wetland, reservoir and subirrigated and subsurface drained cropland are integrated to harvest, treat, and recycle runoff and drainage waters. Prior to WRRI funding, three constructed wetlands were designed, constructed, and linked with water supply reservoirs for corn and soybean production systems using subirrigation. All three systems, located in the Ohio portion of the Maumee River Basin, were operational in the 1997 and 1998 growing seasons, and provided crop yield data. The wetlands were constructed on prior-converted cropland (soils dominantly silty clay) to receive drainage from adjacent cropland, resulting potentially in near zero-discharge from cropland directly to streams, except during extreme precipitation events. Agricultural runoff and subsurface drainage recharge the wetland during each rainfall/runoff event, and the reservoir serves as a supplemental water supply source for subirrigating corn and soybean during the crop growing season. The constructed wetlands at all three sites, primarily designed to serve as runoff and subsurface drainage collection and detention components, have developed wetland vegetation. A comprehensive, baseline wetland vegetation survey was undertaken and completed in 1998, and seasonal wildlife, habitat, and vegetation surveys were initiated for 1998 and 1999 as associated projects. Additional wetland vegetation and plant ecology research was initiated in 1999 as an associated project. WRRI Proposal Objective 2: Examine and determine farm-level economics of integrated subirrigated agricultural production and constructed wetland-reservoir systems. Crop Yield Summary Crop yields have been collected at each of the three sites; four years at Shininger, and three years at DARA and Marsh. The crop yield results at each site (MVRCD, 1999) are summarized below. The crop yield information provided in MVRCD (1999) prepared by R.L. Cooper provides much additional detail and discussion. Shininger. Non-replicated yield data, averaged over four varieties of both corn and soybean, for 1996 (first year of study) from the Shininger site indicated a yield increase of 77 and 21.5 bu/ac for corn and soybean, respectively, for the subirrigated versus conventionally subsurface drained cropland. The 1996 growing season had normal-to-below normal rainfall. Crop seasons in 1997 and 1998 had normal to above normal rainfall. Yield data from 1997 and 1998 indicated a slight increase in yields from the subirrigated systems over the conventional drainage system. The increase in corn yields were 20 and 24 bu/ac for 1997 and 1998, respectively, and the increase in soybean yields were a modest 2.6 and 3.0 bu/ac. These results suggested that production probably benefited more from the more intensive drainage spacing with the subirrigated system compared to the conventionally subsurface drained system. These two growing seasons had above normal precipitation with near uniform rainfall distribution. In 1999 the precipitation was less than in 1997 and 1998, but not as limiting as in 1996. The increase in yields with subirrigation was 56 bu/ac for corn and 14.2 bu/ac for soybean. Averaged over the four years and hybrids, or cultivars, the expected yield advantage from subirrigation would be 43 to 44 bu/ac for corn and 10 to 11 bu/ac for soybean. Yields for subirrigated corn and soybean at this site averaged 180-200 and 65-70 bu/ac, respectively. Marsh: Non-replicated yield data, averaged over two varieties of both corn and soybean, for 1997 (first year of study) and 1998 from the Marsh site indicated no yield for the subirrigated versus conventionally subsurface drained cropland. Crop seasons in 1997 and 1998 had normal to above normal rainfall, and our management of the water at this site was not adequate. Extensive land leveling was required to reduce some of the excess water impacts within both subirrigated fields at this site. Before the 1999 crop season, an additional subirrigation zone was constructed allowing the field manager to better manage the water table in one of the subirrigated fields. In addition, substantial changes were made in crop locations. In 1999 the precipitation was less than in 1997 and 1998, and our site management was greatly improved. The increase in yields with subirrigation was 33 bu/ac for corn and 12.8 bu/ac for soybean, with average yields being 189 and 52 bu/ac for the subirrigated corn and soybean, respectively. DARA: Non-replicated yield data were collected for one variety of both corn and soybean in 1997 (first year of study), 1998 and 1999. For this site, yields on two subirrigated drain spacings were compared to those from conventionally subsurface drained cropland and with cropland with no subsurface drainage. In 1997, yields for subirrigated corn were 165 and 152 bu/ac. Corn yields increased by 32 and 19 bu/ac for the eight and 16 feet subirrigation

drain spacing, respectively, compared to conventionally subsurface drained cropland, and a 48 and 35 bu/ac increase, respectively, compared to the cropland not subsurface drained. Soybean was not planted in 1997. Corn yields in 1998 were 134 and 125 bu/ac, respectively, for the eight and 16 feet subirrigation drain spacing, but soybean yields were 51.4 and 55.9 bu/ac, respectively, for the eight and 16 feet subirrigation drain spacing. Wheat was grown on the comparison cropland areas in 1998. The 1997 and 1998 crop seasons had normal to above normal rainfall, with near uniform rainfall distribution throughout most of the growing season. In both years we experienced some problems in each year with crop damage because of the excess precipitation. Extensive land leveling was required to reduce some of the excess water impacts within both subirrigated fields at this site. Before the 1999 crop season, an additional subirrigation zone was designed for one of the fields to allow the field manager to better manage the water table, but the construction was not accomplished until after the crop season. In addition, some changes were made in crop locations to allow replication, and an improved comparison study was implemented to allow a comparison of our subirrigation results to similar subsurface and surface drained cropland. In 1999 the precipitation was less than in 1997 and 1998, and our site management was improved. However, our soybean fields were severely damaged by pests (mainly ground hogs). Corn yields in 1999 were 146 and 132 bu/ac, respectively, for the eight and 16 feet subirrigation drain spacing compared to 122 bu/ac for both the subsurface drained and non-subsurface drained cropland. Soybean yields were 32 and 38 bu/ac, respectively, for the eight and 16 feet subirrigation drain spacing compared to 22 bu/ac for both the subsurface drained and non-subsurface drained cropland. In 1999, the average increase in yields with subirrigation compared to both the subsurface drained and non-subsurface drained cropland was 17 bu/ac for corn and 13 bu/ac for soybean. Economic Analysis Summary This component of the project focused on the economic impacts of the combined wetland-reservoir-subirrigation system (WRSIS) from the perspective of the farm owner-operator (investor), and the main research made estimates of private farm-level economic impacts for the adoption of WRSIS technology at one of the Northern Ohio Demonstration sites, the Shininger Farm. This site is privately owned and is managed by the owner with the intention to maximize net returns. The data for this study were collected from one of three demonstration sites in Northwest Ohio. The data include capital costs, variable input costs, management costs, maintenance costs, yield benefits, and land allocation. Net Present Value (NPV) analysis was used to judge the economic profitability of WRSIS adoption. NPV analysis employs discounting techniques to explicitly recognize the opportunity cost associated with the timing of a receipt or expenditure flow. Because the WRSIS is expected to have a long lifespan, and income and expenditure flows are expected to differ substantially over this period, analysis techniques that do not account for the differences in the timing of cash flows do not completely account for differences in profitability. The net present value model of the WRSIS investment recognized all sources of private costs and benefits to the farmer. These costs and benefits vary with the following parameters: * Size of the required capital investment * Opportunity cost of capital * Terms of financing * Marginal improvement in commodity yields * Change in acreage under production due to wetlands and reservoir construction * Marginal change in production input costs * Additional WRSIS management and maintenance costs * Change in the market value of the land asset resulting from the WRSIS improvement. * Change in federal and state income tax liabilities resulting from additional commodity sales and changes in tax deductible expenses. Researchers also postulated other benefits that might accrue to society from the adoption of WRSIS technology. Such benefits might include reduced surface or groundwater contamination with agricultural chemicals, reduced deposition of eroded soils offsite, lower water treatment costs due to reduced soil and chemical particulate in surface waters downstream of the WRSIS, etc. Although data were not available to estimate the magnitude of these external benefits, the NPV analysis model was modified to include taxes or subsidies that might be imposed by policymakers to encourage the adoption of environmentally friendly WRSIS technologies. Data were collected for the Shininger and other sites. Estimates were made of the total investments in the WRSIS. Estimates of expected yield benefits were made based on

yield estimates summarized in other studies (Zucker and Brown, 1998). Costs to operate the WRSIS system were estimated based on operating cost data for the Shininger site. Costs of dredging the reservoir and wetland and other periodic maintenance were based on estimates provided by contractors and other knowledgeable professionals. These cost and returns sources were included in the net cash flows in the net present value model. Profitability was estimated on an after-tax basis, since tax deductibility of cash interest, depreciation and other expenses reduce the owner's tax liability. The after-tax net present value of the WRSIS investment is represented as: Where, NPV = The after-tax net present value for the WRSIS I0 = The amount of investment ($) required to construct the WRSIS t = year index T = The length of the planning horizon (30 years) DR = Change in gross revenue resulting from the WRSIS investment. This is the product of changed crop yield, changed cropped acreage, and market price for the commodity. DEC = Change in the economic costs of production resulting from the WRSIS investment. Economic costs include all cash and noncash (e.g., unpaid family labor and management) costs of production excluding financing costs and depreciation. DCC = Change in cash costs of production resulting from the WRSIS investment. These costs are included in the calculation of federal and state tax liabilities. DD = Change in depreciation expenses resulting from the WRSIS investment. Depreciation is calculated using the provisions of current (1997) federal income tax codes. MTR = The individual's marginal tax rate (combined federal and state rate). DLV = Difference in terminal value of land (at the end of the planning horizon) with and without the WRSIS investment. CGR = The individual's capital gains tax rate. k = The after-tax opportunity cost of capital (weighted cost of debt and equity): k = (Pe * ke) + (Pd * kd), where ke (kd) is the cost of equity (debt) and Pe (Pd) is the proportion of equity (debt) financing the investment. S = Subsidy (positive) or Tax (negative) amount due to government or third party payments such as mitigation payments. ESV = Economic Social Value. Environmental benefits such as: improving downstream water quality, reducing agricultural runoff, providing wildlife habitat, and increasing wetland acreage. Table 1 summarizes the assumptions employed in the base-case analysis for the above model. Table 1. Variables and Assumptions of the Base-Case Model. Variable Value Capital Investment costs $60,091 Planning horizon (loan term) 30 Years WRSIS acreage Total acreage 23.5 acres. 20 acres are subirrigated. Crop Mix 50% each of corn and soybeans. Commodity prices Corn: $2.50/bu. Soybeans: $6.00/bu Marginal tax rate 34% (federal + state combined) Down payment percent 25% Financing interest rate 8% (after tax rate is 5.28%) Before-tax Opportunity Cost of Capital 12% Base Crop Yield (control) 150 bu/ac corn, 47 bu/ac soybeans1 Subirrigation Yield Improvements 30% for corn, 43% for soybeans Long term yield growth/yr 1% for both subirrigated and non-subirrigated crops Inflation rate 3% Farm land value inflation 4% Dredging Interval and Cost Dredging every 15 years at a cost of $5000 Net Income/acre $141/ac non-subirrigated and $178 subirrigated Capital Gains Tax Rate 20% Price of recent land sales per acre $2000/ac Subsidy/Third Party Payments (S) $0 Economic Social Value (ESV) $0 1. The long term average yields reported by Zucker and Brown (1998). Actual yields observed from the Shininger site for 1996 were a 46.7% yield increase in soybean and a 73.8% yield increase in corn. However, the three-year average (1996-1998) only saw a yield increase of 24.2% in bean and 40.6% in corn yields. Given the investment requirements at the Shininger site, and with the other assumptions given in Table 1 above, the WRSIS was not profitable. Table 2 summarizes the sources of returns and costs under the base-case scenario. Although the value of yield improvements (discounted value of the thirty year series) was substantial ($35,598), and the discounted 30-year value of tax offsets was also large ($20,340), the WRSIS investment resulted in a negative NPV of $11,241. This suggests that the time-discounted value of costs over the 30 -year time period analyzed exceed the discounted value of revenues by $11, 241. Table 2: Net Present Value Analysis of the Shininger Demonstration Site Under the Base-Case Scenario. Source of Cost or Return Discounted Value Investment $ -60,091 Value of Yield Improvements 35598 Additional variable inputs -8031 Additional labor inputs (system management) -342 Utilities and other operating costs for the SI/Wet system -342 Periodic dredging of wetlands and upland reservoirs -2487 Changed federal and state income tax liabilities 20340 Value of land sales after 30 years 4114 Total Net Present Value $ -11,241 Sensitivity analyses were performed

on this base model. The following are conclusions based on those analyses: * Because of the tax deductibility of cash interest expenses, the NPV of the investment rises with increased marginal tax rates and with increased use of debt financing of the WRSIS. The base-case model essentially breaks even in the investment is 75% debt financed and the operator faces a 47 percent combined federal and state marginal tax rate. * NPV of the WRSIS is a strong function of the level of yield improvement resulting from subirrigation. Under the base case scenario, corn and soybean yields of 225 and 66 bushel per acre essentially resulted in breakeven. * The NPV of the WRSIS is expected to rise for applications with higher-valued crops because this results in greater value for the improved yield. * The receipt of wetland relocation mitigation payments by a farmer can substantially impact the private profitability of the WRSIS. Recent experience is that mitigation payments in Ohio can exceed $20,000 per acre of mitigated wetland. Addition of this payment to the base scenario results in a positive NPV (profit). Applicability to Other Sites: Costs and returns of WRSIS technologies will vary substantially from site to site. There is reason to believe that there may be economies associated with the scale of operation – that is, the construction costs for reservoirs or wetlands of various sizes is not linear. Larger units will have a lower construction cost per cubic foot of capacity. The costs of installing a system also will vary with the topography of the site. The greater the deviation in elevation across the site, the larger the number of zones in the subirrigation system, and the larger the required investment in subirrigation control structures. Even though the magnitude of costs and returns will vary among sites, the net present value model developed in this study can easily be modified to model those situations. This method can easily be used as a management decision aid for farmers considering WRSIS adoption anywhere. WRRI Proposal Objective 1: Characterize, analyze, model hydrologic interactions between integrated subirrigated agricultural production and constructed wetland-reservoir systems, and evaluate the water quality (sediment, pesticide, nitrate and phosphorus transport) impacts and benefits of this integrated system. Monitoring System for Water Quality and Quantity, and Ecological Parameters at the DARA Wetland-Reservoir Subirrigation System Site At the DARA site, an intensive monitoring program was implemented to monitor and analyze the overall performance of the system. The design was completed in 1999, and about 90% of the construction and installation of instrumentation was completed by May 2000. It is only within the past year that much of the WRSIS monitoring program has been initiated. As such, not enough time has yet elapsed to see the long-term trends in movement and storage of water, sediment, nutrients, and pesticides that will aid in fine tuning the management of WRSIS sites. The monitoring program now in place is designed to provide valuable information for at least the next five years and hopefully longer. The instrumentation will allow us to measure and monitor system parameters necessary to fully evaluate the benefits, operation and management, and economics of the system and its components for the next five to ten years. The monitoring system will provide data that shows the dynamics of the linked system. It will allow for analysis of how effective the systems are at achieving the stated objectives of the WRSIS sites. It will also provide information that could be used in the optimization of the design and management of the systems, so that they are better able to meet the stated objectives. Information collected through monitoring of WRSIS components will be used to evaluate benefits, determine the best operation and management strategies, gauge economic viability, and establish the overall environmental impacts of a number of such systems within a larger watershed scale. To help in this regard, a database has been initiated for maintaining WRSIS monitoring information in a format easily accessible to all project collaborators. Many of the ongoing project goals will be addressed using database information as input for computer modeling programs. Hydrological, agricultural, environmental, and ecological focus areas include: determination of system water balance; water routing for water conveyance, storage and water supply; subirrigation water requirements for corn and soybean production; operation and management of system components; farm-level economics; sediment routing and trapping; nutrient and pesticide fate and transport; plant community development and diversity, wetland vegetation, and vegetative habitat for wildlife; net water, sediment, nutrient, and pesticide losses off-site. The ecological impact of the system is also being analyzed through the

monitoring of the diversity of the vegetative growth in and around the wetland and the monitoring of aquatic macro-invertebrates within the wetland. The flow monitoring components of the system measures and records data for six different categories of measurements: climatological, surface flow, partial-pipe flow, pressure pipe flow, water table depths, and impoundment and pump station water levels. A weather station was installed in order to measure and log various climatological parameters. Three H- and HS-flumes and two V-notch weirs were installed in order to allow for measuring surface flow rates at several locations at the site. Flow through these devices will be measured using either area-velocity sensors or submerged probe sensors. There are five locations at the site where flow in pipes with normally partial-pipe flow conditions needs to be measured: the outflow pipe from the east subirrigated zone, the outflow pipe from the west subirrigated zone, the outflow pipe from the wetland to the wetland pump station, the off-site drainage main that empties into the wetland pump station, and the emergency outlet pipe. At these locations, area-velocity sensors were installed in order to measure the flow rate. Pressure pipe flow from the wetland pump station to the supply reservoir and from the supply reservoir to the subirrigated zones will be measured using clamp-on ultrasonic flow transmitters. Eight water table wells were installed within the subirrigated zones. Water table levels within these wells are measured using pressure transducers. Pressure transducers were also installed within the constructed wetland, wetland pump station, and supply reservoir in order to measure the water levels there. Additional details are summarized below as per the summary by B.A. Allred in MVRCD (1999). Water Flow and Storage Monitoring The DARA site schematic map provided in Figure 1 shows the points where the weather station, the three flumes, and the eleven automatic water samplers have been placed. Attached to each sampler is a sensor for measuring water flow. A weather station manufactured by Campbell Scientific was installed to measure rainfall, wind speed and direction, solar radiation, air temperature, and relative humidity every 2 minutes. Precipitation values determine the amount of water added to the site. All other weather variables are used to calculate wetland/reservoir/cropland evapotranspiration rates. A U. S. Weather Bureau Class A evaporation pan containing a water level probe was likewise setup to provide redundant measurements for evapotranspiration calculations. The water level probe within the Class A pan is connected to the weather station data logger. Three flumes and two v-notch weirs are used to measure surface water runoff coming into the wetland itself or the adjacent area to the north that surrounds the pump station (Figure 1). The flumes were manufactured by Plasti-Fab and are made from fiberglass reinforced thermoplastic polyester. One is a 2 ft. H flume and the other two are 1 and 0.4 ft. HS flumes. On the inside bottom of the H flume is a mounting plate for an ISCO 750 Low-Profile Area-Velocity Module that measures flow. For redundant flow measurements, the H flume also has an attached 8 in. stilling well upon which a Belfort FW1 water level recorder is mounted. Both HS flumes use an ISCO 720 Submerged Probe for determining flow rates. To allow continued operation during colder months, the flumes were winterized by constructing an insulated enclosure around them containing a ceramic space heater. One of the two v-notch weirs was placed on the downstream side of the site outlet control structure and the other within the west wall of the 2 ft. high sheet metal barrier surrounding the wetland pump station. Calculation of flow through a v-notch weir requires measurement of water depth at a point upstream. An ISCO 720 Submerged Probe installed within a 3.5 ft. tall, 1 ft. diameter PVC stilling well provides the water depths needed for determining flow through both weirs. Water flow is also measured within the underground pipe and drain network at the DARA site (Figure 1). An ISCO 750 Low-Profile Area-Velocity Module is used to monitor flow rates where partially filled pipe conditions exist. Partial pipe flow is found between the wetland control structure and wetland pump station, within the two main lines connected to the east and west subirrigated fields, downstream of the site outlet control structure, and within the main line from the control plots (Figure 1). Scientific-Pittsburg/Panametrics Model XMT868 Ultrasonic Flowmeters are employed for fully filled pipes containing water under pressure, such as the 4 in. diameter line coming into the reservoir and the 2 in. diameter line leaving it. The ultrasonic flow sensors clamp onto the outside of the two pipes, thereby requiring emplacement underground of a large concrete box structure near the reservoir to house these instruments for easy access. As previously stated, all flume,

v-notch weir, and pipe flow sensors are connected to automatic water samplers. Figure 1. Schematic of the DARA site showing hydraulic structures and water flow monitoring points. WRSIS water storage occurs in the wetland, reservoir, and subirrigated fields. Water level measurements determine the amount stored within each of these three components. For the subirrigated fields, this level, called the water table, is managed according to crop needs. Drain pipes, main lines, and control structures are used to raise the water table into the root zone when there is a soil moisture deficit and to lower it during wet periods. Pressure transducer water level probes manufactured by Electronic Engineering Innovations were installed in monitoring wells to obtain continuous measurements of the water table elevation. The monitoring wells extend 5 ft. into the subsurface and are comprised of 4 in. diameter slotted schedule 40 PVC pipe. To reduce the possibility of surface runoff entering the well, a 4 ft. by 4 ft. plastic apron was laid around it at a depth of 6 in. Also, open slots close to the surface were taped over followed by surrounding this portion of the PVC pipe with a bentonite seal. There are eight monitoring wells at the DARA site. For both the east and west subirrigated fields, two wells are placed within 1 ft. of a drain line and two are placed at a midpoint between drain lines. Positioning the wells in this manner allows for observation at any time of both the maximum and minimum water table elevations, regardless of whether the system is in drainage or subirrigation mode. The same Electronic Engineering Innovations probes are also being used to measure surface water elevations in the wetland and reservoir. The wetland probe is placed in the bottom of the multi-port sampling mast (described later), and like the monitoring well probes, it is connected to the weather station data logger. Since water levels between the two are equivalent, the probe monitoring the reservoir is actually placed in the bottom of the adjacent pump station and connected to a separate Electronic Engineering Innovations data logger. Transport and Storage Monitoring of Nutrients and Sediment At each point on the DARA site where a flow measuring sensor has been placed (ISCO 750 Low-Profile Area-Velocity Module, ISCO 720 Submerged Probe, or Scientific-Pittsburg/Panametrics Model XMT868 Ultrasonic Flowmeter), water samples are automatically collected with an ISCO 6700 Portable Sampler. These samplers hold twenty-four wedge-shaped 1 L bottles. The ISCO 6700 Portable Samplers are activated by the flow sensors during storm and pumping events. To allow for winter sampling, the water collection tubing has been buried underground in 2 in. plastic conduit, and the samplers themselves enclosed within foam insulated barrels containing thermostat controlled heating tape. All automatic water samplers are run off direct power with battery back-up Wetland and reservoir water samples are collected via multi-port sampling masts. Slotted PVC strainers protruding outwards from the mast were installed at each port to remove large debris material during sampling. The ports are vertically spaced either 0.5 or 1 ft. apart. The 0.5 ft. spacings were used near the bottom of the mast and 1 ft. spacings at the top. Plastic tubing was connected to the back of each strainer and strung through the inside of an upright, 1 ft. diameter, corrugated plastic pipe to an outlet at the bottom. A 4 or 6 in. diameter corrugated flexible plastic pipe was then used to carry the sample tubing bundle from the bottom of the mast to the shore of the wetland or reservoir. With a peristaltic pump, water can be drawn through each tube thereby allowing samples to be obtained at different levels within the wetland or reservoir. Wetland/reservoir sampling events take place weekly. The wetland sampling mast is 5.5 ft. tall and that for the storage reservoir is 13 ft. Both were placed in the deepest part of the wetland or reservoir and supported by an attached 2 in. diameter vertical steel pipe which had been driven 3 ft. into the bottom sediment. Additional support for the reservoir sampling mast is provided by four plastic-coated steel cables connected to the top of the mast and anchored into the shoreline. Water was drained out of the wetland in order to install its mast, while placement of the reservoir mast required the use of a floating platform. Water sample analysis provides crucial information on nutrient and sediment cycling at the DARA WRSIS. Both filtered and unfiltered portions are chemically analyzed for all water samples collected from the wetland/reservoir masts, and by the ISCO automatic samplers. Unfiltered portions are tested for total nitrogen, total phosphorous, and total organic carbon. Filtered portions are analyzed for pH, total filterable solids (< 0.22 m), inorganic carbon, dissolved organic carbon, nitrate, ammonia,

total nitrogen, dissolved phosphorous, and total phosphorous. In order to further gauge nitrogen, phosphorous, and carbon cycling within a WRSIS, soil/sediment and vegetation samples are also taken at the DARA site. Cropland soil samples are collected three times a year; before planting (May/April), after fertilization (July), and after harvest, and are obtained in both subirrigated fields and adjacent control plots. During sampling events, soil cores from the surface to a depth of 75 cm are extracted, and sections from 0-15 cm, 15-30 cm, and 30-75 cm analyzed separately. Sediment cores beneath the wetland are obtained at the same three times of the year that cropland soil sampling is conducted. For the wetland, 30 cm deep sediment cores from beneath the basin are extracted, and sections from 0-8 cm, 8-16 cm, and 16-30 cm analyzed separately. Chemical sample analysis then provides cropland/wetland subhorizon estimates for pH, total and available carbon, nitrogen, and phosphorous, nitrate, ammonia, soluble phosphate, dissolved organic carbon, dissolved organic phosphorous, and dissolved organic nitrogen. Cropland vegetation (corn and soybeans) sampling at the beginning of the growing season and just before harvest is being conducted in both the subirrigated and control fields. The same sampling schedule is also being used with regard to wetland vegetation. All vegetation samples are analyzed for total nitrogen, phosphorous, and carbon content. It is only within the past year that much of the WRSIS monitoring program has been initiated. As such, not enough time has yet elapsed to see the long-term trends in movement and storage of water, sediment, nutrients, and pesticides that will aid in fine tuning the management of WRSIS sites. The monitoring program now in place is designed to provide valuable information for at least the next five years and hopefully longer. Water Column Sampling System for the Constructed Wetland and Water Supply Reservoir at the DARA WRSIS Site The constructed wetland and reservoir at the DARA site have been instrumented with a water column water sampling system which allows us to evaluate water quality parameters in the wetland and reservoir (see above). This system was adapted from a prototype sampling system designed by our undergraduate engineering students as a design exercise in 1998. In late 1999, the column system was installed and operational and selected data have been collected using these systems. Modeling of Water Routing in a Wetland-Reservoir-Subirrigation System Using SIMULINK Linked Wetland-Reservoir-SubIrrigation Systems (WRSIS) have the potential to help farmers achieve consistently high corn and soybean yields, improve the quality of water that enters surface water bodies from cropland, and increase wetland acreage. The work conducted within this component thesis focused on providing means to help optimize the design and management of these systems, and to help assess their effectiveness at meeting the aforementioned objectives. This work primarily focused on the development of a flow-routing model for the systems. WRSIS-DEM MODEL The Wetland-Reservoir-SubIrrigation System Design, Evaluation, and Management (WRSIS-DEM) model was developed to simulate the routing of flow at WRSIS sites. The model was developed using SIMULINK (Version 2), a software package that uses block diagrams to represent the models of dynamic systems. The WRSIS-DEM consists of an entire library of blocks that can used to model the different components present at WRSIS sites. The blocks simulate the water balance within these components. Blocks are also available for modeling various different management strategies. Users can link component and management blocks in order to create model representations of different WRSIS sites. Model representations created using WRSIS-DEM could potentially be used in a variety of different ways. They could be used to evaluate system design parameters, such as pump capacities and drain spacings. They could be used to look at how effective existing systems are at handling different situations. Another possible use would be to evaluate the effectiveness of different management strategies, whether they be the implementation of general management strategies or the use of an automated feedback control system. Finally, a model representation of an existing WRSIS site could potentially be a useful tool in making day-to-day management decisions at the site. In order to illustrate how WRSIS-DEM could be used as a design tool, a series of simulations were conducted that looked at how effective a constructed wetland and pump station at the DARA site were at routing different storm events. The storms routed during the simulations were 24-hour storms with the following return periods: 2, 5, 10, 25, and 50 years. Simulations were conducted for scenarios in which the wetland was 100%, 125%, 150%, and 200% of the size of the actual wetland at the site. It was

determined that increasing the size wetland did not have much impact on how effective the system was at retaining water from the storms. In addition, it took longer for the wetland water level to recede to an acceptable level when the size of the wetland was increased. Simulations were then conducted in which an additional pump was added to the pump station. The simulation results showed that adding the pump caused an additional an additional 11 to 14% of the storm water to be retained. These results indicate that the effectiveness of the current system at retaining water is limited by the ability of the pumps to keep up with flow. This work was completed in late summer, 1999. The student offered the following recommendations: In the future, it might prove useful to use water quantity data obtained from existing WRSIS sites to test the validity of the model algorithms contained within WRSIS-DEM. In particular, the DARA WRSIS site has a monitoring system currently in place that could be used to obtain the data necessary for this purpose. Calibration tests could be conducted in order to determine fitted values for the outflow relationships used to estimate outflow from the subirrigated zones, outflow from the wetland, and emergency outflow to off-site. Calibration tests could also be conducted to obtain a fitted value for the effective virtual reservoir area for both subirrigated zones. Once these calibrated values were obtained, results predicted using the WRSIS-DEM representation of the DARA WRSIS site could be compared with the data obtained by the monitoring system for storm events and day-to-day operation of the system. One of the useful aspects of the WRSIS-DEM model is that it can be used to simulate different management strategies, whether it is the implementation of general management guidelines or the use of an automated feedback control system. Simulations could be set up that look at how effective these different strategies are at meeting certain objectives, such as minimizing the amount of wet stress that crops are exposed to because of the water table depth being too shallow. The results from these simulations could then be used to help develop a management guide for WRSIS sites. The results in Chapter 4 of this thesis show how WRSIS-DEM could potentially be used as a design tool. Future work could entail developing a design procedure for future sites in which an entire set of simulations is run. These simulations would look at how the system handles a standard set of design events. These events could entail a single storm event, several storm events over a period of time, or extended periods of dry weather. In this way, optimal values for pump capacities, wetland size, drain spacing, etc., for the site could be determined. Modeling of Water and Sediment Routing in a Wetland-Reservoir-Subirrigation System Using the WEPP Watershed Model Before this work was conducted, there was no one-computer simulation model that had the capability to simulate the components and functions of the WRSIS systems at the field or watershed scale. The Water Erosion Prediction Project (WEPP) hillslope and watershed models (Flanagan and Nearing, 1995) were of interest to the author and his goal to model the efficiency of runoff, subsurface drainage water, and sediment detainment capacity of the WRSIS. However, some model modifications, especially in the water balance algorithms of the WEPP hillslope model were needed. While the current version of the WEPP hillslope model (Flanagan and Nearing, 1995) is considered a robust erosion prediction model, it contains little more that a basic subsurface drainage component. In addition, the WEPP model does not have the capability to adequately model the hydrology of agricultural lands that have controlled drainage and subirrigation systems on them, and subsequently the impact of controlled drainage and subirrigation on soil loss. The overall goal of this component of the research was to modify the WEPP hillslope model, so that when it is linked with the WEPP watershed model, the linked model can be used to route runoff, subsurface drainage and subirrigation waters and sediment through the components of a WRSIS. The modified model is called Water Erosion Prediction Project-Water Table Management (WEPP-WTM). In addition, several drainage related studies were identified and completed. The following is a summary of the work conducted, and the main conclusions and recommendations for future work. This work is summarized by individual thesis chapter and objectives. Objectives 1-4: Drainage Modeling Studies Leading to Improved Runoff and Drain Flow Prediction Capability: The results of a series of background studies thought to be of interest and necessary towards the improvement of the predictive capability of WEPP were presented in this chapter. Measured drain flow and runoff data from the

drainage experiment at the OARDC North Central Branch station (Schwab et al., 1963; 1975; and 1985) were used in this study. Objective one was to evaluate runoff and drain flow predictions from DRAINMOD, using a range of saturated hydraulic conductivity data sets developed for the same site derived from seven different Ksat estimation methods. DRAINMOD (Version 4.6) simulations were conducted for the years 1962-1964, and 1967-1971. Model predictions were compared to measured outflows from Schwab et al. (1963; 1975; and 1985). The analyses showed that no one Ksat estimation method provided the smallest deviation in outflows when individual years were considered, except for drain flow in 1967-1971. For these years, the simulation results with the van Schilfgaarde equation estimated Ksat values produced the smallest average deviation. The van Schilfgaarde equation estimated Ksat simulations also produced the smallest deviation in runoff in three of the five years that also had the smallest drain flow deviations. Overall, the simulation results with the van Schilfgaarde equation estimated Ksat values produced the smallest total deviation for both drain flow and runoff over all eight test years. The rank order (smallest to largest total deviation) of the Ksat methods for drain flow were van Schilfgaarde, Hooghoudt, and Kirkham equations estimated Ksat methods, followed by auger hole, monolith, core methods, and then the MUUF soil database method. The rank order of the Ksat methods for runoff was van Schilfgaarde, Hooghoudt, Kirkham, auger hole, MUUF soil database, core, and Monolith. Based on the results of this research, a conclusion was reached to use the van Schilfgaarde equation based Ksat in all further analyses in this chapter. Where drain flow and water table depth measurements are available and/or practical to obtain, Ksat estimates made with the van Schilfgaarde equation may provide more reliable modeling results since they take into account the overall effect of backfill, drain spacing and depth, deep percolation, drain pipe parameters, etc. Objective two was to analyze the relative impact of changes in drainage trench backfill properties on runoff and drainage flows. An exponential maximum drain flow equation as a function of year was developed using the maximum drain flow versus year data obtained from the backfill alteration study of Taylor and Fausey (1982). The van Schilfgaarde equation estimated saturated hydraulic conductivity values obtained in the previous analysis were adjusted using this equation over time. Using these adjusted Ksat values in DRAINMOD improved the outflow prediction accuracy of the model. Determining the changes in hydraulic conductivity of backfill for different subsurface drainage system spacings, depths, trench widths, pipe and backfill material properties is considered a major research need. Developing empirical relations for changes in hydraulic conductivity with time, such as Equation 2.15 may not only improve drain flow prediction capability, but improve the use of models like DRAINMOD for drainage system design and evaluation. Objective three was to evaluate monthly Potential EvapoTranspiration (PET) adjustment factors used in DRAINMOD to predict drain flow and runoff. To determine the monthly PET adjustment factors for North Central Ohio conditions, the estimated monthly Penman-Monteith PET values were divided by the estimated monthly Thornthwaite PET values. Overall, when DRAINMOD was run with these monthly PET adjustment factors, the outflow prediction accuracy of the model worsened. Therefore, until further study is conducted to better warrant their use, a value of 1.0 for the PET adjustment factors was recommended. If monthly pan or lake evaporation data are available, they could be used to determine monthly PET adjustment factors in place of using the Penman-Monteith equation estimated PET values. In general, if the Thornthwaite daily PET estimates are after all proven not to be appropriate, the water balance algorithms in DRAINMOD have to be checked and tested using the daily Penman-Monteith equation or pan evaporation data. Objective four was to evaluate the effects of the Kirkham-Hooghoudt equations on drain flow and runoff prediction accuracy with DRAINMOD against an empirical equation, and to determine the relative contribution of the Kirkham equation to drain flow predictions compared to the Hooghoudt equation alone. An assumption was made that the empirical equation (Eq. 2.12) developed by Hoffman (1963) best described the water table depth-drain flow relationship at the experimental site. This equation was then used in place of the Kirkham and Hooghoudt equations to evaluate the effects of the Kirkham-Hooghoudt equations on drain flow and runoff prediction. Overall, the analyses showed that in comparison to drain flow predictions using Equation 2.12, the Kirkham-Hooghoudt equations did not

predict drain flows as well, but did predict runoff better than that from simulations using Equation 2.12. In addition, careful selection of a value for the drainage coefficient (DC) is necessary when using the Kirkham-Hooghoudt equations since drain flow predicted by the Kirkham and Hooghoudt equations is limited to the value of DC. The contribution of the Kirkham equation to drain flows was evaluated using DRAINMOD, with and without the Kirkham equation; or stated another way, with the Kirkham-Hooghoudt equations and the Hooghoudt equation alone. The analyses showed that the addition of the Kirkham equation to the Hooghoudt equation improved drain flow prediction accuracy of DRAINMOD compared to the Hooghoudt equation alone. However, this capability may decrease the runoff prediction accuracy of the model. Again, careful selection of the DC value is important. Based on these results, a decision was made to incorporate the Kirkham equation into the subsurface drainage algorithms of WEPP-WTM model. Considering the variability of measured outflow results, drain flow predictions by the Kirkham-Hooghoudt solution in DRAINMOD were considered to be satisfactory, as long as it is used with appropriate input parameters such as Ksat, DC, and monthly PET factors. However, we also have to consider that some years most of the drain flow and runoff depths measured at the field site were a result of the constant intensity irrigation events. For these irrigation events, the input data for rainfall are equally distributed hourly constant values. These types of constant intensity storms are not seen often in nature. For this reason, if the rainfall measurement interval is less than an hour, using less than hourly time interval rainfall data, such as with the breakpoint option in WEPP, may increase the prediction accuracy of the model. This should be evaluated in future work. For the overall simulation results using DRAINMOD, when drain flow prediction accuracy improved, runoff prediction accuracy generally worsened. One reason this result may have occurred is that in all simulations performed in this study, Green-Ampt infiltration parameters determined by Skaggs et al. (1981) were held constant. Infiltration rate affects runoff. The values of the Green-Ampt parameters by Skaggs et al. (1981) were based on core method Ksat values. Further study is warranted in the selection of Green-Ampt parameter values and the use of various Ksat methods for estimating Green-Ampt parameter values. Also, it might be interesting to evaluate the effect of time based adjustments to Green-Ampt parameter values, similar to what was done in this study for backfill effects on Ksat. Objectives 5-6: Simulating Water Flow to a Subsurface Drain in Layered Soil The HYDRUS-2D model was used to develop drain flow-water table elevation curves to be compared to the following: i) drain flow-water table relationship described by Hoffman (1963) as the best empirical relationship for the measured drain flow and corresponding midspace water table elevation data from the OARDC site; and ii) the relationship described using the Kirkham and Hooghoudt equations. For this analysis, the drain was represented as a completely permeable half circle with radius equal to the effective radius of the drain. To prevent water entry into the profile from the drain, the boundary represented by the drain was considered as a seepage face with pressure head equal to zero at the beginning of the simulation. Drain flow and corresponding water table depth data from 1960-1962 were used. In addition, saturated hydraulic conductivity (Ksat) values from the core data of Schwab et al. (1963) were used. Objective five was to simulate drain flow into subsurface drainage pipes for a layered soil profile using HYDRUS-2D (Simunek et al., 1996). This research was conducted to help determine the ability of the model to predict drain flow-water table elevation relationships. It considered two cases of water loss at the soil surface: with and without evapotranspiration. The model was then used to evaluate the effect of backfill on drain flow-water table depth relationships with and without evapotranspiration. HYDRUS-2D underpredicted drain flow compared to the empirical and the Kirkham-Hooghoudt equations for water table elevations above 70 cm (27.5 in). However, HYDRUS-2D predictions were very close to those using the empirical and the Kirkham-Hooghoudt equations for water table elevations below 70 cm. There was no difference in the HYDRUS-2D curves for the cases where ET = 0 and for an ET rate of 0.3 cm/day. There was little difference between the HYDRUS-2D curves for the no backfill simulation and for the backfill simulation used with backfill soil Ksat values obtained forty years after installation of the drains at the site. In the backfill simulation scenario, the model produced slightly higher drain flow

rates than those obtained without simulating backfill when the midspace water table elevation was greater than 70 cm (27.5 in), but still underpredicted drain flow compared to the empirical and the Kirkham-Hooghoudt equations. To better reflect conductivity values for the backfill in 1960-1962, a range of saturated hydraulic conductivity values within the limits of the undisturbed soil core Ksat values published by Schwab et al. (1963) were assigned to the backfill layers. The best HYDRUS-2D results were obtained when a value of 2.54 cm/hr (1 in/hr) was used for all backfill layers. The resulting curve showed substantial improvement in drain flow predictions from HYDRUS-2D especially when the water table elevation was greater than 70 cm. In the range of water table elevations from 70 to 90 cm, the Kirkham-Hooghoudt equations overpredicted drain flow by approximately 82% and HYDRUS-2D underpredicted drain flow by 52%. Within the scope of the analyses presented above and the available data, objective 1 was met as discussed above. Drain flow-water table elevation curves from HYDRUS illustrated the capability of using HYDRUS-2D to predict drain flows. The drain flow results showed that the HYDRUS-2D model can be used to predict drain flows, at least within the scope of the available input data. No specific limitations in model capability were found. However, there were limitations in model application because of the lack of appropriate input data. Further analysis using backfill Ksat values greater than 2.54 cm/hr (1 in/hr) should be performed. Objective six was to develop an equation similar to that developed by Salem and Skaggs (1998) to predict drain flow rates for transition conditions of the water table for a layered soil. To develop a new equation similar to that developed by Salem and Skaggs, (1998) for layered soils, a key result of the previous work must have been met. The equation by Salem and Skaggs was developed by fitting SWMS-2D (Simunek et al., 1994) drain flow results especially for transitional water table conditions that occur between two endpoint conditions: that modeled by the Kirkham equation and that modeled by the Hooghoudt equation. Modeling the transitional conditions between those covered by the Kirkham equation and those covered by the Hooghoudt equation for a layered soil did not produce the same drain flow values at one endpoint of the transition as was accomplished by Salem and Skaggs (1998). At the lower end of the transition (approximately 70 cm; 27.5 in), HYDRUS-2D was able to produce the same drain flow rate as produced by the Hooghoudt equation. However, at the upper end of the transition (approximately 90 cm; 35.4 in), HYDRUS-2D was not able to produce the same drain flow rates as produced by the Kirkham equation. At this point in the research, an equation similar to that of Salem and Skaggs could not be developed. Further research is recommended, however. This research needs to be conducted using input data from a subsurface drainage experiment site at which drain flows, midspace water table elevations, and saturated hydraulic conductivity values both in the original soil and the backfill are measured at the same time. Objective 7: Evaluation of the Hydrology Component of the WEPP Hillslope Model for Subsurface Drained Cropland Objective seven was to gain some assessment of the hydrology component of the WEPP hillslope model (Version 97.3) for cropland with subsurface drainage, and to evaluate the runoff, drain flow, and water table depth prediction accuracy of the WEPP hillslope model against measured runoff and drain flow data from Ohio, and predicted water table depths from DRAINMOD (Version 4.6). Three years of measured drain flow and runoff data from the OARDC drainage experiment were used. Simulations using the WEPP hillslope model were conducted for the years 1969 through 1971. WEPP daily predicted drain flow and runoff values were compared to the measured outflows, and WEPP daily predicted midspace water table depths were compared to those predicted by DRAINMOD. The analyses for drain flow showed that i) drain flow simulation results with WEPP produced very large average deviation values when compared to the measured data; ii) daily drain flows were overpredicted for all storm events, furthermore, large amounts of daily drain flow were predicted at times when there was little or no measured drain flow; and iii) predicted cumulative drain flows at the end of the evaluation season for each year were almost four times larger than the measured drain flows. The analyses for runoff showed that i) WEPP produced large average deviations between daily predicted and measured runoff depths; ii) WEPP overpredicted runoff for most daily storms, overpredicted cumulative runoff for the evaluation season for all three years. Overprediction of runoff was expected considering the very low values of WEPP predicted baseline effective conductivity. The

analyses of the WEPP predicted midspace water table depth suggest that WEPP may not be truly simulating water table depth. There is no continuous water table depth prediction in WEPP, and its algorithms allow the water table to move quickly between the soil surface and bottom of the soil profile. The calculated standard errors and average deviations between WEPP and DRAINMOD predicted midspace water table depths are very large, in the range of 0.5 to 0.75 m (1.64 to 2.46 ft). Some of the possible reasons that WEPP drain flow, runoff, and water table depth predictions may be so poor are: the 24 hour time step used to calculate these values in WEPP is large; a large amount of deep seepage from the bottom of the soil profile was simulated by WEPP; WEPP predicted baseline conductivity values appear to be very low especially for use in drain flow calculations for poorly drained cropland; WEPP actually is predicting a perched water table, not a water table produced with saturated conditions from the bottom of the soil profile; and lastly it seems that the soil water content predictions of WEPP throughout the soil profile may not be accurate for subsurface drained cropland. Each of these issues should be researched. For better drain flow, runoff, water table depth, and soil water content predictions with WEPP, the following suggestions are recommended. The time step should be decreased to some value less than a day, such as an hour. By offering extra input values such as an option whether to simulate deep seepage or not or assign a vertical Ksat value with the thickness for impermeable layer, deep seepage can be controlled. As an alternative to the water balance equation used in WEPP, water balance equations used in some more sophisticated models such as DRAINMOD and SWATRE (Belmans et al., 1983) could be used. Input parameters related to prediction of water table depth based on lab or field measurements, such as soil water retention and drained volume capacity should be used in WEPP. The user should be allowed the option to enter saturated hydraulic conductivity data, and use these data in place of the WEPP baseline effective conductivity for the prediction of drain flow. Lastly, the soil water distribution in the soil profile should be related to the true water table depth. Objective 8: Modification of the WEPP Hillslope Model to Incorporate Water Table Management Practices Objective eight was to modify the WEPP hillslope model (Version 97.3) to help improve the water balance, runoff, drain flow, and water table depth prediction capabilities of WEPP for cropland where water table management systems exist or are planned. The modified model is WEPP-Water Table Management (WTM). Most of the procedures incorporated into the modified water balance algorithms were taken from DRAINMOD. Predicted PET, plant root depth, depressional storage depth, and saturated hydraulic conductivity adjustments for frozen soils from WEPP were retained. Upward flux rate from the water table was calculated using the concept of matrix flux potential by Memon et al. (1986). The estimated runoff related sediment yield was predicted using the erosion prediction components of the WEPP hillslope model. WEPP-WTM predicts hourly runoff, drain flow, subirrigation flow, controlled drainage and subirrigation excess flows, water table depth, and daily sediment yields from the fields on which any of the water table management practices (or any combination of these) is planned or present. Daily outputs are presented in the water balance output file of WEPP-WTM. WEPP-WTM offers options to the user to use field or lab measured soil water retention data, water table depth-upward flux and drained volume data, saturated hydraulic conductivity of soil layers, and daily PET values. The model also allows the user to control deep seepage and depressional storage depth. The developed WEPP-WTM can be used especially for slightly sloped field sized areas at which subsurface lateral water lost from the soil profile is negligible. In addition, this model was developed for humid regions where the water table is close to the soil surface most of the year. Objective 9: Field Testing of the WEPP Water Table Management (WEPP-WTM) Model for Subsurface Drained Cropland Objective nine was to evaluate the performance of the Water Erosion Prediction Project-Water Table Management (WEPP-WTM) model in simulating runoff, drain flow, and water table depth for subsurface drained cropland conditions. The runoff, drain flow, and daily water table depth prediction accuracy of WEPP-WTM for field sized areas was tested against field measured data from two sites. Three years (1969, 1970, and 1971) of field data obtained from the OARDC North Central Ohio site were used for testing the drain flow and runoff predictions. There were no continuous

water table depth measurements at the OARDC site. Water table depth predictions were evaluated against a five year field data set from Aurora, North Carolina (Skaggs, 1978). The analysis of WEPP-WTM using constant and adjusted van Schilfgaarde equation estimated Ksat values indicated that using the adjusted saturated horizontal hydraulic conductivity (Ksat) values generally improved the drain flow prediction accuracy of the model while it decreased the runoff prediction accuracy of the model. Overall, WEPP-WTM produced drain flow and runoff results similar to those from DRAINMOD. The WEPP-WTM model produced average deviations for drain flow that were better than all of those obtained with WEPP and in most cases better than those obtained with DRAINMOD. However, runoff predictions from WEPP-WTM were similar, but poorer than those obtained from DRAINMOD, but much better than those from WEPP. To evaluate the water table depth prediction accuracy of WEPP-WTM, standard errors were compared with those obtained from published results using DRAINMOD, ADAPT, and SWATREN for the Aurora, North Carolina site. Overall, the predictions of water table depth from WEPP-WTM were very comparable to those from the other models. The ranked overall mean of the standard errors for all three drain spacings from the DRAINMOD 1, ADAPT 1, DRAINMOD 2, ADAPT 2, WEPP-WTM, and SWATREN water table depth predictions were 14.65, 16.87, 17.27, 17.47, 17.85, and 18.42 cm (5.77, 6.64, 6.80, 6.88, 7.03, and 7.25 in), respectively. The overall mean of the average deviations from all the models except DRAINMOD 1 was 14 cm (5.5 in). For DRAINMOD 1, an average deviation of 11.4 cm (4.5 in) was calculated from the values given by Skaggs (1978 and 1982). The student made a few additional recommendations. The runoff related sediment yield prediction capability of WEPP-WTM was not tested (site data was not available yet), and therefore, testing this component is needed. The WEPP-WTM was tested against data from individual plots and field sized areas. The WEPP watershed model (Ascough II et al., 1997) should now be evaluated for watershed scale capability after WEPP-WTM model is connected with it. The WEPP-WTM model does not simulate preferential flow to the drains through cracks, which can occur in clayey soils during hot summer months or other day periods. Algorithms simulating preferential flow could be added to the model and evaluated, possibly on conditions similar to those evaluated by Workman and Skaggs (1990 and 1991) with PREFLO. The WEPP-WTM model was developed for humid regions. For the possible use of the model for semi arid regions, the runoff prediction of the model for these regions should to be tested. The time lag between a rise in the ditch water level (weir depth changes) and the midspace water table response may be a problem in modeling subirrigation. This time lag could possibly by evaluated using the HYDRUS-2D model (Simunek et al., 1996). The effect of the time lag could then be incorporated into the water table depth prediction algorithms of WEPP-WTM and then evaluated. Objectives 10-11: Using WEPP-WTM Model for the DARA WRSIS Watershed The overall purpose of the research presented in this chapter was to evaluate the WEPP-WTM model for one of the WRSIS field sites. The modeling evaluation was conducted using a limited amount of data from this site. Objectives ten and eleven were, respectively: a) prepare input data to be used with the WEPP-WTM linked WEPP watershed model for predicting runoff volumes entering the wetland of the DARA WRSIS site; and b) compare runoff volumes predicted by the linked model with measured runoff volumes for a seven month time period in 1999. Most of the input data except horizontal saturated hydraulic conductivity values for the linked model were prepared. Runoff depth measurements from a 0.61-m (2-ft) H flume at the DARA site started in February in 1999. During the measurement period, most of the runoff to the flume came from the comparison plots. The daily measured and WEPP-WTM linked WEPP watershed model predicted runoff volumes were generated for a seven month (February 11-August 20) period in 1999. During this time period, nine main runoff events were recorded, but only a limited amount of these event data were unusable for this evaluation, and therefore additional site specific event data will be required to fully evaluate this model. WRRI Proposal Objective 3: Develop a technical design and management guide for subirrigated agricultural production and constructed wetland-reservoir systems, and conduct an applications and design workshop to teach agricultural producers and consultants how to use water table management for environmental and economic benefit. For results, please see the materials under the Publications and Information Transfer Program sections

of this report. Collaboration, Stakeholder Participation, and Support The project continues to enjoy great interdisciplinary, multi-agency, and stakeholder participation. The overall project is a cooperative team effort between the Maumee Valley RC&D (MVRC&D), USDA-Natural Resources Conservation Service (NRCS), USDA-Agricultural Research Service (ARS) Soil Drainage Research Unit, The Ohio State University (OSU), Michigan State University (MSU), Heidelberg College (HC), Soil and Water Conservation Districts (SWCD), farm cooperators and county commissioners, Ohio and Michigan Land Improvement Contractors (O&MLICA), Drainage Products Industry (ADS, Hancor, Haviland, Baughman), ODNR Division of Wildlife (SW), USF&WS, USACOE, and other local and state agencies and organizations. The overall project funding has been provided, in part, by USEPA GLNPO; Lake Erie Protection Fund; OARDC and OSU Extension; Ohio Sea Grant College Program; USGS Water Resources Competitive Grants Program; Water Resources Center, The Ohio State University; USDA-ARS Soil Drainage Research Unit; USDA-CSREES Hatch Proj. 965; Overholt Drainage Education and Research Program, Dept. Food, Agric., and Biol. Engr., The Ohio State University; and the cooperating landowners, agencies and organizations. A second WRRI funded sub-project to the overall WRSIS project was initiated in FY 1999 (see elsewhere in this report). Summary This innovative, ecologically sound crop production system will recycle runoff and drainage waters, reduce runoff, sediment, and agricultural chemical discharges to streams, improve water quality, increase wildlife habitat, increase wetland acres, and enhance farm profitability. The demonstration project team (farmers, state and federal agency personnel, university faculty) continue to provide high level input to proposed research and help evaluate application of results to users. Integrated research and demonstration efforts will produce a management guide with focus on environmental and economic benefits, site identification, water supply, engineering design, construction, and system operation and management. Several professional papers were completed and presented in 1999 and others are accepted for presentation and submittal in 2000. The overall project and its various sponsors have been summarized in a variety of technology transfer outlets and outreach publications. We anticipate that our overall project will continue through 2005, and possibly beyond. We seek additional resources to continue our work. References Ascough II, J.C., C. Baffaut, M.A. Nearing and B.Y. Liu. 1997. The WEPP watershed model: I. Hydrology and erosion. Transactions of the ASAE 40(4):921-933. Baumer, O.W. 1989. SCS Soil Parameters Preparation Program for DRAINMOD. DMSOIL User's Manual. USDA-Soil Conservation Service, National Soil Survey Laboratory, Lincoln, NE. 24 pp. Belcher, H.W., G.E. Merva and W.H. Shayya. 1993. SI-DESIGN: A simulation model to assist with the design of subirrigation systems. IN:Proceedings of the ICID Workshop on Subsurface Drainage Simulation Models. The Hague. September 4 and 5, 1993, pp. 295-308. Belmans, C., J.G. Wesseling and R.A. Feddes. 1983. Simulation model of the water balance of a cropped soil: SWATRE. J. Hydrology 63 (1983):271-286. Breve M.A., R.W. Skaggs, H. Kandil, J.E. Parsons and J.W. Gilliam. 1992. DRAINMOD-N: A nitrogen model for artificially drained soils. IN:Proceedings of the Sixth International Drainage Symposium. ASAE. St. Joseph, MI. Publication No. 13-92:327-336. Brown, L.C. and P. Bierman. 1994. Water management strategies for balancing sustained crop production and water resource protection. State Project. Ohio Agricultural Research and Development Center. Ohio State University. Brown, L.C., B.J. Czartoski, N.R. Fausey and H.W. Belcher. 1998. Constructed wetland and subirrigation linkage provides high yield potential and environmentally sound corn and soybean production systems. 524-530. In Proc. of the 7'th International Drainage Symposium. ed. L.C. Brown. ASAE. 738 p. Brown, L.C., E.J. Kladivko and R.F. Turco. 1994. Subsurface drainage impacts on agricultural chemical movement to ground and surface water. In: A.S. Felsot, J.J. Jenkins and N.N. Ragsdale (editors). Pesticide Management: Minimizing Environmental Impacts. Lewis Publishers. (In review). Chung, S.O., A.D. Ward, N.R. Fausey, W.G. Knisel and T.J. Logan. 1992a. An evaluation of the ADAPT water table management model. IN:Proceedings Sixth International Drainage Symposium. ASAE Publication No. 13-92:337-344. Chung, S.O., A.D. Ward and C.W. Schalk. 1992b. Evaluation of the hydrologic component of the ADAPT water table management model. Transactions of the ASAE

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Irrigation Subirrigation Hydrology Water Reuse Wetlands Integrated Wetland and Reservoir Management

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Brown, L.C., Fausey, N.R., Czartoski, B.J., Belcher, H.W., Hothem, J.A., N'jie, N.M., Oztekin, T., Luckeydoo, L., Batte, M.T., Davis, C., Shininger, F., Chester, P., Clevenger, B., Davis, L., Andre, P., Sutton, D. 1999. Marketing wetlands for profit. Journal of Soil and Water Conservation 54(3):606-607. (Extended Abstract – not peer reviewed). Hothem, J.A. and L.C. Brown. 1998. Modeling of water routing in a wetland-reservoir-subirrigation system using SIMULINK. Paper No. 982096. Presented at 1998 ASAE Annual Meeting. ASAE: St. Joseph, MI. 11 pp. L.M. Luckeydoo. 1999. Vegetation Surveys for Constructed Wetlands of the Wetland Reservoir Subirrigation Systems. Presented at the 108th Annual Meeting of The Ohio Academy of Science. OAS 99(1):A-30 (Abstract). Myers, M., Miller, B.A., Jacobs, M., N'jie, N.M., Soboyejo, A., Brown, L.C. 1998. Water column sampling system for the constructed wetland and water supply reservoir at the DARA WRSIS site. Paper No. 982094. Presented at 1998 ASAE Annual Meeting. ASAE: St. Joseph, MI. 10 pp. Oztekin, T., Hothem, J.A., N'jie, N.M., Luckeydoo, L., Mills, G., Brown, L.C., Fausey, N.R., Czartoski, B.J. 1998. Monitoring system for water quality and quantity, and ecological parameters at the DARA wetland-reservoir subirrigation system site. Paper No. 982110. Presented at 1998 ASAE Annual Meeting. ASAE: St. Joseph, MI. 7 pp. Richards, S.T., Batte, M.T., Brown, L.C., Czartoski, B.J., Fausey, N.R., Belcher, H.W. 1998. Farm level economics and capital costs analysis of three wetland reservoir subirrigation system sites in Northwestern Ohio. Paper No. 982020. Presented at 1998 ASAE Annual Meeting. ASAE: St. Joseph, MI. 16 pp. Richards, Steve, Marvin T. Batte, Larry C. Brown, Bernie Czartoski, Norm Fausey and Bud Belcher. 1999. Economics of a Wetland-Reservoir Subirrigation System in Northwestern Ohio. Paper presented at the American Agricultural Economics Association Annual Meetings, Nashville, TN, August 1999. (Peer reviewed). Tornes, L., B.C. Atherton, L.C. Brown, R.M. Gehring, B. Slater, J.R. Steiger, T.L. Zimmerman, N.R. Fausey, G.S. Hall and M. Debrock. 1998. Soil property database for design, construction, operation and management of agricultural water management systems for irrigation, constructed wetlands, drainage, and environmental considerations. Paper No. 982109. Presented at 1998 ASAE Annual Meeting. ASAE: St. Joseph, MI. 16 pp. Zucker, L.A. and L.C. Brown. (Eds.). 1998. Agricultural Drainage: Water Quality Impacts and Subsurface

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Basic Project Information

Basic Project Information	
Category	Data
Title	Nutrient Cycling in Integrated Cropland/Wetland/Reservoir Management Systems
Project Number	C-07
Start Date	09/01/1998
End Date	02/28/2001
Research Category	Water Quality
Focus Category #1	Irrigation
Focus Category #2	Wetlands
Focus Category #3	Nutrients
Lead Institution	Ohio State University

Principal Investigators

Principal Investigators			
Name	Title During Project Period	Affiliated Organization	Order
Larry C. Brown	Associate Professor	Ohio State University	01
Norman Fausey	Professional Staff	Ohio State University	02

Problem and Research Objectives

The Midwestern US comprises the most productive agricultural region in the world. The predominant agricultural management systems in this region receive extensive nutrient inputs. However, most of these management systems do not effectively utilize or retain all of the added nutrients, leading to growing problems with nonpoint source contamination of surface and ground waters. Some of these problems may be exacerbated by traditional technologies for managing soil water. In many parts of the Midwest, soil drainage, the removal of excess water from the surface and profile of cropland soils by either gravity or artificial means, is an indispensable agricultural practice. In areas such as northwestern Ohio, once known as the "Great Black Swamp," water management practices are critically important for continued prosperous agriculture, the quality of Lake Erie water, the local economy, and for the restoration and preservation of wildlife habitat areas. Landowners there are encouraged to utilize technologies for surface drainage, subsurface drainage, and best management practices necessary for sustained agricultural performance and improved water quality. Nevertheless, the quality of Lake Erie water is still affected by nonpoint source agricultural runoff, and is substantially impaired by current cropping management practices combined with traditional, but effective, surface and subsurface water management techniques. Influxes of sediment, nitrogen, phosphorus, and agricultural chemicals are the greatest environmental concerns. Ironically, when the original wetlands were converted to productive cropland through the installation of drainage systems, the ecological capacity of the landscape to filter

sediment, retain nutrients, and purify surface water arising from the new agricultural land was lost. Inventory data indicate that 22 states have lost 50% or more of their original wetlands. In the North Central Region's dominant drainage states of Ohio, Iowa, Indiana and Illinois, over 85% of the original wetland acreage has been lost. Within the eight-county Maumee Valley Resource Conservation and Development Area (RC&D), total wetland loss is estimated at 122,555 acres. Loss of wetlands, as associated with declines in wildlife habitat, adverse effects on water quality, and other impairment of healthy ecosystem function, is an important environmental issue. In typical farming communities of northwest Ohio, 80–90% of all land use is agricultural. Voluntary restoration of wetlands in this area has been minimal, largely due to tradition and economic considerations. For successful adoption by landowners, wetland development must make sense within an agricultural context, and must be cost-effective in the absence of government subsidies. Progressive farmers and their organizations, natural resource conservation agencies, environmental agencies and organizations, and others seek guidance to help society and agriculture better understand how to recreate valuable wetlands, while conserving our existing beneficial wetlands. The development and demonstration of integrated landscape management systems, which combine the productive functions of cropland and improved water use with the ecological functions of wetlands and reservoirs, offer great promise. Exciting and innovative new projects are currently underway to evaluate the management, hydrology, and economics of such cropland/wetland/reservoir (C/W/R) systems. However, critically important questions concerning nutrient cycling through these systems, and their ultimate impacts on water quality, remain to be addressed. There is increasing awareness and excitement about the potential for integrating diverse ecosystem types within a landscape to provide environmental benefits while sustaining agricultural production. Although numerous research programs currently address the potential component functions of particular ecosystems (for example, the 'filtering' capacity of wetlands or riparian strips), very few have attempted to develop truly integrated landscape management systems. One such system, recently implemented in Ohio, combines crop, wetland, and reservoir ecosystems in an innovative closed-loop design by which water and nutrients are recycled within a farm. This innovative, ecologically-sound production system has the potential to greatly reduce the discharge of sediments and agricultural chemicals to streams and improve water quality, to increase wetland area and wildlife habitat, and to recycle water and nutrients for improved crop production and enhanced farm profitability. We are investigating and modeling nutrient cycling dynamics and related water quality impacts of newly developed integrated cropland/wetland/reservoir (C/W/R) landscape management systems in Ohio. Three operational C/W/R landscape management systems function as partially closed loops, through which water and nutrients are recycled among individual component ecosystems (cropland, wetland, water supply reservoir). In these systems, runoff and drainage from cropland is collected and directed through a constructed wetland, and then stored in an on-farm reservoir. During the crop season, the cropland is subirrigated by supplying water from the reservoir back through the subsurface drainage lines beneath the crops. These systems use appropriate, state-of-the-art water table management technologies to achieve goals of improved water quality, increased wetland acres and biodiversity, and enhanced farm profitability. This work builds on established research, demonstration, and education projects in Ohio, and we will provide critical information on the cycling and transport of nutrients in cropland/wetland/reservoir management systems. This work does not duplicate, but builds upon a substantial infrastructure provided by two existing projects that 1) demonstrate construction and management (funded by USEPA et al.), and 2) evaluate hydrology and economics of C/W/R systems for corn and soybean production on field-sized areas (Economic and Hydrologic Analysis of Integrated Wetland-Reservoir and Subirrigated Agricultural Production Systems, Brown and Batte, funded by WRRI in 1997). Funds from USEPA are currently being used to demonstrate the construction and management of cropland/wetland/reservoir systems at three sites in Ohio. The existing demonstration project funded by USEPA/GLNPO demonstrates construction and management of permanent wetland/reservoirs linked directly to subirrigated corn and soybean production systems on field-sized

areas in the Maumee River basin in Ohio. The demonstration project is managed by a team of farmers, local, state and federal agency personnel, university faculty, the drainage industry, and others, including Dr. Brown and Dr. Fausey (Co-PIs on the new work). The construction, management, and instrumentation phases are fully funded. Three systems are fully operational. Each site has a subirrigated C/W/R system area, and a conventionally subsurface drained (not subirrigated) comparison area. Each site offers some unique characteristics that, when combined over all three sites, allow excellent research opportunities over a range of conditions. Research funded in 1997 by WRRI (Brown and Batte) is evaluating the hydrology and economics of these systems. For the research on hydrology and economics of these systems, the objectives are: 1) to characterize, analyze, and model hydrologic interactions in subirrigated cropland/wetland/reservoir systems, 2) to evaluate farm-level economics of these systems, and 3) to develop a technical design and system management guide for these systems, and to conduct an applications and design workshop to teach agricultural producers and consultants how to use water table management for environmental and economic benefits. This new work adds a missing, yet essential, component of research (nutrient cycling) to the evaluation of the functioning and environmental impacts of these systems. The new project takes advantage of this existing research program, and extends it to include detailed characterization and preliminary modeling of nutrient stocks and flows within and among the component ecosystems of the C/W/R management system. Such an ecosystem analysis is critically essential for understanding the functioning and potential environmental impacts of these systems. The specific objectives of the new project are stated below, each with a summary statement. Research Objectives Objective 1: To quantify the cycling and transport of nutrients (soluble and sediment bound) within and between the ecosystem components of existing cropland/wetland/reservoir landscape management systems. We have begun to collect hydrologic and economic data from three C/W/R management systems (all three systems are managed by farmers). However, detailed information on nutrient cycling is lacking. Assessing inputs, storage, and outputs of critical nutrients, such as nitrogen, carbon, and phosphorus, and interactions with sediments for each component ecosystem, as well as for the whole system, is essential for understanding system function and for evaluating potential water quality and crop production benefits. We are building upon our success in a related project in southern Ohio where we recently developed system level nitrogen budgets for a subirrigated/controlled drainage system, a central component of the C/W/R landscape management system. Objective 2: To initiate the development of a preliminary system-level model of nutrient flows and recycling for cropland/wetland/reservoir landscape management systems. Data on nutrient stocks and flows generated from the first objective will allow us to initiate the construction of preliminary system-level models of nutrient cycling. Coupled with hydrologic models currently being developed for the system, these models will eventually aid in understanding overall system function, and will allow us to evaluate different management scenarios in a future stage of the project. Such models can also be powerful tools for communicating principles of system design and operation to engineers, natural resources managers and technicians, farmers, and other end-users. Clearly, the market for these technologies is well established.

Methodology

Overall Approach The overall approach is an ecosystem analysis of nutrient stocks and flows within and among each of the components of the C/W/R system. Over the funded study period, quarterly estimates will be made of total ecosystem nutrient stocks (C, N, P), and nutrient and sediment inflows and outflows will be measured on a continuous basis with automated sampling equipment (equipment is funded). This information will be used to initiate the preliminary construction of simulation models that will allows us eventually to assess system function and water quality impacts over a range of management scenarios. Existing Funded Demonstration Project The new research is focusing on three constructed and operational sites: Defiance Agricultural Research Association (DARA) site (near

Defiance County airport and weather station); Fred Shininger farm (Fulton County); and Marsh Foundation (Van Wert County, Farm Focus Site). The most intensive research and evaluation will be conducted at the DARA site. Each site consists of a subirrigated area for corn and soybean production, a constructed wetland, and a constructed upground reservoir (or existing pond). Runoff and subsurface discharges from adjacent cropland are routed to the constructed wetland. Water from the wetland is pumped to the upground reservoir where it is stored for water supply. During the crop season, water is pumped into the subirrigated cropland, where a water table is held at a 14- to 20-inch depth throughout most of the growing season. Each site has numerous locations to measure and sample surface and subsurface flows, subirrigation water use, runoff, etc. The DARA site is currently being instrumented so that water flow rates and volumes can be measured, and sediment and water samples can be collected for each component of this integrated system. Complete details of the currently funded components are summarized by Brown and Batte's WRRI project. Approach for Objective 1: To quantify the cycling and transport of nutrients (soluble and sediment bound) within and between the ecosystem components of existing cropland/wetland/reservoir landscape management systems. Total stocks of carbon, nitrogen, and phosphorus will be estimated for each component ecosystem at least 4 times per year. The first sampling event was initiated in June 1999. In the crop systems, estimates will be based on soil and vegetation samples; in the constructed wetlands, on soil/sediment, water, and vegetation samples; and in the reservoirs, on sediment and water samples. Soil samples will be taken in the crop systems to the depth of the drainage tiles (approx. 75 cm) using a soil probe, separated into 0-15 cm and 15-75 cm depths, and analyzed at the Ohio State University Soil Ecology Laboratory for total and available C, N, and P. Total nutrient contents in the soil profile will be determined one time each year, as they are unlikely to change significantly during this time. However, available (extractable) concentrations of C, N, and P are likely to be much more dynamic, and represent a large fraction of the mobile nutrients that are available for crop uptake, transport between compartments, or loss from the system. Concentrations of nitrate, ammonium, phosphate, and dissolved organic C, N and P will be determined four times a year (early spring, after fertilization, at harvest, mid-winter). In the wetland, soil sampling will be conducted similarly, except that cores will only be taken to the effective rooting depth of the aquatic vegetation, and samples of deposited sediments will be taken separately. In the cropland and wetland systems, vegetation samples will be taken twice annually (spring and fall) to allow estimates of standing stocks and uptake of nutrients during the growing season. Water samples from the wetlands and reservoirs will be taken, on an hourly to a weekly basis depending upon rainfall and runoff events, using standard sampling bottles and techniques. Additional water samples to meet the specific needs of the proposed work will be also taken. Total C and N concentrations in soil, sediment and vegetation samples will be determined using a Carlo-Erba C/N analyzer, total P will be determined colorimetrically following acid digestion. Nitrate, ammonium, and phosphate in extracts and water samples will be determined colorimetrically using microplate methods; dissolved organic carbon will be determined using a Dohrmann TOC/DOC analyzer, and dissolved organic N and P will be determined colorimetrically following persulfate digestion of liquid samples. Monitoring of water levels and flows from each system compartment will be conducted as a part of the currently funded WRRI project. Runoff and subsurface discharge will be monitored and evaluated before, during and after selected storm events (hopefully 10 to 20 storm events annually), and during selected less-dynamics times throughout the year. One-liter water samples will be collected during flow events. All samples required for the proposed project will be analyzed for nitrate and soluble phosphorus, and for dissolved organic C, N, and P at OSU's Soil Ecology Laboratory and Environmental Chemistry Laboratory. All concentration data will be analyzed on a flow-weighted basis. Sediment samples will be analyzed by gravimetric methods, and for total C, N, and P contents. Sedimentation rates are already being assessed seasonally and annually. Inflows and outflows from each flow control point will be measured at the time of sampling using automatic flow rate and volume measurement devices (already funded). Rainfall at each site will be measured using manually read rain gauges; a weather station is being installed at the DARA site (funded), and local weather records are available in each county. Crop growth and production characteristics will be

measured during each crop season. Crop yield, crop production management, tillage, and nutrient and pesticide application data will be collected from each cooperator. This will allow estimation of total nutrient imports and exports to the crop system through fertilizer inputs and harvested grain. Estimates of respiratory losses of carbon and inputs of nitrogen through fixation by the soybean crops will be based on literature values for comparable cropping systems; estimates of losses of nitrogen through denitrification from the crop systems and wetlands will be based on literature values and on results of plot-level research on other subirrigated systems in Ohio currently being conducted by the PIs. Approach for Objective 2: To initiate the development of a preliminary system-level model of nutrient flows and recycling for cropland/wetland/reservoir landscape management systems. We have begun the identification and evaluation of several system-level budget and ecological simulation models. Eventually, we will possibly modify one or more of these models using our data on nutrient stocks and flows from the component ecosystems, as well as our data from the southern Ohio research. We have had great success developing system-level nitrogen budgets for subirrigation/controlled drainage systems in poorly drained soils in southern Ohio. Initially, sediment, carbon, nitrogen, and phosphorus transport at the DARA site will be evaluated using our preliminary simple compartmentalized dynamic simulation models. We eventually hope (with future funding) to evaluate these models linked with more elaborate mechanistic models requiring detailed inputs on soil characteristics, cropping system, meteorological data, etc, collected from the DARA site and then from the other two sites. In conjunction with hydrologic management simulation modeling work (funded), these preliminary system-level models could be used to conduct computer simulations based on long-term climatic records and different management scenarios to evaluate the nutrient recycling and crop production potential of C/W/R systems under various scenarios and at different locations throughout the Midwest. Currently, DRAINMOD-N, ADAPT (Agricultural Drainage and Pesticide Transport), and GLEAMS are three such models that have the capability to model nutrient cycling and water table management scenarios. For the funded WRRI project (Brown and Batte) ADAPT will be used to model erosional processes and nitrogen and phosphorus transformations and transport (based upon algorithms adapted from GLEAMS). Because of its wider acceptance throughout the US to evaluate the hydrology of agricultural land use areas and wetland hydrology, and its relatively new nitrogen component, DRAINMOD-N will be used in addition to ADAPT. For conditions at all sites, our expected results from the proposed project on nutrient cycling will easily feed into, and enhance predictions from the funded, long-term simulation work that will be used to develop matrices of crop yield, nitrogen and phosphorus transport relationships. Technology Transfer Objective (taken from Brown and Batte, found elsewhere in this report): Develop a technical design and management guide for subirrigated agricultural production and constructed wetland-reservoir systems, and conduct an applications and design workshop to teach agricultural producers and consultants how to use water table management for environmental and economic benefit. Although the technology transfer objective was not explicitly stated in the new project proposal, the new work is very strongly connected to the overall project, and thus to the technology transfer objective. All research and demonstration results will feed into management guide development, with a primary focus on environmental and economic benefits of water table management and constructed wetlands, site identification, water supply, engineering design, construction, and system operation and management. All aspects of the overall project feed into Dr. Brown's educational activities conducted cooperatively by Ohio State University Extension, the demonstration project and its cooperators and technical advisors, and the Overholt Drainage Education and Research Program at The Ohio State University. Outreach is also linked to activities of the new regional NCR Project 195 "Mississippi River Watershed Nutrient Sources and Control." Previously, Brown and Batte predicted that results from all components of the overall project would have implementation implications for the entire Midwest, and within the past year researchers and technical agency personnel from across the Midwest have expressed an interest in developing a new future project with a comprehensive regional application of this technology.

Principal Findings and Significance

This project is strongly linked to the 1997 WRRI funded project Economic and Hydrologic Analysis of Integrated Wetland-Reservoir and Subirrigated Agricultural Production Systems (Brown and Batte), and the Marketing Wetlands for Profit project funded by USEPA and others (MVRCD, 1999). Background information and many additional details regarding the overall project and the work related to the current project are presented in the Brown/Batte materials found elsewhere in this report. Duplication of these materials below was minimized. The project initiated funding (WRRI and state or other federal funds) for one Ph.D. student (N'Jie) in January 1999 and one M.S. student (Kemerer) in April 1999, and several undergraduates. Both students are in the University's Environmental Science Graduate Program. An additional Ph.D. student Luckeydoo (funded through another federal source) is conducting research on vegetation composition and development of constructed wetlands receiving agricultural drainage. In December 1998, Dr. Subler joined a consulting firm in Washington State, and is no longer contributing to the project on a regular basis. Below is a summary of research activities relevant to the current project regarding nitrogen, carbon, and phosphorus cycling, plant biomass, and sediment that is being addressed at the DARA site in Defiance County by N'Jie and Kemerer. The key summaries are: monitoring system at DARA, water flow and storage monitoring, and transport and storage monitoring of nutrients and sediment. The reader is referred to the Brown/Batte materials elsewhere in this report for additional information. Monitoring System at DARA An extensive monitoring program was implemented at the DARA site to monitor and analyze the overall performance of the system. About 90% of the construction and installation of instrumentation was completed by May 2000. It is only within the past year that much of the WRSIS monitoring program has been initiated. As such, not enough time has yet elapsed to see the long-term trends in movement and storage of water, sediment, nutrients, and pesticides that will aid in fine tuning the management of WRSIS sites. The monitoring program now in place is designed to provide valuable information for at least the next five years and hopefully longer. Hydrological, agricultural, environmental, and ecological focus areas include: determination of system water balance; water routing for water conveyance, storage and water supply; subirrigation water requirements for corn and soybean production; operation and management of system components; farm-level economics; sediment routing and trapping; nutrient and pesticide fate and transport; plant community development and diversity, wetland vegetation, and vegetative habitat for wildlife; net water, sediment, nutrient, and pesticide losses off-site. The ecological impact of the system is also being analyzed through the monitoring of the diversity of the vegetative growth in and around the wetland and the monitoring of aquatic macro-invertebrates within the wetland. The flow monitoring components of the system measures and records data for six different categories of measurements: climatological, surface flow, partial-pipe flow, pressure pipe flow, water table depths, and impoundment and pump station water levels. A weather station was installed in order to measure and log various climatological parameters. Three H- and HS-flumes and two V-notch weirs were installed in order to allow for measuring surface flow rates at several locations at the site. Flow through these devices will be measured using either area-velocity sensors or submerged probe sensors. There are five locations at the site where flow in pipes with normally partial-pipe flow conditions needs to be measured: the outflow pipe from the east subirrigated zone, the outflow pipe from the west subirrigated zone, the outflow pipe from the wetland to the wetland pump station, the off-site drainage main that empties into the wetland pump station, and the emergency outlet pipe. At these locations, area-velocity sensors were installed in order to measure the flow rate. Pressure pipe flow from the wetland pump station to the supply reservoir and from the supply reservoir to the subirrigated zones will be measured using clamp-on ultrasonic flow transmitters. Eight water table wells were installed within the subirrigated zones. Water table levels within these wells are measured using pressure transducers. Pressure transducers were also installed within the constructed wetland, wetland pump station, and

supply reservoir in order to measure the water levels there. Additional details are summarized below from those prepared by B.A. Allred in MVRCD (1999). Water Flow and Storage Monitoring The DARA site schematic map provided in Figure 1 shows the points where the weather station, the three flumes, and the eleven automatic water samplers have been placed. Attached to each sampler is a sensor for measuring water flow. A weather station manufactured by Campbell Scientific was installed to measure rainfall, wind speed and direction, solar radiation, air temperature, and relative humidity every 2 minutes. Precipitation values determine the amount of water added to the site. All other weather variables are used to calculate wetland/reservoir/cropland evapotranspiration rates. A U. S. Weather Bureau Class A evaporation pan containing a water level probe was likewise setup to provide redundant measurements for evapotranspiration calculations. The water level probe within the Class A pan is connected to the weather station data logger. Three flumes and two v-notch weirs are used to measure runoff coming into the wetland itself or the adjacent area to the north that surrounds the pump station (Figure 1). The flumes were manufactured by Plasti-Fab and are made from fiberglass reinforced thermoplastic polyester. One is a 2 ft. H flume and the other two are 1 and 0.4 ft. HS flumes. On the inside bottom of the H flume is a mounting plate for an ISCO 750 Low-Profile Area-Velocity Module that measures flow. For redundant flow measurements, the H flume also has an attached 8 in. stilling well upon which a Belfort FW1 water level recorder is mounted. Both HS flumes use an ISCO 720 Submerged Probe for determining flow rates. To allow continued operation during colder months, the flumes were winterized by constructing an insulated enclosure around them containing a ceramic space heater. One of the two v-notch weirs was placed on the downstream side of the site outlet control structure and the other within the west wall of the 2 ft. high sheet metal barrier surrounding the wetland pump station. Calculation of flow through a v-notch weir requires measurement of water depth at a point upstream. An ISCO 720 Submerged Probe installed within a 3.5 ft. tall, 1 ft. diameter PVC stilling well provides the water depths needed for determining flow through both weirs. Water flow is also measured within the underground pipe and drain network at the DARA site (Figure 1). An ISCO 750 Low-Profile Area-Velocity Module is used to monitor flow rates where partially filled pipe conditions exist. Partial pipe flow is found between the wetland control structure and wetland pump station, within the two main lines connected to the east and west subirrigated fields, downstream of the site outlet control structure, and within the main line from the control plots (Figure 1). Scientific-Pittsburg/Panametrics Model XMT868 Ultrasonic Flowmeters are employed for fully filled pipes containing water under pressure, such as the 4 in. diameter line coming into the reservoir and the 2 in. diameter line leaving it. The ultrasonic flow sensors clamp onto the outside of the two pipes, thereby requiring emplacement underground of a large concrete box structure near the reservoir to house these instruments for easy access. As previously stated, all flume, v-notch weir, and pipe flow sensors are connected to automatic water samplers. Figure 1. Schematic of the DARA site showing hydraulic structures and water flow monitoring points. WRSIS water storage occurs in the wetland, reservoir, and subirrigated fields. Water level measurements determine the amount stored within each of these three components. For the subirrigated fields, this level, called the water table, is managed according to crop needs. Drain pipes, main lines, and control structures are used to raise the water table into the root zone when there is a soil moisture deficit and to lower it during wet periods. Pressure transducer water level probes manufactured by Electronic Engineering Innovations were installed in monitoring wells to obtain continuous measurements of the water table elevation. The monitoring wells extend 5 ft. into the subsurface and are comprised of 4 in. diameter slotted schedule 40 PVC pipe. To reduce the possibility of runoff entering the well, a 4 ft. by 4 ft. plastic apron was laid around it at a depth of 6 in. Also, open slots close to the ground surface were taped over followed by surrounding this portion of the PVC pipe with a bentonite seal. There are eight monitoring wells at the DARA site. For both the east and west subirrigated fields, two wells are placed within 1 ft. of a drain line and two are placed at a midpoint between drain lines. Positioning the wells in this manner allows for observation at any time of both the maximum and minimum water table elevations, regardless of whether the system is in drainage or subirrigation mode. Similar probes are also being used to measure surface water elevations in the

wetland and reservoir. The wetland probe is placed in the bottom of the multi-port sampling mast (described later), and like the monitoring well probes, it is connected to the weather station data logger. Since water levels between the two are equivalent, the probe monitoring the reservoir is actually placed in the bottom of the adjacent pump station and connected to a separate Electronic Engineering Innovations data logger. Transport and Storage Monitoring of Nutrients and Sediment At each point on the DARA site where a flow measuring sensor has been placed (ISCO 750 Low-Profile Area-Velocity Module, ISCO 720 Submerged Probe, or Scientific-Pittsburg/Panametrics Model XMT868 Ultrasonic Flowmeter), water samples are automatically collected with an ISCO 6700 Portable Sampler. These samplers hold twenty-four wedge-shaped 1 L bottles. The ISCO 6700 Portable Samplers are activated by the flow sensors during storm and pumping events. To allow for winter sampling, the water collection tubing has been buried underground in 2 in. plastic conduit, and the samplers themselves enclosed within foam insulated barrels containing thermostat controlled heating tape. All automatic water samplers are run off direct power with battery back-up Wetland and reservoir water column samples are collected via multi-port sampling masts. This system was adapted from a prototype sampling system designed by our undergraduate engineering students as a design exercise in 1998. In late 1999, the column system was installed and operational and selected data have been collected using these systems. The mast is a stick of 12-in i.d. corrugated, smooth inside-wall, polyethylene PE tubing. Each mast is sized length-wise to stand vertically in the wetland or reservoir from the bottom of the water column to one foot above the water surface in each basin. Slotted PVC strainers protruding outwards from the mast were installed at each port to remove large debris material during sampling. The ports are vertically spaced either 0.5 or 1 ft. apart. The 0.5 ft. spacings were used near the bottom of the mast and 1 ft. spacings at the top. Plastic tubing was connected to the back of each strainer and strung through the inside of an upright, 1 ft. diameter, corrugated plastic pipe to an outlet at the bottom. A 4 or 6 in. diameter corrugated flexible plastic pipe was then used to carry the sample tubing bundle from the bottom of the mast to the shore of the wetland or reservoir. With a peristaltic pump, water can be drawn through each tube thereby allowing samples to be obtained at different levels within the wetland or reservoir. Wetland/reservoir sampling events take place weekly. The wetland sampling mast is 5.5 ft. tall and that for the storage reservoir is 13 ft. Both were placed in the deepest part of the wetland or reservoir and supported by an attached 2 in. diameter vertical steel pipe which had been driven 3 ft. into the bottom sediment. Additional support for the reservoir sampling mast is provided by four plastic-coated steel cables connected to the top of the mast and anchored into the shoreline. Water was drained out of the wetland in order to install its mast, while placement of the reservoir mast required the use of a floating platform. Water sample analysis provides crucial information on nutrient and sediment cycling at the DARA WRSIS. Both filtered and unfiltered portions are chemically analyzed for all water samples collected from the wetland/reservoir masts, and by the ISCO automatic samplers. Unfiltered portions are tested for total nitrogen, total phosphorous, and total organic carbon. Filtered portions are analyzed for pH, total filterable solids (< 0.22 m), inorganic carbon, dissolved organic carbon, nitrate, ammonia, total nitrogen, dissolved phosphorous, and total phosphorous. In order to further gauge nitrogen, phosphorous, and carbon cycling within the DARA WRSIS, soil/sediment and vegetation samples are also taken. Cropland soil samples are collected three times a year; before planting (May/April), after fertilization (July), and after harvest, and are obtained in both subirrigated fields and adjacent control plots. During sampling events, soil cores from the surface to a depth of 75 cm are extracted, and sections from 0-15 cm, 15-30 cm, and 30-75 cm analyzed separately. Sediment cores beneath the wetland are obtained at the same three times of the year that cropland soil sampling is conducted. For the wetland, 30 cm deep sediment cores from beneath the basin are extracted, and sections from 0-8 cm, 8-16 cm, and 16-30 cm analyzed separately. Chemical sample analysis then provides cropland/wetland subhorizon estimates for pH, total and available carbon, nitrogen, and phosphorous, nitrate, ammonia, soluble phosphate, dissolved organic carbon, dissolved organic phosphorous, and dissolved organic nitrogen. Cropland vegetation (corn and soybeans)

sampling at the beginning of the growing season and just before harvest is being conducted in both the subirrigated and control fields. The same sampling schedule is also being used with regard to wetland vegetation. All vegetation samples are analyzed for total nitrogen, phosphorous, and carbon content. The wetland vegetation sampling by N'Jie and Kemerer is integrated with that of Luckeydoo. Crop yields have been collected at each of the three sites; four years at Shininger, and three years at DARA and Marsh. The crop yield results at each site (prepared by R.L. Cooper for MVRCD, 1999) are summarized in the Brown/Batte materials. The field sampling schedule was developed and implemented in spring 1999, and laboratory analysis of many field soil and water samples is well underway. We anticipate water and soil sampling to continue through 2001. Preliminary results from some selected analysis of nitrogen, phosphorus, and wetland vegetation sampling at DARA in 1999 follows. Nitrogen: Initial findings revealed that for February through May, 1999 (grab samples), the average nitrate N (NO3-N) and ammonium N (NH4-N) concentration in runoff entering the wetland was 0.83 and 0.15 mg/L, respectively. Over the same period, the average concentration of NO3-N and NH4-N in the subsurface drainage entering the wetland was 11.39 and 0.00 mg/L, respectively. For June through August, 1999 (automated sampling), the average NO3-N and NH4-N concentration in runoff entering the wetland was each 0.03 mg/L. The average NO3-N and NH4-N concentration in subsurface drainage entering the wetland was 0.94 and 0.01 mg/L. Samples and data yet to be reduced should help us evaluate the reduction in N loads that were previously lost to nearby streams. Phosphorus and Sediment: The reservoir and wetland both exhibited sediment and phosphorus retention. A significant increase in the total filterable solids was found between the surface and bottom waters of the reservoir (p=0.03), but not in the wetland. Total phosphorus levels were lower at greater depths in drained-only plots and higher in subirrigated plots, suggesting that transport of phosphorus through the soil profile was not enhanced by subsurface drainage. Wetland Vegetation: Case studies of terrestrial and aquatic vegetation development and structure with passive revegetation on the constructed wetland sites were conducted using a seasonally permanent plot technique, and observations were made using Braun-Blanquet scales. Diversity was calculated using Simpson's and Shannon-Wiener indices. The Defiance County site had the highest species richness in 1998 at 51 species, with 33% being wetland indicator species. In 1999, species richness in Defiance County decreased to 31 species with 35% considered wetland indicator species. Seed bank analysis of the Defiance location soils showed a potential of seven additional wetland species not present during the 1998 field surveys. The examination of the seed bank identified needed wetland modifications for the Defiance County site, where a mudflat component was added in early 1999. Results thus far indicate that, over time and with careful management of the hydrology, there is potential for inclusion of additional wetland species. Summary The monitoring system at DARA will allow us to measure and monitor system parameters necessary to fully evaluate the benefits, operation and management, and economics of the system and its components for the next five to ten years. The monitoring system will provide data that shows the dynamics of the linked system. It will allow for analysis of how effective the systems are at achieving the stated objectives of the WRSIS sites. It will also provide information that could be used in the optimization of the design and management of the systems, so that they are better able to meet the stated objectives. Information collected through monitoring of WRSIS components will be used to evaluate benefits, determine the best operation and management strategies, gauge economic viability, and establish the overall environmental impacts of a number of such systems within a larger watershed scale. To help in this regard, a database has been initiated for maintaining WRSIS monitoring information in a format easily accessible to all project collaborators. Many of the ongoing project goals will be addressed using database information as input for computer modeling programs. Results from this research will help characterize ecological processes and management factors that influence transport and storage of nutrients in and out of integrated cropland/wetland/reservoir landscape management systems. Ultimately we will use our results to develop an assessment of the actual reduction of plant nutrients normally lost to receiving waters, establish the potential benefits/impact of these systems on nutrient fate at a local level, and subsequently forecast to a small watershed scale. Our expected results will certainly extend

well beyond those to be determined by the recently completed WRRI funded research of Brown and Batte (see elsewhere in this report). Our research is very important for building a foundation for future GIS/remote sensing and watershed modeling research that can evaluate various application scenarios and predict environmental impacts on watershed and regional scales. This innovative, ecologically sound crop production system will recycle runoff and drainage waters, reduce runoff, sediment, and agricultural chemical discharges to streams, improve water quality, increase wildlife habitat, increase wetland acres, and enhance farm profitability. The demonstration project team (farmers, state and federal agency personnel, university faculty) will provide high level input to proposed research and help evaluate application of results to users. Integrated research and demonstration efforts will produce a management guide with focus on environmental and economic benefits, site identification, water supply, engineering design, construction, and system operation and management. References 1. Backlund, V.L., E.A. Ross, P.H. Willey, T.L. Spofford and D.M. Renner. 1995. Effect of agricultural drainage on water quality in humid portion of Pacific Northwest. J. Irrig. and Drain. Engrg., ASCE 121(4):289-291. 2. Brown, L.C., E.J. Kladivko and R.F. Turco. 1998. Subsurface drainage impacts on agricultural chemical movement to groundwater and surface water. In Pesticide Management: Minimizing Environmental Impacts. Lewis Pub. (in final editorial). 3. Davenport, L.A., Jr., W.D. Lembke and B.A. Jones, Jr. 1975. Denitrification in laboratory sand columns. Trans. ASAE 18(1):95-99,105. 4. Evans, R.O., R.W. Skaggs and J.W. Gilliam. 1995. Controlled versus conventional drainage effects on water quality. J. Irrig. and Drain. Engrg., ASCE 121(4):271-276. 5. Fausey, N.R., L.C. Brown, H.W. Belcher and R.S. Kanwar. 1995. Drainage and water quality in the Great Lakes and Cornbelt states. J. Irrig. and Drain. Engrg., ASCE 121(4):283-288. 6. Kimmelshue J.E., J.W. Gilliam and R.J. Volk. 1995. Water management effects on mineralization of soil organic matter and corn residue. Soil Sci. Soc. Am. J., 59:1156-1162. 7. Madramootoo, C.A., G.T. Dodds and A. Papadopoulos. 1993. Agronomic and environmental benefits of water-table management. J. Irrig. and Drain. Engrg., ASCE 119:1052-1065. 8. Maumee Valley Resource Conservation and Development Area (MVRCD). 1999. Marketing Wetlands for Profit, Final Report. Submitted to USEPA. 9. Ritter, W.F., R.P. Rudra, P.H. Milburn and S. Prasher. 1995. Drainage and water quality in Northern United States and Eastern Canada. J. Irrig. and Drain. Engrg., ASCE 121(4):296-301. 10. Shirmohammadi, A., R.D. Wenberg, W.F. Ritter and F.S. Wright. 1995. Effect of agricultural drainage on water quality in Mid-Atlantic states. J. Irrig. and Drain. Engrg., ASCE 121(4):302-306. 11. Skaggs, R.W., M.A. Breve and J.W. Gilliam. 1995. Hydrologic and water quality impacts of agricultural drainage. Crit. Rev., Environ. Sci. and Tech., 24:1-32. 12. Skaggs, R.W. and J.W. Gilliam. 1981. Effect of drainage system design and operation on nitrate transport. Trans. ASAE 24(4):929-934, 940. 13. Thomas, D.L., C.D. Perry, R.O. Evans, F.T. Izuno, K.C. Stone and J.W. Gilliam. 1995. Agricultural drainage effects on water quality in Southeastern U.S. J. Irrig. and Drain. Engrg., ASCE 121(4):277-282. 14. Walker, S.E., S. Kim, N. Jiang, G.F. McIsaac, J.K. Mitchell, M.C. Hirschi and R.A.C. Cooke. 1998. Modeling water quality in tile-drained watersheds. Pps. 236-241. In: Drainage in the 21st century: Food Production and the Environment. L.C. Brown (Ed.). ASAE Publication No. 02-98. ASAE:St. Joseph, MI. 15. Willardson, L.S., B.D. Meek, L.B. Grass, G.L. Dickey and J.W. Bailey. 1972. Nitrate reduction with submerged drains. Trans. ASAE 15(1):84-85, 90. 16. Zucker, L.A. and L.C. Brown. 1998. Agricultural Drainage: Water Quality Impacts and Drainage Studies in the Midwest. The Ohio State University. 40 Pp.

Descriptors

Agroecosystems Nutrient Cycling Integrated Cropland/Wetland/Reservoir Management Systems Wetlands Irrigation Ponds

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Water Resources Research Institute Reports

Conference Proceedings

Brown, L.C., B.J. Czartoski, N.R. Fausey, and H.W. Belcher. 1998. Integrating constructed wetlands, water supply reservoirs, and subirrigation into a high yield potential corn and soybean production system. In: Proceedings of the 7th International Drainage Symposium. Vol. 7:02-98, ASAE: St. Joseph, MI. Pp. 523-529. L.C. Brown, N.R. Fausey, B.J. Czartoski, H.W. Belcher, J.A. Hothem, N.M. N'Jie, T. Oztekin, L. Luckeydoo, M.T. Batte, C. Davis, Fred, Marge, and Bill Shininger, P. Chester, B. Clevenger, L. Davis, P. Andre, D. Sutton. 1999. Marketing Wetlands for Profit. Pp. 85-86 In Meeting Program/Proceedings of the Annual Meeting of the SWCS, August 8-11, 1999, Biloxi, Louisiana. 216 pp.

Other Publications

Brown, L.C., Fausey, N.R., Czartoski, B.J., Belcher, H.W., Hothem, J.A., N'jie, N.M., Oztekin, T., Luckeydoo, L., Batte, M.T., Davis, C., Shininger, F., Chester, P., Clevenger, B., Davis, L., Andre, P., Sutton, D. 1999. Marketing wetlands for profit. Journal of Soil and Water Conservation 54(3):606-607. (Extended Abstract – not peer reviewed). L.M. Luckeydoo. 1999. Vegetation Surveys for Constructed Wetlands of the Wetland Reservoir Subirrigation Systems. Presented at the 108th Annual Meeting of The Ohio Academy of Science. OAS 99(1):A-30 (Abstract). Myers, M., Miller, B.A., Jacobs, M., N'jie, N.M., Soboyejo, A., Brown, L.C. 1998. Water column sampling system for the constructed wetland and water supply reservoir at the DARA WRSIS site. Paper No. 982094. Presented at 1998 ASAE Annual Meeting. ASAE: St. Joseph, MI. 10 pp. Oztekin, T., Hothem, J.A., N'jie, N.M., Luckeydoo, L., Mills, G., Brown, L.C., Fausey, N.R., Czartoski, B.J. 1998. Monitoring system for water quality and quantity, and ecological parameters at the DARA wetland-reservoir subirrigation system site. Paper No. 982110. Presented at 1998 ASAE Annual Meeting. ASAE: St. Joseph, MI. 7 pp.

Basic Project Information

Basic Project Information	
Category	**Data**
Title	Enhanced Removal of DBP Precursors During Precipitative Softening Through Co-Adsorption Processes
Project Number	C-04
Start Date	09/01/1998
End Date	02/28/2001
Research Category	Engineering
Focus Category #1	Water Supply
Focus Category	Treatment

Focus Category #2	
Focus Category #3	Methods
Lead Institution	Ohio State University

Principal Investigators

Principal Investigators			
Name	**Title During Project Period**	**Affiliated Organization**	**Order**
Harold W. Walker	Assistant Professor	Ohio State University	01

Problem and Research Objectives

The reaction of Natural Organic Matter (NOM) and chlorine during chlorination of drinking water can result in the formation of disinfection by-products (DBPs) such as trihalomethanes and haloacetic acids [ ]. DBPs are probable carcinogens, and short-term exposure can lead to dizziness, headaches, as well as problems associated with the central nervous system. Recent studies have also linked DBPs to increased incidence of miscarriage [ ], rectal and bladder cancer [,], and neural tube birth defects [ ]. As a result of the health effects associated with DBPs, as well as microbial pathogens, nearly 40% of water treatment plants in the United States will have to upgrade their systems by 2001 at an estimated cost of $10 billion [ ]. It is estimated that 80% of water treatment facilities will have to make changes to meet regulatory requirements by the year 2005 [6]. In the state of Ohio, 125 water treatment plants utilize lime softening for the removal of hardness and turbidity [ ]. To be in compliance with upcoming United State Environmental Protection Agency (USEPA) regulations regarding DBPs, these and other lime softening plants around the country will be required to remove 20-30% of the natural organic matter (a major DBPs precursor) present in their source water [ ]. Improvements in the removal of organic matter will most likely be accomplished through alteration of the softening process (so-called "enhanced precipitative softening"), or through the addition of unit operations such as activated carbon. Enhanced softening involves raising the amount of lime added during treatment (roughly 5 to 10 times) and subsequently results in greater chemical costs and the increased production of sludge. Although enhanced softening results in greater precipitation of CaCO3, previous research indicates that even high dosages of lime (200 mg/L) may be ineffective at removing some DBP precursors, especially low molecular weight humic materials such as fulvic acid [ ]. Adsorption of fulvic acid to CaCO3 precipitates during the softening process is low, primarily due to electrostatic repulsion arising from the high negative charge density of fulvic acid and the negatively charged CaCO3 surface. In addition, CaCO3 particles formed during softening have low surface area (5 m2/g) and therefore minimal sites for humic adsorption, compared to other coagulants such as ferric chloride (230 m2/g). While the formation of Mg(OH)2 during softening can aid in removing DBP precursors, the precipitation of magnesium occurs only at high pH, a condition uncommon in most water treatment plants [ ]. In this research, we are investigating means to increase the removal of DBP precursors during lime soda softening. In particular, we are examining whether the adsorption of humic and fulvic acids to CaCO3 precipitates during lime softening can be significantly improved through the "co-adsorption" of synthetic polymers. By co-adsorption, we mean any process by which more than one type of polymer simultaneously or sequentially adsorb to a solid surface. We believe the affinity of disinfection by-product precursors for calcium carbonate precipitates can be increased significantly through co-adsorption, and in particular, by the formation of humic-polymer complexes and/or through the attachment of humic material to polymer-coated CaCO3 surfaces. Specific objectives of this research include; (1) To examine the removal of DBP precursors by lime softening in the presence of a number of different synthetic

polymers. (2) To determine the properties of organic matter and synthetic polymer (e.g., molecular weight, charge, hydrophobicity) that influence DBP precursor removal during co-adsorption. (3) To identify the importance of specific co-adsorption mechanisms that influence organic matter removal during softening, such as precipitate surface modification and organic matter/polymer interactions. Furthermore, a significant component of this work involves the transfer of information to scientists and engineers working in the water treatment field, regulators, and to other water treatment professionals.

Methodology

Adsorption Experiments The adsorption of humic acid onto model $CaCO_3$ particles is being examined in batch experiments. The purpose of these experiments is to ascertain the factors controlling the adsorption of humic substances to $CaCO_3$ particles in a model system. In particular, we are examining the adsorption of humic materials to bare and polymer-coated calcium carbonate particles. We suspect that coating the particles with cationic polymer will significantly improve the adsorption capacity of these materials. These experiments will help elucidate the mechanisms controlling the adsorption of humic materials under different conditions, information important in developing strategies for increasing humic adsorption. To carry out an adsorption experiment, humic acid is diluted into carbonate buffer, $CaCO_3$ particles are added, and then the mixture is incubated for at least 2 hours at 23 *C. Control experiments are carried out to verify that the amount adsorbed does not change significantly after the 2 hour incubation period. The pH at the beginning of each adsorption experiment is adjusted to either 7.5 or 9.5 using either 0.1 M HCl or 0.1 M NaOH. The particles are allowed to reach equilibrium with respect to pH prior to conducting an adsorption measurement. No significant change in pH has been observed over the course of an adsorption experiment. After incubation, the $CaCO_3$ particles are separated from the liquid phase by filtration through sterile 0.22 mm pore size Millex disposable filters (Millipore, Bedford, MA). Control tubes containing humic acid and no $CaCO_3$ particles are treated in an identical manner. In no case has any significant removal of organic matter onto filter media been observed, and therefore, the measured change in organic matter concentration is due solely to adsorption to the surface of the $CaCO_3$ particles. In addition, it has been verified that the filtration step removes all measurable amounts of $CaCO_3$ particles from suspension. The fluid concentration of organic matter, before and after exposure to $CaCO_3$ particles, is determined by measuring UV light absorbency using a UV-VIS 2401PC double beam spectrophotometer (Shimadzu Corporation, MD). The adsorbed amount is calculated by measuring the depletion of organic matter in solution. The adsorption of cationic polymer (polyacrylamide) onto $CaCO_3$ is determined in a similar way. However, the depletion of cationic polymer in solution was determined by measuring the total organic carbon using a total organic carbon analyzer (TOC 5000A, Shimadzu Corporation, MD). The adsorption of humic acid on cationic polymer-coated particles is also determined using the UV-VIS 2401 PC double beam spectrophotometer. Cationic polymer is prepared at high concentration (90 mg/L) using carbonate buffer. Next, 200mm of a 20g/L well-mixed calcium carbonate solution is added to 5 ml of the cationic polymer solution and the mixture is incubated for at least two hours. Following this incubation period, the suspension is centrifuged for at least two hours in order to separate the particles from any cationic polymer remaining in solution. The particles are then resuspended in fresh buffer, exposed to humic acid solution, and the pH adjusted using NaOH or HCl. This mixture is incubated for at least two hours, after which time, the pH of the solution is again checked. The particles are separated from humic acid by filtration through 0.22mm pore size Millex-GV disposable filters (Millipore, Bedford, MA). The depletion of humic acid in solution is monitored spectrophotometrically. Control tubes containing humic acid and no particles are treated in identical manner to ensure that there is no adsorption on to the filter surface. Humic acid concentration is measured at 323 nm, a wavelength where the polymer does not adsorb light. Therefore, the concentration measured by this spectrophotometric technique represents only the contribution due to humic acid. Control experiments verified, however, little desorption of

polymer during the course of an experiment. Electrophoretic Mobility Measurements The electrophoretic mobility of calcium carbonate particles is determined using an electrophoretic light scattering instrument (ZetaPlus, Brookhaven Instrument Corp., NY). These experiments are used to determine the role of electrostatic interactions in controlling the adsorption process. All mobility measurements are carried out at 25 oC and a salt concentration of 0.001 M KCl. The pH of solution is adjusted by adding varying amounts of either 0.1 M NaOH or 0.1 M HCl. Each calculated mobility value represents the average of at least 10 independent measurements.

Principal Findings and Significance

The data in Figure 1 through Figure 4 show the adsorption of humic acid to bare and cationic polymer-coated calcium carbonate particles at two different pH values: 7.5 and 9.5. As can be seen, at high pH the adsorption of humic acid is significantly greater onto the coated particles as compared to the bare particles (Figure 1). The amount of humic acid adsorbed varied with the characteristics of the cationic polymer. Specifically, coating the particles with cationic polymers that have low charge density (5 and 20%) has no significant effect on the amount of humic acid adsorbed. However, the amount of humic acid adsorbed greatly increased when the particles are coated with high charge cationic polymers (35 and 55%). The same trend is observed when particles are coated with low molecular weight cationic polymers, however the overall amount of humic acid adsorbed decreased when compared to high molecular weight cationic polymers (Figure 3). At pH 7.5, the adsorption of humic acid onto bare particles is significantly greater than at pH 9.5 (Figure 2 and 4). The greater adsorption at low pH is due to the lower negative surface charge of the particles at pH 7.5 as compared to pH 9.5. This is confirmed by the electrophoretic mobility measurements (see figure 5). We also observed that there is no measurable effect on humic acid adsorption when coating the particles with cationic polymers for both high and low molecular weight polymers (Figures 2 and 4) at pH 7.5. This is probably a result of low cationic polymer adsorption onto calcium carbonate particles at this low pH (data not shown). These data suggest that coating the $CaCO_3$ particles with a positively charged polymer greatly increases the amount of humic acid adsorption at pH 9.5 (the typical pH in water softening plants). Using these data, the optimum cationic polymer characteristics and dosage for best humic acid removal are being examined. Future work will focus on further examining the effect of polymeric additives on the adsorption of humic substances to $CaCO_3$ particles. In particular, we are currently examining the influence of these cationic polymers on the adsorption of humic acid that is extracted from natural sources. Also, we plan to examine the influence of polymeric additives on the structure of $CaCO_3$ flocs. Floc structure will determine the settling characteristics of $CaCO_3$ particles and therefore will significantly effect the removal of organic matter during softening in large-scale operations. To examine floc structure we will measure the coagulation kinetics of $CaCO_3$ particles by monitoring the change in the mean size of suspensions using a photon correlation spectrometer. We will also directly examine floc structure by transmission electron microscopy. Summary The adsorption of humic acid onto bare calcium carbonate particles was examined at two pH values: 7.5 and 9.5. The amount of humic acid adsorption is significantly greater at pH 7.5 as compared to pH 9.5. Coating the particles, with the cationic polymers significantly enhanced humic acid adsorption at high pH values and the amount adsorbed varies greatly with the cationic polymer charge density and molecular weight. At low pH values there is no measurable effect for coating the particles with the cationic polymer on the amount of humic acid adsorbed. The adsorption of humic acid extracted from natural sources is now being examined. We are also investigating the effect of the cationic polymer additives on the structure of $CaCO_3$ flocs. References Hook J. J., Water Treatment and Examination, 23, 234, 1974 Waller, K., Swan, S. H., DeLorenze, G., and B. Hopkins, Epidemiology, 9, 134 1998. Hildesheim, M. E., et al., Epidemiology, 9, 29, 1997. Cantor, K. P. et al., Epidemiology, 9, 21, 1997. Bove, F. J., et al., "Public drinking water contamination and birth weight, and selected birth defects: A case-control study", New

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Descriptors

Water Treatment Enhanced Coagulation Natural Organic Matter Precipitation Fulvic Acid Calcium Carbonate Disinfection By-Products

Articles in Refereed Scientific Journals

Book Chapters

Dissertations

Water Resources Research Institute Reports

Conference Proceedings

Bob, M. and H. W. Walker, 2000, "Enhanced removal of DBP precursors during precipitative softening through co-adsorption processes", presented at the American Chemical Society, 74th Colloids and Surface Science Symposium, Bethlehem, PA, June 19-21, 2000.

Other Publications

Basic Project Information

Basic Project Information	
Category	**Data**
Title	Sonochemical Remediation of PCB Contaminated Sediments
Project Number	C-05
Start Date	09/01/1998
End Date	02/28/2001
Research Category	Engineering
Focus Category #1	Toxic Substances
Focus Category #2	Sediments
Focus Category #3	Treatment
Lead Institution	Ohio State University

Principal Investigators

Principal Investigators			
Name	**Title During Project Period**	**Affiliated Organization**	**Order**
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Yu-Ping Chin	Associate Professor	Ohio State University	02

Problem and Research Objectives

In December 1997, EPA released the report, "The Incidence and Severity of Sediment Contamination in Surface Waters of the United States" documenting the severity of sediment contamination. Of the 96 Areas of Probable Concern, 39 are located within nine states in the North Central Region, many contaminated with polychlorinated biphenyls (PCBs) (US EPA, 1997b) . For example, the Ottawa River in Ohio has a fish consumption advisory in effect due to PCB levels more than 30 times the USFDA health standard for fish filets. Moreover, the EPA estimates that in the United States approximately 10% of the sediment underlying surface waters is sufficiently contaminated to pose risks to fish, humans, and wildlife (Bolattino and Tuchman, 1993) . It is difficult to treat sediments or soils because the sorbed hydrophobic contaminants are less accessible. Currently, capping the sediments in place or extraction and removal to a hazardous waste landfill is the most common method of treatment. However, the contaminants are not destroyed and pose a potential future risk. Moreover, episodic events such as storms and ships may compromise the capping material (by re-suspension) which could potentially mobilize the contaminants. One of the EPA's four goals for managing contaminated sediment is to better understand the fundamental processes involving contaminated sediment and to develop solutions (US EPA, 1998) . Ultrasonic irradiation of contaminated sediments may provide an on-site treatment technology that removes the contaminant from the sediment and subsequently destroys the contaminant through sonochemical oxidation. Research into the fundamental factors affecting sonochemical remediation of contaminated sediments will increase the understanding of this potential treatment process as well as lend insight into the factors affecting desorption of contaminants from sediments. The development of this treatment technology will provide an alternate solution to existing sediment remediation technologies. Existing treatment technologies such as capping have the limitation that the pollutants are not destroyed and pose a future risk. Incineration is also used, but is prohibitively expensive and labor intensive. Conversely, sonication of sediments can be performed on a ship, does not require dewatering, and since sonication destroys the contaminants, the sediments can be replaced after treatment. The proposed process is potentially more energy efficient and environmentally benign than conventional sediment remediation technologies. The purpose of this project is to investigate the application of ultrasound to sediment polluted with PCBs. PCBs are an EPA priority pollutant and persist in the environment due to their unreactive nature. They are extremely hydrophobic and tend to partition from the aqueous phase to the gas or solid phase. Ultrasound applied to polluted sediment is a two-step process. First, the physical effects of acoustic cavitation have the potential to clean the sediment surface by the jets of imploding cavitation bubbles impinging on the particles and shear forces from microstreaming near the particle surface. Then, the PCBs will preferentially partition to the cavitation bubble (due to its high octanol/water partitioning coefficient (log Kow > 5) and high Henry's Law constant (H ~ 50 Pa m3 mol-1)) where they will be destroyed by pyrolysis or oxidation with OHo radical. In this proposed remediation process, the sediment does not need to be dewatered and dried for remediation. Also, this process is transportable and has the potential to be used on a ship as dredging occurs. Specifically, the goals of this research are: 1) to demonstrate the ability of sonication to remove PCB from synthetic and natural sediments; 2) to show that sonochemical techniques destroy the PCB once it enters the soluble phase; 3) to characterize the role of sediment matrix parameters in sonochemical remediation; and 4) to identify key design variables in the sonochemical remediation of

contaminated sediments.

Methodology

PCB Removal from Model Systems Due to the complexity of natural systems it is often beneficial to investigate well-characterized systems prior to the use of more complex matrices such as sediments. We have begun to study the removal of a model PCB, 4-chlorobiphenyl (4-CB), from solid particles. Comparing the sonochemical desorption from minerals such as illite, alumina, and manganaese dioxide, and three different size silica gels, we will be able to determine relative effects of surface area, particle diameter, and internal pore size. The solids used were well characterized for particle diameter, surface area, pore diameter, and organic content by the manufacturer. In addition, in a set of experiments, various concentrations of humic substances (e.g., Aldrich humic acid) were be sorbed to the particles prior to 4-CB sorption in order to determine the effect of organic matter on ultrasonic desorption and destruction of 4-CB. In continuing experiments, 4-Chlorobiphenyl will be sorbed onto the particles over a period of at least 3 days or until apparent short term saturation is reached. For sonochemical experiments a 20 kHz Probe sonicator or a 16 and 20 kHz Near-Field Acoustical Processor (NAP) were used. The reactors are temperature controlled with a water jacketed reactor and circulating constant temperature bath. Reactors are specially designed and the reacting solution will be continuously stirred to keep the solids in suspension. The sonochemical energy entering the reactor were measured by calorimetry. Dosimetry, as determined by the hydroxylation of terephthalic acid is being performed to determine the effect of solids on radical formation. In order to properly characterize the sonicating system, many controls are being performed. Initially, PCB destruction kinetics were performed in the absence of solids under controlled conditions. Additionally, vigorous shaking at a constant rate with 4-CB laden solids will enhance desorption processes (through shearing effects) in the absence of sonication. The effect of solids on the absorption of ultrasonic waves into solution and bubble dynamics will be measured by calorimetry and terephthalic acid oxidation in our blank experiments. Due to safety concerns, experiments with 4-CB will be conducted only in the small probe sonicator. The effectiveness of the NAP in sonochemical desorption will determined by correlating particle size changes and OH radical generation in the two reactors. We are studying the effect of 4-CB destruction in the presence of well-characterized solids as discussed previously. 4-CB is monitored in the solid and aqueous phases as a function of time for each experiment. In both of these systems matrix parameters such as pH, temperature, and ionic strength are controlled. Once destruction and desorption kinetics have been established, parameters such as physical characteristics of the particle, particle concentration, and humic acid concentration will be varied to determine optimal conditions and effects. Aqueous phase and solid phase samples will be extracted with hexane. Solids will be separated from liquid phases by centrifugation. A gas chromatograph coupled with electron capture detector (GC-ECD) will be used to follow 4-CB concentrations for the duration of the experiment. Finally, 4-CB derivatives formed from sonolysis will be followed using gas chromatography with an ion selective mass spectrometer (GC-MS). The violent nature of cavitation may shear particles, remove organic matter coating, disperse aggregates and dissolve aggregates. To observe this effect, the particle size, solution composition, and surface were monitored. Scanning electron microscope (SEM) techniques were used to investigate changes in the surface of the solids brought about by ultrasonic irradiation. In addition, a particle size analyzer monitored the relative size distribution of the solids. Finally, ion-coupled plasma-mass spectrometry (ICP-MS) was used to determine if dissolution of particles was occurring. PCB Removal from Natural Contaminated Systems After the process is characterized in the well-controlled system, contaminant removal and destruction from actual sediments will be explored. Sediment will be collected from three sites: the Ottawa River located in Northern Ohio; the shipping channel of the Cuyahoga River in Northeastern Ohio; and where Fields Brook flows into the Ashtabula River in Northeastern Ohio. All of these sites are contaminated with various amounts of PCBs as well as other organic and inorganic

species (Bolattino and Tuchman, 1993) . Near-shore clean and contaminated samples will be obtained with an Eckman sampler. Standard on-site analysis will be conducted for parameters such as dissolved oxygen, pH, and temperature. Samples will be transported to the laboratory in amber glass jars with Teflon screw caps at 4 °C. The sediment will be characterized for particle size distribution, organic matter content, and reactive inorganic species such as iron. Organic contaminants will be extracted as described in McGroddy et al. (1996) and quantified by GC-MS. After investigating the 4-CB model system, spiking the model contaminant on a clean sediment similar to the contaminated system may help compare the model system to the natural system as well as give us insight into controlling factors in the natural system. For example, the model system will use a monodisperse particle size whereas the river sediments will have a size distribution and range of pore diameters. Clean sediment samples will be spiked with 4-CB and removal and destruction will be monitored. Contaminated sediments will then be subjected to sonication. PCBs and byproducts will be followed in aqueous solution and in the sediment by GC-MS. NOM released into solution will be monitored by total organic carbon analysis (TOC). In addition, with a particle size analyzer, the particle size distribution will be followed throughout the duration of each experiment.

Principal Findings and Significance

Initial Controls and Experiments In Fall 1998 equipment required for this project including a probe sonicator, NAP, circulating water-bath, Teflon double diaphragm pump, and GC-ECD were installed in the laboratory. In addition, specialized reactors to run sonochemical experiments were designed and built in the OSU Glass Shop. Preliminary experiments and controls were conducted in the first 6 months of this project. An analytical technique to remove 4-CB from particles using hexane extractions and detection on the GC-ECD was developed. In addition, a method was developed using the Mastersizer particle sizer to investigate changing particle sizes during sonication. Proper lens cleaning and sampling and stirring protocols were developed to obtain accurate and reproducible results. Various techniques were employed to sorb 4-CB to 2 and 20 g/L silica and alumina solutions. These experiments resulted in essentially no sorption of 4-CB to bare particles under our specified conditions. Efforts continue in this area to determine appropriate pH buffers and solution conditions to obtain appropriate levels of sorption of 4-CB to humic acid laden particles. Furthermore, in these initial experiments, particle dispersion was problematic. In an attempt to keep particles dispersed throughout the duration of a sonication experiment, a new probe reactor was designed. Sonolysis of PCB in aqueous phase. 4-Chlorobiphenyl was used as a model PCB in our study. Initially the sonication of 4-CB in distilled water was conducted to determine the efficiency of ultrasound in destroying 4-CB in aqueous solution. Figure 1 shows that the degradation of 4-CB follows first-order kinetics, with a k value of 0.132±0.0090 min-1. In addition, after 20 minutes, more than 90% of the 4-CB was destroyed. Therefore, PCB is amenable to destruction by sonication. Sonication effect on particles. Before studying the destruction of PCB contaminated sediments, it is necessary to know the effect of sonication on particles. Changes in the surface structure and the size of particles are expected to be important factors that will affect the mechanisms of desorption of PCB from particles into the aqueous phase as well as on degradation efficiency of PCB during sonication. For all the particles tested, compared to only hydrodynamic mixing, sonication decreases the particle size, following a first-order kinetic regime. An increasing rate of particle size reduction was observed with increasing diameter and surface area (Table 1). In control experiments to monitor the particle size change at different pH values (silica at pH 6, alumina at pH 2), no apparent difference in the rate of size reduction was found at different pH values. It seems that rate constant of reduction (k) for bigger particles is faster than that for smaller particles for the same type of particle. For the alumina particles, the larger rate constant of particle size reduction corresponds to the particle with a larger surface area. This may be due to the more porous structure of the larger surface area particles. Also, for silica and alumina with the same initial size, the size reduction rate for silica is

faster than alumina in the probe system, but opposite in NAP system. This may be caused by the different structures of the particles and different reactor configurations (i.e., batch vs. continuous circulation). Efficiencies of the two sonochemical systems were compared by normalizing k values in the NAP to that of the probe based on the power density measured in the reactors as follows: (1) In the above equation, k value is the first-order k value and PDNAP and PDprobe are the power densities in the NAP and probe reactors, respectively. Therefore, we can use the normalized k of NAP to compare with the kobs obtained from the probe system. Using the silica particle with an initial size of 55 mm as an example, we calculate a knormalized in NAP as 0.1769 min-1 which is almost ten times the kobs (0.0176 min-1) in probe system. Hence, the efficiency of the NAP is much higher than the probe. Therefore, it is better to apply a NAP in the actual treatment system. Similar results have been obtained in other studies investigating the degradation of 4-nitrophenol and surfactants (Hua et al., 1996; Pee et al., 2000). The structure of the particles before, during, and after sonolysis was analyzed using scanning electron microscopy (SEM). Figures 2 and 3 show the two images of silica particles (initial diameter of 55 mm) before sonication and after 60 minutes of sonication. Compared to initial and non-sonicated particles, the surface of the particles became both smoothed and pitted as a result of sonication. In addition, we found that there are many small particles formed during sonication, likely a result from the breakup of large particles. The dissolution of alumina and silica in the aqueous phase was measured using ICP-OES. Compared to hydrodynamic mixing only, the concentration of silica or alumina in aqueous solution increases with increasing sonication time. The concentration for all the particles after 60 minutes of sonication and only hydrodynamic mixing are listed in Table 2. For all the particles tested, the concentration after sonication was 6-20 times that of only mixing. Assuming that the decrease of the particle size was due entirely to the dissolution of particle and the particles are approximately spherical, the expected aqueous silica and alumina concentrations were calculated. The calculated concentrations were thousands of times higher than the actual concentration measured from ICP-OES. Therefore, it appears that the small particles are formed dominantly from the breakup of large particles. Based on these results, it seems that two mechanisms are occurring simultaneously: microstreaming acts to smooth particle surfaces and dissolve particles and microjets imploding on the particle surfaces both shear and pit the surface of the particles. Effect of particles on the degradation rate of 4-CB The degradation of 4-CB was investigated in the presence of silica and alumina particles at 2 and 20 g/L. As the particle concentration increases, the observed first-order degradation rate constant for 4-CB decreases with sizes of the silica particles. However, the presence of a small concentration of alumina particles reduces the degradation rate constant slightly but the reduction does not seem to increase with concentration. Particle concentrations of 200 g/L are currently being investigated to verify these trends. However, the dissolution of the particles observed in the presence of sonication does correlate with the reduction in the degradation rate constant of 4-CB. Clearly, the composition of the particles is important in their interaction with the ultrasound. In a complementary effort, a chemical engineering undergraduate student was recruited to conduct an honors thesis project. He is focussing on determining the OH radical concentrations in the presence of different particles (both chemically and physically different) to determine particle effects on OH radical generation. Future Work In the last phase in our study we will determine the ability of sonication to both remove and degrade 4-CB from particles. REFERENCES: Bolattino, C. and M. Tuchman. (1993) A Summary of Contaminated Sediment Activities within the United States Great Lakes Areas of Concern. Hua, I., R. Hochemer, and M.R. Hoffmann. (1995) Environ. Sci. Technol. 29, 2790-2796. McGroddy, S. E., J. W. Farrington and P. M. Gschwend. (1996) Environ. Sci. Technol. 30, 172-177. Pee, G. Y., L. K. Weavers, and J. F. Rathman. (2000) To be presented at the National Meeting of the American Chemical Society, Division of Environmental Chemistry, "Sonochemical Degradation of Surfactants." United States Environmental Protection Agency (1997) The Incidence and Severity of Sediment Contamination in Surface Waters of the United States Vol. 2. EPA 823-R-97-007. United States Environmental Protection Agency (1998) Fact Sheet: Contaminated Sediment: EPA's Report to Congress. EPA-823-F-98-001.

Descriptors

Sonochemical Remediation Sediments PCB Polychlorinated Biphenyls Oxidation Toxic Substances Ultrasound Sonolysis

Articles in Refereed Scientific Journals

Book Chapters

Dissertations

Water Resources Research Institute Reports

Conference Proceedings

Lu, Y., and L. K. Weavers, August 20, 2000, "Sonochemical Remediation of PCB Conaminated Sediments", in Proceedings, National Meeting of the American Chemical Society, Division of Environmental Chemistry, (Extended abstract).

Other Publications

Lu, Y., April 15, 2000, "Sonchemical Remediation of PCB Contaminated Sediments", The 2000 Edward F. Hayes Graduate Research Forum, The Ohio State University, Columbus, Ohio.

Basic Project Information

Basic Project Information	
Category	**Data**
Title	Enhanced Removal of DEP Precursors During Precipitative Softening Through Co-Adsorption Processes
Project Number	C-08
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Research Category	Biological Sciences
Focus Category #1	Treatment
Focus Category #2	Water Quality
Focus Category #3	Waste Water
Lead Institution	Ohio State University

Principal Investigators

Principal Investigators			
Name	Title During Project Period	Affiliated Organization	Order
Harold W. Walker	Assistant Professor	Ohio State University	01

Problem and Research Objectives

The chlorination of drinking water can result in the formation of disinfection by-products (DBPs) such as trihalomethanes and haloacetic acids [ ]. DBPs are probable carcinogens, and short-term exposure can lead to dizziness, headaches, as well as problems associated with the central nervous system. Recent studies have also linked DBPs to increased incidence of miscarriage [ ], rectal and bladder cancer [,], and neural tube birth defects [ ]. As a result of the health effects associated with DBPs, as well as microbial pathogens, nearly 40% of water treatment plants in the United States will have to upgrade their systems by 2001 at an estimated cost of $10 billion [ ]. It is estimated that 80% of water treatment facilities will have to make changes to meet regulatory requirements by the year 2005. In the state of Ohio, 125 water treatment plants utilize lime softening for the removal of hardness and turbidity [ ]. To be in compliance with upcoming United State Environmental Protection Agency (USEPA) regulations regarding DBPs, these and other lime softening plants around the country will be required to remove 20-30% of the natural organic matter present in their source water [ ]. Improvements in the removal of organic matter will most likely be accomplished through alteration of the softening process (so-called "enhanced precipitative softening"), or through the addition of unit operations such as activated carbon. Enhanced softening involves raising the amount of lime added during treatment (roughly 5 to 10 times) and subsequently results in greater chemical costs and the increased production of sludge. Although enhanced softening results in greater precipitation of $CaCO_3$, previous research indicates that even high dosages of lime (200 mg/L) may be ineffective at removing some DBP precursors, especially low molecular weight humic materials such as fulvic acid [ ]. Adsorption of fulvic acid to $CaCO_3$ precipitates during the softening process is low, primarily due to electrostatic repulsion arising from the high negative charge density of fulvic acid and the negatively charged $CaCO_3$ surface. In addition, $CaCO_3$ particles formed during softening have low surface area (5 m2/g) and therefore minimal sites for humic adsorption, compared to other coagulants such as ferric chloride (230 m2/g). While the formation of $Mg(OH)_2$ during softening can aid in removing DBP precursors, the precipitation of magnesium occurs only at high pH, a condition uncommon in most water treatment plants [ ]. In this research, we are investigating means to increase the removal of DBP precursors during lime soda softening. In particular, we are examining whether the adsorption of humic and fulvic acids to $CaCO_3$ precipitates during lime softening can be significantly improved through the "co-adsorption" of synthetic polymers. By co-adsorption, we mean any process by which more than one type of polymer simultaneously or sequentially adsorb to a solid surface. We believe the affinity of disinfection by-product precursors for calcium carbonate precipitates can be increased significantly through co-adsorption, and in particular, by the formation of humic-polymer complexes and/or through the attachment of humic material to polymer-coated $CaCO_3$ surfaces. Specific objectives of this research include; (1) To examine the removal of DBP precursors by lime softening in the presence of a number of different synthetic polymers. (2) To determine the properties of organic matter and synthetic polymer (e.g., molecular weight, charge, hydrophobicity) that influence DBP precursor removal during co-adsorption. (3) To identify the importance of specific co-adsorption mechanisms that influence organic matter removal during softening, such as precipitate surface modification and organic matter/polymer interactions. Furthermore, a significant component of this work involves the transfer of information to scientists and engineers working in the water treatment field, regulators, and to other water treatment professionals.

Methodology

A Ph.D. student in the Department of Civil and Environmental Engineering and Geodetic Science, Mr. Mustafa Bob, is currently assigned to the project. Mr. Bob began working on the project on January 1, 1999. Mr. Bob recently completed his M.S. degree in Environmental Engineering and therefore has a good background for the current project. In addition to assigning a student to the project, supplies and equipment have been purchased including calcium carbonate particles, miscellaneous reagents, and glassware. Polymeric additives have been purchased from Polydyne Inc. Humic substances have been obtained from two sources: Aldrich Chemical Corporation and the International Humic Substances Society (IHSS). IHSS humic substances have been extensively characterized previously. The size and hydrophobicity of Aldrich humic acid has been examined in our laboratory using ultrafiltration and UV measurements, respectively. Adsorption Experiments- The adsorption of humic acid onto model $CaCO_3$ particles is currently being examined in batch experiments. The purpose of these experiments is to ascertain the factors controlling the adsorption of humic substances to $CaCO_3$ particles in a model system. These experiments will help elucidate the mechanisms controlling the adsorption of humic materials under different conditions, information important in developing strategies for increasing humic adsorption. To carry out an adsorption experiment, humic acid is diluted into carbonate buffer, $CaCO_3$ particles are added, and then the mixture is incubated for at least 2 hours at 23 °C. Control experiments are carried out to verify that the amount adsorbed does not change significantly after the 2 hour incubation period. The pH at the beginning of each adsorption experiment is adjusted to either 7 or 9 using either 0.1 M HCl. The particles are allowed to reach equilibrium with respect to pH prior to conducting an adsorption measurement. No significant change in pH has been observed over the course of an adsorption experiment. After incubation, the $CaCO_3$ particles are separated from the liquid phase by filtration through sterile 0.1 ?m pore size Millex disposable filters (Millipore, Bedford, MA). Control tubes containing humic acid and no $CaCO_3$ particles are treated in an identical manner. In no case has any significant removal of organic matter onto filter media been observed, and therefore, the measured change in organic matter concentration is due solely to adsorption to the surface of the $CaCO_3$ particles. In addition, it has been verified that the filtration step removes all measurable amounts of $CaCO_3$ particles from suspension. The fluid concentration of organic matter, before and after exposure to $CaCO_3$ particles, is determined by measuring total organic carbon (TOC) using a total organic carbon analyzer (TOC5000, Shimadzu Scientific Instruments, MD). The adsorbed amount is calculated by measuring the depletion of organic matter in solution.

Principal Findings and Significance

The data in Figure 1 show the adsorption of humic acid to calcium carbonate particles at two different pH values: 7.5 and 9.5. As can be seen, adsorption of humic acid is significantly greater at pH 7.5 as compared to pH 9.5. Preliminary data suggest that the greater adsorption at low pH is due to the lower negative surface charge of the particles at pH 7.5 as compared to pH 9.5. The data also suggest that humic acid has a high affinity for the particles at low equilibrium concentrations, however, the amount adsorbed reaches a maximum upon saturation of the $CaCO_3$ surface. Preliminary measurements with cationic polyelectrolytes suggest that coating the $CaCO_3$ particles with a positively charged polymer at pH 9.5 (the typical pH in water softening plants) greatly increases the amount of humic acid adsorption. Future Work- Future work will focus on further examining the effect of polymeric additives on the adsorption of humic substances to $CaCO_3$ particles. In particular, we are currently examining the influence of humic acid chemical composition, polymer size and charge, pH, ionic strength, and $CaCO_3$ surface properties (electrostatic potential, surface area, minerology) on humic acid adsorption. Our main goals in these experiments are to elucidate the mechanisms controlling the adsorption process and

determine optimum conditions for organic matter adsorption during polymer-assisted softening. We also plan to examine the influence of polymeric additives on the structure of CaCO3 flocs. Floc structure will determine the settling characteristics of CaCO3 particles and therefore will significantly effect the removal of organic matter during softening in large-scale operations. To examine floc structure we will measure the coagulation kinetics of CaCO3 particles by monitoring the change in the mean size of suspensions using a photon correlation spectrometer. We will also directly examine floc structure by transmission electron microscopy.

Descriptors

Disinfection By-Products, Waste Treatment, Softening, Natural Organic Matter, Precipitation

Articles in Refereed Scientific Journals

Book Chapters

Dissertations

Water Resources Research Institute Reports

Fiscal Year 1998 Program Report, Report No. GRO-2691-03, Ohio Water Resources Center, Earl Whitlatch, The Ohio State University

Conference Proceedings

Other Publications

Basic Project Information

Basic Project Information	
Category	**Data**
Title	In-Situ Destruction of Solvents by Permanganate Oxidation
Project Number	C-06
Start Date	09/01/1998
End Date	02/28/2001
Research Category	Engineering
Focus Category #1	Groundwater
Focus Category #2	Treatment
Focus Category #3	Toxic Substances
Lead Institution	Ohio State University

Principal Investigators

Principal Investigators			
Name	**Title During Project Period**	**Affiliated Organization**	**Order**
Franklin W. Schwartz	Professor	Ohio State University	01

Problem and Research Objectives

The contamination problems posed by chlorinated solvents, like PCE, TCE, and DCE are well known. When dissolved in contaminant plumes or present as DNAPLs, solvents pose an extremely difficult challenge in cleanup. For the past six years, our research group has undertaken fundamental studies to explore reaction pathways, and the kinetics of reactions of oxidation reactions involving MnO_4-. This study takes the next logical step in moving from small-scale batch and column tests to large-tank tests. The objectives of the study are: (i) to undertake proof-of-concept studies to determine the efficacy of DNAPL removal in large-scale flooding schemes, (ii) to elucidate how the efficiency of DNAPL removal is influenced by flow by-passing due to multiphase effects and the presence of reaction products, CO_2 and MnO_2, and (iii) to develop further promising electrical and optical monitoring schemes.

Methodology

To meet the objectives of the study, we had constructed a large plastic flow tank, 6 ft long, 2 ft wide, and 3 ft deep (Figure 1, A). Initially, there were problems with leakage around the bottom joints in that necessitated the installation of a tank liner. The tank was instrumented with a line of multi-level samplers down gradient from the emplaced TCE source. These mini-sampling wells consisted of filter points connected to 1/8 in o.d. Teflon tubing and supported by a thin dowel. In addition, we modified the electrical/optical monitoring system developed by Gheith and Schwartz (1998) for use with TCE. Briefly, this system lets us look through the narrow diameter glass-walled casing into the tank using a CCD camera, and make resistivity measurements with an emplaced system of electrodes installed on the glass column (Figure 1, B). The modifications involved the addition of gold-coated wire as an electrode, and wires with non-reactive coatings. The wires from each electrode were plugged into a switch box that lets us select an appropriate combination of electrodes to provide a Wenner arrangement for resistivity measurements. The monitoring system required significant further enhancement before it could be used. The multilevel sampling points in the tank provided water samples that were analyzed for dissolved TCE, Cl-, and MnO_4-. The MnO_4- in particular is useful for tracking the overall reaction. The large number of samples coming out of a tank experiment necessitated the development of rapid analytical approaches. One result of our work so far is a new fast screening technique for measuring MnO_4- concentrations in large numbers of samples. This approach is described in detail a following section. Also, we had little experience with using the electrical monitoring system in systems with MnO_4-. We undertook a series of scooping experiments to evaluate the performance of this system. This approach is also reported in a subsequent section. For each experiment the tank was filled with flint sand. Inlet and outlet chambers are provided at the upstream and downstream ends of the tank for flow control. Water and MnO_4- solution were pumped into and out of the tank using Ismatec peristaltic pumps (Cole Palmer Instrument Company, Chicago). The actual flow-tank experiments involved the emplacement of a zone of residually saturated DNAPL (850 mL TCE) in a zone 1x 2 x 0.5 feet. To date we have conducted one large flow-tank experiment. The results are now being analyzed. Digital Image-based Monitoring Method The conventional approach for measuring MnO_4- concentrations in aqueous solutions relies on UV-Vis spectrophotometry. This analytical procedure requires several experimental steps, including solution transfer from some reaction vessel to a cuvette and scanning of a certain range

of wavelengths. During the transfer step and the one or two minutes of required for scanning, reactions are still underway that utilize MnO4-. There are obvious difficulties then in simultaneously handling a number of samples with rapid reaction rates. To overcome this problem, we have developed a quick quantification scheme for measuring the concentration of MnO4- in aqueous phases. This digital image-processing method provides the relative concentration of residual MnO4- indirectly as a function of the transmittance (T) of visible light. Transmittance is the ratio of the emerging light intensity (I) to the incident light intensity (Io). It is logarithmically related to the absorbance (A) of light passing through the solution (Eq. 1). (1) The absorbance of light in a permanganate solution is directly proportional to the concentration of an absorbing species (e.g. MnO4-). This effect is known as the Beer-Lambert Law; (2) where [C] is the concentration of the absorbing species in the solution, a is molar absorptivity, and l is the length of a light path. Therefore, the concentration can be obtained from the negative logarithmic relationship with the transmittance as; (3) where s is a slope of relationship between the transmittance and the concentration and b is an intercept. Both parameters, s and b are estimated from the calibration of standards. MnO4- exhibits a maximum absorbance at the wavelength of 525nm (Stewart, 1965), which falls in the range (500-578 nm) for green in the visible spectrum. Thus, the transmittance of green light through the potassium permanganate solution will be influenced mostly by the absorbance by MnO4-. The brightness level, in other word, the luminance in the green channel for a selected area in an image can then be interpreted as the transmittance of light in the green spectral range. The luminance level in the green channel provided by image processing software can be compared with those of standards and converted to some concentration of using equation (Eq. 3). However, the concentration of standards would be represented on a relative scale as would the unknowns. Digital images were taken using a Nikon Coolpix" 950 Digital Camera under ambient light. In order to minimize any interference, test tubes were placed in the center of a rounded screen set, which was made of non-reflective white panels (Figure 2). The positions of tubes, exposure and shutter speed for camera were optimized from a series of test shots. The same conditions were applied to the entire set of digital photographs. Adobe Photoshop" was used to obtain the brightness level in the green channel, in other word, transmittance in green, for an 1100-pixel square in the center of each tube image (Figure 2). Due to a slight variation in the brightness over the course of the experiments, a small correction was applied onto the data to maintain consistency in the brightness based on the brightness of background screen. Standards for the residual permanganate concentration (%) were prepared by mixing the initial permanganate solution (100 %) with a solution (0 %) in which MnO4- was used up through the oxidation reaction. Calibration of the standards showed a linear relationship between log [transmittance in green] and the residual permanganate concentration (%) (Figure 3). For some cases where there were significant reactions in the DNAPL phase, diffusive transfer of reaction products from the organic phase caused the aqueous phase to become dark brown and cloudy with suspended particles. Because this effect resulted in an abnormally low transmittance in green, the image-based monitoring scheme couldn't be used once these products started to accumulate and affected the brightness. Fortunately, this problem tended to develop midway through an experiment so that the rate of MnO4- loss could be estimated using early-time data that were unaffected by the formation of particles. Electrical Conductivity Monitoring System Electrical monitoring schemes usually depend on measuring the change in the electrical resistivity with time. Here we utilized a Wenner array involving a set of vertically emplaced electrodes. For an array of current electrodes, A and B, and potential electrodes, M and N, the resistvity, r, is expressed by the equation (4) where I is the current introduced into the earth, and DV is the potential difference between the potential electrodes. Total dissolved solids (TDS) are found to be proportional to electrical conductivity, which is the reciprocal of resistivity. The monitoring scheme uses the relationship between electrical conductivity and total dissolved solids (TDS). Because potassium permanganate (KMnO4) very soluble in ground water, while trichloroethylene (TCE) is sparingly soluble (~1100mg/L), measurements of electrical conductivity measurement are useful in monitoring how the KmnO4 is being utilized.. Electrodes were equally spaced along a 1x30(cm) (DxL) glass tube (Figure 4). The electrodes were made from gold-plate wires wrapped around the surface of the glass tube and equally spaced along the tube at 2.54 (cm)

intervals from the bottom. Each electrode was connected to one cable of a colored-ribbon. The ribbon cable was plugged into a switch box that determined the appropriate combination of electrodes to provide the resistivity measurements. The voltage difference DV was measured between two successive nodes while the current I is generated between the two outside nodes. This arrangement yielded the average apparent resistivity between the two inner nodes. A direct current, with a low frequency of 100Hz, was generated by arbitrary waveform generator made by The Ohio State Geological Sciences Electrical Shop. The use of low frequency current helped in reducing the polarization at the source and sink nodes and preventing electrolysis. Current and voltage were measured using 6-digit HP Multimeters (HP 34401A). Figure 4. Glass tube (Probe) design and connections of the electrical devices.

Principal Findings and Significance

Imaged-Based Scheme for the Rapid Measurement of KmnO4. The image-based monitoring approach was validated using a kinetic batch experiments with TCE, where the MnO4-concentration was monitored using a conventional analytical approach (UV-Vis spectrophotometer). As mentioned, the concentration of MnO4- can be determined simply by observing how the purple color disappears. We tested this photographic approach by comparing results from the digital image capture method with conventional spectrophotometric measurement. It is worth recognizing that the spectrometric method may underestimate the concentration because the scanning starts from the upper wavelength for a certain range of wavelengths. Absorbance at the lower wavelength (418 nm) for the reaction product (MnO2) could be higher than what it should be at the time when absorbance at the higher wavelength (526nm) for the reactant (MnO4-) is measured because the reaction has been progressing during the scanning time. Generally, the photographic estimates of MnO4- consumption agreed reasonably well with the results obtained from the UV-Vis spectrometer (Figure 5), even though the digital image capture technique (DIC) were slightly higher than the UV spectrometric analysis (UV). The digital-photographic monitoring approach appears to provide a fast and inexpensive alternative to the conventional spectrophotometric analysis. Electrical Conductivity Monitoring A batch experiment was conducted to test this monitoring scheme. Solutions with zero 1, 2, 3, 4, 5 mM of KMnO4 were prepared and used to saturated the Flint Silica #15 (natural sand, obtained from U.S. Silica, Ottawa-Illinois plant) in a glass cylinder. Five monitoring tubes were tested in separate experiment to obtain factors for every electrode. The electrode systems were also tested with zero, 100, and 1000 mg/L TCE solutions to verify that TCE is not conductive. Figure 6 shows that the electrical conductivity devices were capable of monitoring KMnO4 concentrations. Changing TCE concentration changes made no measurable differences in the electrical conductivity. The electrical monitoring system was tested further in a small three-dimensional sand tank. This glass tank had dimensions of 51x25x28 (cm3) (Figure 7). Input and output chambers at the two ends of the tank were used to help maintain flow conditions. These chambers were separated from the sand by two hard plastic screens with 1.3 (cm) mesh size. The screens were wrapped with a thin layer of glasswool to prevent the sand from entering the chambers. Flint silica sand with a volume of 43x25x25 (cm3) was used to fill the tank The Flint Silica was manually dumped into the tank and then saturated in the ambient flow for two weeks before the experiment began. Figure 6. Electrical conductivity change vs. different concentrations for Potassium Permanganate (top) and TCE (bottom). Figure 7. Diagrams of glass tank used in the experiment: top view (left) and side view (right). An ambient flow was maintained across the tank. Water was pumped into the inflow chamber at different locations to redistribute the flow to the upstream end of the tank. The outflow was controlled in the same manner. De-ionized water from Millipore RO system was delivered to the tank. The flow rate was controlled by Ismatec model mv-ge peristaltic pump (Cole-Palmer Instrument Company, Chicago, Illinois). The inflow rate was fixed at 2.85 ml/min. This inflow rate produced an average linear velocity of 6.57 cm/day. Five glass tubes were used as probes and

installed at different locations to monitor the electrical conductivity change. An amount of 0.03g pure TCE was injected near and at upstream of probe number 1, developing the dissolved plume for two days. Fluid samples were collected at three different depths (Figure 7) at each probe one day after TCE injection. Samples were analyzed by GC for TCE concentration. Voltage changes were measured at every electrode to calculate electrical conductivity using equation (1). 2.5mM of potassium permanganate solution was delivered after two days of development of TCE plume and replaced the de-ionized water delivery. Figure 8 shows the TCE concentration change before and after the reaction of TCE and KMnO4 took place. The figure indicates that the oxidation reaction of TCE by KMnO4 was fast and effective in the removal of TCE. Figure 8. TCE concentration change vs. time before and after the permanganate injection. The results of this experiment suggest that the electrode system is able to measure details of the KMnO4 distribution. Because of the small quantities of TCE in the system, the KMnO4 concentration did not change appreciably through the system. Overall we see this monitoring approach as being useful for evaluating the sweep efficiency and displacement patterns during the flooding scheme. Opportunities remain to improve the accuracy of the approach. Summary Cleanup schemes involving the in situ oxidation of chlorinated solvents, like PCE, TCE, and DCE, are attracting considerable interest. To date there has been significant work to elucidate mechanisms and pathways and a few field-pilots that provided generally positive encouragement. Our study here has been designed to contribute (i) to the development of monitoring/analytical approaches that may be applied both in the laboratory and the field, and (ii) to the study of factors that impact source-zone flooding. To date we have made good progress with the development of monitoring/analytical approaches with a paper submitted on a new rapid analytical approach appropriate to the rapid analysis of samples containing KMnO4-. Logistical problems with the construction of the large flow tank and debugging of the monitoring system has caused delays in the completion of activities related to (ii). This work is going on, as we write, and we expect that the large tank experiments will be completed in a few months. References Gheith, H.M. and Schwartz, F.W., 1998, Electrical and visual monitoring small scale three-dimensional experiments, Journal of Contaminant Hydrology, 34, 191-205. Stewart, R., 1965. Oxidation by permanganate. In: K.B. Wiberg (Editor), Oxidation in organic chemistry, part A. Academic Press, New York, NY, pp. 1068.

Descriptors

Groundwater Treatment In-Situ Oxidation Permanganate Chlorinated Solvents DNAPL PCE TCE DCE Toxic Substances

Articles in Refereed Scientific Journals

Seol, Y., S. Lee, and Frank W. Schwartz, 2000, "Oxidation of DNAPL mixtures using potassium permanganate with a phase-transfer-catalyst; kinetic results from a digital photographic monitoring method", Ground Water Monitoring and Remediation, In Review.

Book Chapters

Dissertations

Water Resources Research Institute Reports

Conference Proceedings

Other Publications

Basic Project Information

Basic Project Information	
Category	**Data**
Title	Water Resources Center Information Transfer Activities
Project Number	B-04
Start Date	03/01/1999
End Date	02/28/2000
Research Category	Not Applicable
Focus Category #1	None
Focus Category #2	None
Focus Category #3	None
Lead Institution	Water Resources Center

Principal Investigators

Principal Investigators			
Name	**Title During Project Period**	**Affiliated Organization**	**Order**
E. Earl Whitlatch	Associate Professor	Ohio State University	01

Problem and Research Objectives

A series of tasks were continued in FY99 to transfer and disseminate information and technology developed by researchers affiliated with the Water Resources Center to a wide range of state, federal, county, and municipal agencies; to the private sector, academic community, and to private citizens throughout Ohio. Task 1: Water Luncheon Seminars The Water Resources Center (WRC) continued to co-sponsor a bi-monthly Water Luncheon Seminar Program for the water resources community of Central Ohio. This program, which was developed cooperatively with the Ohio Department of Natural Resources (ODNR), Ohio Environmental Protection Agency (OEPA), Natural Resources Conservation Service (NRCS), District Office of the United States Geological Survey (USGS), and the Cooperative Extension Service of The Ohio State University, continues to attract more than 350 water resources professionals annually from federal, state, county, and municipal agencies, the private sector, and the academic community. The seminar series provides a forum to discuss current state, federal, and local water policy issues, problems, programs, and research results. In addition to providing the speaker for one meeting a year, the WRC provides the administrative and financial support for producing and mailing the announcements and organizing the seminars. The WRC also provides technical equipment to assist speakers with their presentations. Task 2: WATER Newsletter The WRC continued to meet with leading water resources officials in the state for purposes of sharing information on current water management and policy issues; seeking continued support for our water research program and disseminating the information and technology developed through this program and others at universities throughout the state and region. The center also continued to publish its news-letter "WATER," which focuses on Ohio's water research, technology, current issues, legislation in process, education, and center activities. WATER has a wide circulation that includes public officials, water managers

throughout Ohio, university researchers both statewide and nationwide, and the general public. It has been well received. Task 3: Water Management Association of Ohio (WMAO) Since August 1989, WRC has been the administrative and communications center for WMAO. This not-for-profit, 300 member, statewide organization promotes and supports the development, conservation, control, protection, and utilization of water resources in Ohio for all beneficial purposes. WMAO is the only Ohio organization that is solely concerned with managing Ohio's water. WRC provides staff support, office space, and equipment to WMAO as a portion of the information transfer program. Task 4: Ohio Water Education Program (OWEP) The WRC continues to provide administrative and financial support to carry this educational program to Ohio's primary and secondary students in grades K-12. The Center assists in introducing Ohio teachers to the Water Education for Teachers (WET) program through facilitator workshops and administrative support. WET is co-sponsored by the Division of Water, Ohio Department of Natural Resources. The focus has been to provide Ohio educators training in Ohio's water resources. Providing administrative and financial support for initial training workshops, materials, and publications are ways the WRC continues to be involved. Task 5: Water Resources Center's Library WRC has maintained a library of water resources-related publications since 1965 and continues to provide support for the operation of this service. Task 6: Directory of Water Resources Research at Ohio Colleges and Universities Federal and state agencies have indicated a need for both historical and state-of-the-art information on water resources research being carried out at colleges and universities throughout Ohio. WRC is developing a report indexed by key word, author, subject, geographic area, river basin, and sub-basin. An important part of the report will be theses and dissertations, and research done by university faculty, university departments, and university research centers. This is an on-going activity of WRC.

Methodology

Principal Findings and Significance

Descriptors

Information Transfer

Articles in Refereed Scientific Journals

Book Chapters

Dissertations

Water Resources Research Institute Reports

Conference Proceedings

Other Publications

Basic Project Information

Basic Project Information	
Category	**Data**
Title	Ultrasonic Cleaning of Fouled Membranes During Drinking Water Treatment
Project Number	B-05
Start Date	03/01/1999
End Date	02/28/2001
Research Category	Engineering
Focus Category #1	Water Supply
Focus Category #2	Treatment
Focus Category #3	Economics
Lead Institution	Ohio State University

Principal Investigators

Principal Investigators			
Name	**Title During Project Period**	**Affiliated Organization**	**Order**
Harold W. Walker	Assistant Professor	Ohio State University	01
Linda K. Weavers	Assistant Professor	Ohio State University	02

Problem and Research Objectives

In December 1997, EPA released the report, "The Incidence and Severity of Sediment Contamination in Surface Waters of the United States" documenting the severity of sediment contamination. Of the 96 Areas of Probable Concern, 39 are located within nine states in the North Central Region, many contaminated with polychlorinated biphenyls (PCBs) (US EPA, 1997b) . For example, the Ottawa River in Ohio has a fish consumption advisory in effect due to PCB levels more than 30 times the USFDA health standard for fish filets. Moreover, the EPA estimates that in the United States approximately 10% of the sediment underlying surface waters is sufficiently contaminated to pose risks to fish, humans, and wildlife (Bolattino and Tuchman, 1993) . It is difficult to treat sediments or soils because the sorbed hydrophobic contaminants are less accessible. Currently, capping the sediments in place or extraction and removal to a hazardous waste landfill is the most common method of treatment. However, the contaminants are not destroyed and pose a potential future risk. Moreover, episodic events such as storms and ships may compromise the capping material (by re-suspension) which could potentially mobilize the contaminants. One of the EPA's four goals for managing contaminated sediment is to better understand the fundamental processes involving contaminated sediment and to develop solutions (US EPA, 1998) . Ultrasonic irradiation of contaminated sediments may provide an on-site treatment technology that removes the contaminant from the sediment and subsequently destroys the contaminant through sonochemical oxidation. Research into the fundamental factors affecting sonochemical remediation of contaminated sediments will increase the understanding of this potential treatment process as well as lend insight into the factors affecting desorption of contaminants from sediments. The development of this treatment technology will provide an alternate solution to existing sediment remediation technologies. Existing treatment technologies such as capping have the limitation that the

pollutants are not destroyed and pose a future risk. Incineration is also used, but is prohibitively expensive and labor intensive. Conversely, sonication of sediments can be performed on a ship, does not require dewatering, and since sonication destroys the contaminants, the sediments can be replaced after treatment. The proposed process is potentially more energy efficient and environmentally benign than conventional sediment remediation technologies. The purpose of this project is to investigate the application of ultrasound to sediment polluted with PCBs. PCBs are an EPA priority pollutant and persist in the environment due to their unreactive nature. They are extremely hydrophobic and tend to partition from the aqueous phase to the gas or solid phase. Ultrasound applied to polluted sediment is a two-step process. First, the physical effects of acoustic cavitation have the potential to clean the sediment surface by the jets of imploding cavitation bubbles impinging on the particles and shear forces from microstreaming near the particle surface. Then, the PCBs will preferentially partition to the cavitation bubble (due to its high octanol/water partitioning coefficient (log Kow > 5) and high Henry's Law constant (H ~ 50 Pa m3 mol-1)) where they will be destroyed by pyrolysis or oxidation with OHo radical. In this proposed remediation process, the sediment does not need to be dewatered and dried for remediation. Also, this process is transportable and has the potential to be used on a ship as dredging occurs. Specifically, the goals of this research are: 1) to demonstrate the ability of sonication to remove PCB from synthetic and natural sediments; 2) to show that sonochemical techniques destroy the PCB once it enters the soluble phase; 3) to characterize the role of sediment matrix parameters in sonochemical remediation; and 4) to identify key design variables in the sonochemical remediation of contaminated sediments.

Methodology

PCB Removal from Model Systems Due to the complexity of natural systems it is often beneficial to investigate well-characterized systems prior to the use of more complex matrices such as sediments. We have begun to study the removal of a model PCB, 4-chlorobiphenyl (4-CB), from solid particles. Comparing the sonochemical desorption from minerals such as illite, alumina, and manganaese dioxide, and three different size silica gels, we will be able to determine relative effects of surface area, particle diameter, and internal pore size. The solids used were well characterized for particle diameter, surface area, pore diameter, and organic content by the manufacturer. In addition, in a set of experiments, various concentrations of humic substances (e.g., Aldrich humic acid) were be sorbed to the particles prior to 4-CB sorption in order to determine the effect of organic matter on ultrasonic desorption and destruction of 4-CB. In continuing experiments, 4-Chlorobiphenyl will be sorbed onto the particles over a period of at least 3 days or until apparent short term saturation is reached. For sonochemical experiments a 20 kHz Probe sonicator or a 16 and 20 kHz Near-Field Acoustical Processor (NAP) were used. The reactors are temperature controlled with a water jacketed reactor and circulating constant temperature bath. Reactors are specially designed and the reacting solution will be continuously stirred to keep the solids in suspension. The sonochemical energy entering the reactor were measured by calorimetry. Dosimetry, as determined by the hydroxylation of terephthalic acid is being performed to determine the effect of solids on radical formation. In order to properly characterize the sonicating system, many controls are being performed. Initially, PCB destruction kinetics were performed in the absence of solids under controlled conditions. Additionally, vigorous shaking at a constant rate with 4-CB laden solids will enhance desorption processes (through shearing effects) in the absence of sonication. The effect of solids on the absorption of ultrasonic waves into solution and bubble dynamics will be measured by calorimetry and terephthalic acid oxidation in our blank experiments. Due to safety concerns, experiments with 4-CB will be conducted only in the small probe sonicator. The effectiveness of the NAP in sonochemical desorption will determined by correlating particle size changes and OH radical generation in the two reactors. We are studying the effect of 4-CB destruction in the presence of well-characterized solids as discussed previously. 4-CB is monitored in the solid and aqueous phases as

a function of time for each experiment. In both of these systems matrix parameters such as pH, temperature, and ionic strength are controlled. Once destruction and desorption kinetics have been established, parameters such as physical characteristics of the particle, particle concentration, and humic acid concentration will be varied to determine optimal conditions and effects. Aqueous phase and solid phase samples will be extracted with hexane. Solids will be separated from liquid phases by centrifugation. A gas chromatograph coupled with electron capture detector (GC-ECD) will be used to follow 4-CB concentrations for the duration of the experiment. Finally, 4-CB derivatives formed from sonolysis will be followed using gas chromatography with an ion selective mass spectrometer (GC-MS). The violent nature of cavitation may shear particles, remove organic matter coating, disperse aggregates and dissolve aggregates. To observe this effect, the particle size, solution composition, and surface were monitored. Scanning electron microscope (SEM) techniques were used to investigate changes in the surface of the solids brought about by ultrasonic irradiation. In addition, a particle size analyzer monitored the relative size distribution of the solids. Finally, ion-coupled plasma-mass spectrometry (ICP-MS) was used to determine if dissolution of particles was occurring. PCB Removal from Natural Contaminated Systems After the process is characterized in the well-controlled system, contaminant removal and destruction from actual sediments will be explored. Sediment will be collected from three sites: the Ottawa River located in Northern Ohio; the shipping channel of the Cuyahoga River in Northeastern Ohio; and where Fields Brook flows into the Ashtabula River in Northeastern Ohio. All of these sites are contaminated with various amounts of PCBs as well as other organic and inorganic species (Bolattino and Tuchman, 1993) . Near-shore clean and contaminated samples will be obtained with an Eckman sampler. Standard on-site analysis will be conducted for parameters such as dissolved oxygen, pH, and temperature. Samples will be transported to the laboratory in amber glass jars with Teflon screw caps at 4 °C. The sediment will be characterized for particle size distribution, organic matter content, and reactive inorganic species such as iron. Organic contaminants will be extracted as described in McGroddy et al. (1996) and quantified by GC-MS. After investigating the 4-CB model system, spiking the model contaminant on a clean sediment similar to the contaminated system may help compare the model system to the natural system as well as give us insight into controlling factors in the natural system. For example, the model system will use a monodisperse particle size whereas the river sediments will have a size distribution and range of pore diameters. Clean sediment samples will be spiked with 4-CB and removal and destruction will be monitored. Contaminated sediments will then be subjected to sonication. PCBs and byproducts will be followed in aqueous solution and in the sediment by GC-MS. NOM released into solution will be monitored by total organic carbon analysis (TOC). In addition, with a particle size analyzer, the particle size distribution will be followed throughout the duration of each experiment.

Principal Findings and Significance

Initial Controls and Experiments In Fall 1998 equipment required for this project including a probe sonicator, NAP, circulating water-bath, Teflon double diaphragm pump, and GC-ECD were installed in the laboratory. In addition, specialized reactors to run sonochemical experiments were designed and built in the OSU Glass Shop. Preliminary experiments and controls were conducted in the first 6 months of this project. An analytical technique to remove 4-CB from particles using hexane extractions and detection on the GC-ECD was developed. In addition, a method was developed using the Mastersizer particle sizer to investigate changing particle sizes during sonication. Proper lens cleaning and sampling and stirring protocols were developed to obtain accurate and reproducible results. Various techniques were employed to sorb 4-CB to 2 and 20 g/L silica and alumina solutions. These experiments resulted in essentially no sorption of 4-CB to bare particles under our specified conditions. Efforts continue in this area to determine appropriate pH buffers and solution conditions to obtain appropriate levels of sorption of 4-CB to humic acid laden particles. Furthermore, in these initial experiments, particle

dispersion was problematic. In an attempt to keep particles dispersed throughout the duration of a sonication experiment, a new probe reactor was designed. Sonolysis of PCB in aqueous phase. 4-Chlorobiphenyl was used as a model PCB in our study. Initially the sonication of 4-CB in distilled water was conducted to determine the efficiency of ultrasound in destroying 4-CB in aqueous solution. Figure 1 shows that the degradation of 4-CB follows first-order kinetics, with a k value of 0.132 ± 0.0090 min-1. In addition, after 20 minutes, more than 90% of the 4-CB was destroyed. Therefore, PCB is amenable to destruction by sonication. Sonication effect on particles. Before studying the destruction of PCB contaminated sediments, it is necessary to know the effect of sonication on particles. Changes in the surface structure and the size of particles are expected to be important factors that will affect the mechanisms of desorption of PCB from particles into the aqueous phase as well as on degradation efficiency of PCB during sonication. For all the particles tested, compared to only hydrodynamic mixing, sonication decreases the particle size, following a first-order kinetic regime. An increasing rate of particle size reduction was observed with increasing diameter and surface area (Table 1). In control experiments to monitor the particle size change at different pH values (silica at pH 6, alumina at pH 2), no apparent difference in the rate of size reduction was found at different pH values. It seems that rate constant of reduction (k) for bigger particles is faster than that for smaller particles for the same type of particle. For the alumina particles, the larger rate constant of particle size reduction corresponds to the particle with a larger surface area. This may be due to the more porous structure of the larger surface area particles. Also, for silica and alumina with the same initial size, the size reduction rate for silica is faster than alumina in the probe system, but opposite in NAP system. This may be caused by the different structures of the particles and different reactor configurations (i.e., batch vs. continuous circulation). Efficiencies of the two sonochemical systems were compared by normalizing k values in the NAP to that of the probe based on the power density measured in the reactors as follows: (1) In the above equation, k value is the first-order k value and PDNAP and PDprobe are the power densities in the NAP and probe reactors, respectively. Therefore, we can use the normalized k of NAP to compare with the kobs obtained from the probe system. Using the silica particle with an initial size of 55 mm as an example, we calculate a knormalized in NAP as 0.1769 min-1 which is almost ten times the kobs (0.0176 min-1) in probe system. Hence, the efficiency of the NAP is much higher than the probe. Therefore, it is better to apply a NAP in the actual treatment system. Similar results have been obtained in other studies investigating the degradation of 4-nitrophenol and surfactants (Hua et al., 1996; Pee et al., 2000). The structure of the particles before, during, and after sonolysis was analyzed using scanning electron microscopy (SEM). Figures 2 and 3 show the two images of silica particles (initial diameter of 55 mm) before sonication and after 60 minutes of sonication. Compared to initial and non-sonicated particles, the surface of the particles became both smoothed and pitted as a result of sonication. In addition, we found that there are many small particles formed during sonication, likely a result from the breakup of large particles. The dissolution of alumina and silica in the aqueous phase was measured using ICP-OES. Compared to hydrodynamic mixing only, the concentration of silica or alumina in aqueous solution increases with increasing sonication time. The concentration for all the particles after 60 minutes of sonication and only hydrodynamic mixing are listed in Table 2. For all the particles tested, the concentration after sonication was 6-20 times that of only mixing. Assuming that the decrease of the particle size was due entirely to the dissolution of particle and the particles are approximately spherical, the expected aqueous silica and alumina concentrations were calculated. The calculated concentrations were thousands of times higher than the actual concentration measured from ICP-OES. Therefore, it appears that the small particles are formed dominantly from the breakup of large particles. Based on these results, it seems that two mechanisms are occurring simultaneously: microstreaming acts to smooth particle surfaces and dissolve particles and microjets imploding on the particle surfaces both shear and pit the surface of the particles. Effect of particles on the degradation rate of 4-CB The degradation of 4-CB was investigated in the presence of silica and alumina particles at 2 and 20 g/L. As the particle concentration increases, the observed first-order degradation rate constant for 4-CB decreases with sizes of the silica particles. However, the presence of a small concentration of alumina

particles reduces the degradation rate constant slightly but the reduction does not seem to increase with concentration. Particle concentrations of 200 g/L are currently being investigated to verify these trends. However, the dissolution of the particles observed in the presence of sonication does correlate with the reduction in the degradation rate constant of 4-CB. Clearly, the composition of the particles is important in their interaction with the ultrasound. In a complementary effort, a chemical engineering undergraduate student was recruited to conduct an honors thesis project. He is focussing on determining the OH radical concentrations in the presence of different particles (both chemically and physically different) to determine particle effects on OH radical generation. Future Work In the last phase in our study we will determine the ability of sonication to both remove and degrade 4-CB from particles.

Descriptors

Membranes Waste Treatment Sonication

Articles in Refereed Scientific Journals

Book Chapters

Dissertations

Water Resources Research Institute Reports

Conference Proceedings

Y. Lu and L. K. Weavers, August 20, 2000, To be presented at the National Meeting of the American Chemical Society, Division of Environmental Chemistry, "Sonochemical Remediation of PCB Conaminated Sediments." (Extended abstract)

Other Publications

Lu, Y., April 15, 2000, The 2000 Edward F. Hayes Graduate Research Forum, "Sonchemical Remediation of PCB Contaminated Sediments."

Information Transfer Program

USGS Internship Program

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Student Support					
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Masters	N/A	3	1	N/A	4
Ph.D.	1	5	1	N/A	7
Post-Doc.	N/A	N/A	N/A	N/A	N/A
Total	1	15	2	N/A	18

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