Abstract: This project was part of a larger five-year, multi-phase research and demonstration effort to study water quality and agricultural drainage wells (ADWs). The goal was to evaluate the use of constructed wetlands for treatment of subsurface drainage prior to release to groundwater through ADWs and to develop design and operation criteria for these treatment wetlands.

Background

Subsurface drainage tiles in the Corn Belt provide a major economic benefit to row-crop production, but they also transport agricultural chemicals to the water supply. Nitrate-nitrogen (NO$_3$-N) is a common contaminant in subsurface drainage water, with concentrations typically exceeding 10 mg L$^{-1}$, the EPA maximum contaminant level (MCL) set for public drinking water supplies. Discharge of subsurface drainage water to surface watercourses raises water quality concerns, including new worries about hypoxia, the oxygen-limiting zones devoid of aquatic species in the Gulf of Mexico. However, more serious problems may arise when these drainage systems discharge to an agricultural drainage well (ADW) where the excess water is injected into a receiving aquifer.

If ADWs were closed, a significant reduction in crop production (estimated to be 20 to 30 percent for one sample watershed) would result from excess wetness unless alternate outlets were developed (at a cost of $316 to $2,150 per ha). If ADWs are left open, contamination must be reduced. While improving agricultural chemical management practices can reduce contamination, it is unlikely (particularly for nitrate) that contamination problems can be economically solved by in-field changes alone. Optimum solutions would involve a combination of in- and off-field changes, with constructed wetlands being one of the most promising off-field approaches for reducing agricultural chemical concentrations in drainage. While wetlands can remove a variety of agricultural contaminants, they may prove especially effective at removing nitrate.

This report covers the first three years of a five-year, three-phase research and demonstration project with the Leopold Center providing funding for phase 1 and part of phase 2. The objectives of the project are to:

- Develop optimum sizing and design criteria for constructed wetlands discharging to ADWs,
- Develop recommended operational procedures to maximize contaminant removal efficiency of constructed wetlands, given seasonal temperature and drainage flow variations, and
- Evaluate and demonstrate the use of constructed wetlands for nitrate and herbicide removal from subsurface drainage prior to release to groundwater through ADWs.

In phase 1, model simulation studies were conducted to examine the effects of watershed-to-wetland ratio and wetland depth on nitrate loss in constructed wetlands. In phase 2, replicate constructed wetland cells are being monitored under field conditions. By measuring inflow and outflow concentrations and discharges over time, the potential of the wetlands for reducing nitrate movement to an...
ADW can be evaluated. The operation of the wetlands is based on results from phase 1 and from subsequent monitoring of the wetlands themselves. Phase 2 monitoring will continue for several years to examine long-term trends in nitrate removal. Phase 3 will unite actual field situations with the predictive models in order to create site-specific plans for drainage control wetland systems.

Approach and methods

Phase 1 Model simulation studies were conducted to estimate the effect of a watershed-to-wetland ratio and water depth and to determine the ratios and depths at which the phase 2 wetland cells would be operated. For these simulations, a simple model of wetland hydrodynamics was combined with a reaction rate expression for nitrate loss.

Phase 2 The original site intended for the phase 2 research/demonstration work was the ADW research site near Gilmore City in north central Iowa. Two wetland cells (8.5 x 35.5 m each) were constructed in late 1993. After several unsuccessful attempts to establish cattails in the wetlands in 1994 and 1995, it became apparent that the wetland cells in Gilmore City were not going to be functional in time to use for this study. The researchers sought an alternate site and identified nine wetland cells (8 x 45 m each) constructed in 1992 in a previously cropped field at the ISU Agronomy Agricultural Engineering Research Center (AAERC), located west of Ames, as suitable for the project. The source of water for the wetlands is a county tile that drains an estimated 146 ha of cropland. Water is pumped from the tile into a distribution tank and then flows into the wetlands (Figure 2). V-notched weirs in the distribution tank control the volume of water flowing into each wetland. Flows were randomly assigned to the wetlands so that three receive 1/39, three receive 3/39, and three receive 9/39 of the total water representing low, medium, and high flows. Inflow water from the tile as well as outflow water from each of the wetlands was metered and a flow-weighted sample was collected in a glass reservoir. Throughout the 1996 and 1997 field season samples were collected daily from the inflow and each outflow reservoir and analyzed for nitrate. Estimates of groundwater outflow were based on seepage studies done in late fall and early spring of 1995 and 1996 when evapotranspiration was at a minimum. Precipitation and evapotranspiration (ET) data were obtained from the National Climatic Data Center station located north of the site. Continuous water quality monitors recorded the temperature and D.O. (dissolved oxygen) concentrations within each of the wetlands.

As is true for natural wetlands, constructed wetlands gain water via precipitation, surface water inflows, and groundwater inflows, and lose water via evapotranspiration, surface water outflows, and groundwater outflows. The relative importance of these processes can vary widely between wetlands and within the same wetland over time.

For this study, detailed water budgets were calculated for each wetland cell. Water budgets provide a measure of differences in flow rates and nominal residence times among wetland cells and within wetland cells over time.
However, water budgets do not offer any information on patterns of water movement and circulation within wetlands. A tracer study was conducted to examine the pattern of water flow within a wetland cell.

Results and discussion

**Phase 1** In spite of the complexity of wetlands, research suggests that loss rates of nitrate and a great many other contaminants are consistent with a general model, in which surfaces such as sediment and organic litter provide most of the active sites for contaminant sorption or transformation, and in which loss rates are limited by contaminant transport to these active sites. According to this model, a variety of interacting factors including water depth, litter quality, and dissolved oxygen concentration could affect contaminant loss rates.

The results reported describe preliminary model simulations based on hydrologic and nitrate loading data from a tile drainage system common to row-crop production in central Iowa. These simulations offered estimates of how well-constructed wetlands reduce nitrate concentrations in tile drainage water and how wetland area and depth would affect removal rates.

Two sets of simulations were carried out. The first set examined wetland size by varying the watershed-to-wetland ratio from 100 to 50 (i.e., varying the area of the wetland from 1 to 2 percent of the watershed area). As could be expected, outlet concentrations of NO$_3^-$-N were lower for lower watershed-to-wetland ratios and were always below the MCL at watershed-to-wetland ratios of 67 and 50.

The second set of simulations considered the effect of wetland depth on NO$_3^-$-N removal by varying depth from 25 to 100 cm when the watershed-to-wetland ratio was 67. Surprisingly, depth had little effect on nitrate removal in these simulations. The model is still rather simplistic and does not incorporate some of the indirect effects of changing water levels. Model development and refinement will continue through phase 3 of this project.

**Phase 2** During the sample periods of 1996 and 1997, respectively, about 3.8 cm (14 percent) and 3.7 cm (22 percent) of water were drained through the tile. This resulted in similar hydrologic loadings for both years. The wetland water budgets indicate that this tile flow was the primary water source while surface outflow was the primary loss process. As illustrated for 1997 in Figure 3, direct precipitation, evapotranspiration, and seepage barely affected the overall water budget. The tracer study revealed a range of flow paths through the wetland. The fact that water can take different flow paths through a wetland means it can have different residence times and should be expressed more accurately as residence time distributions. In all wetlands, the nitrate concentration in the outflow was less than in the inflow, but the difference was greatest in the low-flow wetlands, as would be expected because of their longer residence time.
Water flows through the AAERC wetlands complex during the 1997 field season (Fig. 3)

Residence time is obviously likely to be a primary determinant of the effect of wetlands on nitrate reduction. It is expected that the percentage of nitrate reduction by wetlands will be inversely related to residence times. Low-flow wetlands are expected to remove a greater share of their nitrate load than are high-flow wetlands, and all wetlands are expected to remove a greater percentage of the nitrate load during lower flow periods. However, mass removal is confounded by the fact that mass loads are inversely related to residence time (i.e., when nitrate mass loading rate is high, residence time is low), with the result that mass removal (as opposed to percentage of reduction) could be highest at the lowest residence times, because these correspond to the highest mass loading rates. Inflow concentrations of NO3-N ranged from 13.5 mg L\(^{-1}\) to 20.4 mg L\(^{-1}\) in 1996 (Figure 4), and from 9.7 mg L\(^{-1}\) to 15.2 mg L\(^{-1}\) in 1997, exceeding the MCL on all but a few rare occasions. Outflow concentrations were continually lower than inflow concentrations for all loading rates, but the difference was greatest in the low flow wetlands, as would be expected because of their longer residence time.

Reductions in nitrate concentrations ranged from 9 to 58 percent in 1996 and from 4 to 36 percent in 1997, with the greatest reductions for the low-flow (longer retention time) wetlands. For these wetlands, average outflow concentrations were reduced to below 10 mg L\(^{-1}\). Percentage reductions on a mass basis were larger, as expected, ranging from 15 to 74 percent in 1996 and 9 to 54 percent in 1997, in part because evapotranspiration and seepage also helped reduce outflow volumes.

While the low-flow wetlands had lower outflow concentrations, the high-flow wetlands removed more nitrate per unit wetland area. A major research challenge is predicting the optimal watershed-to-wetland ratio where the amount of water intercepted and the residence time are balanced to best achieve water quality goals.

Nitrate removal efficiency was clearly related to hydrologic loading rate and residence time, with the low-flow wetland cells having a percentage removal efficiency approximately six times higher than that of the high-flow wetland cells. However, these differences in nitrate removal efficiency do not demonstrate that the wetlands differed in nitrate removal capacity. Given the same loading rates and residence
times, both kinds of wetlands might have removed equivalent masses of nitrate and achieved similar percentage reductions.

There is reason to believe that loss rate coefficients increase as wetlands mature, in part due to decreased oxygen availability. Both temperature and D.O. concentrations can affect nitrate loss, and the data indicate that the wetland residence time can impact both of these variables. Continuing research at the AAERC wetland facility seeks to define these relationships and to develop a general model of nitrate fate in constructed wetlands.

Conclusions

The Leopold Center has provided funding for the preliminary portion of this ongoing investigation into the effectiveness of constructed wetlands in the removal of nitrate from agricultural runoff. Results demonstrate the importance of watershed-to-wetland ratio and residence time as primary factors in the use of wetlands to achieve water quality goals. Continuing research at the AAERC wetlands facility seeks to define these relationships and to develop a general model of nitrate fate in constructed wetlands.

Education and outreach

Researchers on this project prepared seven publications ranging from papers for proceedings to a book chapter. Presentations were made at conferences on clean water, groundwater protection, and water resources. *Iowa Farmer Today* printed articles on the constructed wetlands study and concerns about nitrate in subsurface drainage water. The project also was featured in a 1997 Iowa State Fair display sponsored by the ISU College of Agriculture. In addition to speaking to tour groups at the Gilmore City research site, the project investigators have made presentations over the past four years to groups in Ames, Cedar Rapids, Des Moines, Clarion, Charles City, Spencer, Fort Dodge, Kanawha, and Humboldt, Iowa; Champaign, Illinois; and Mankato, Minnesota.

For more information contact William Crumpton, Botany, Iowa State University, Ames, Iowa 50011; (515) 294-4752; e-mail crumpton@iastate.edu.