U.S. Geological Survey Research at Management Systems Evaluation Areas, 1991–95

INTRODUCTION

The Management Systems Evaluation Areas (MSEA) program was established in 1990 in response to growing concerns about the effects of agricultural practices on the Nation's water resources. Scientists from the U.S. Geological Survey (USGS), the Agricultural Research Service, the U.S. Environmental Protection Agency, and State agricultural experiment stations conducted multi-disciplinary research at scales that ranged from the laboratory to the basin. The USGS MSEA research evaluated processes and factors that govern the behavior of agrichemicals in the environment, developed new tools for hydrologic investigations, and characterized the hydrogeology and water quality of study sites.

Prevailing and modified farming systems were studied at 10 locations in 8 Midwestern states (fig. 1). The sites were established in areas where more than 50 percent of the land was in corn and soybean production and that were underlain by distinct hydrogeology (Onstad and others, 1991). Sites examining alluvial settings were located in Minnesota, Nebraska, and Ohio; loess and glacial till settings were examined in Iowa and Missouri (Kilpatrick, 1996).

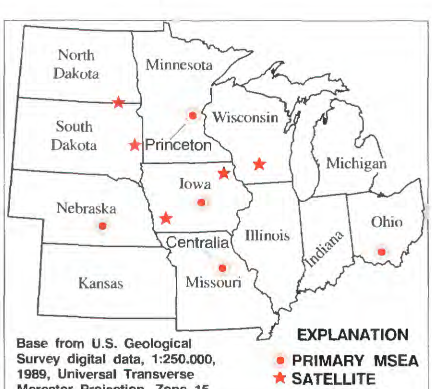

Figure 1. Location of study sites.

AGRICHEMICAL FATE AND TRANSPORT

Most agrichemical applications are either fertilizers or pesticides. Fertilizers include the plant nutrients nitrogen (N), phosphorous, and potassium. Nitrogen accounts for the largest input of agrichemicals to croplands, and its use in commercial fertilizers has increased 20-fold since 1945 (Puckett, 1995; Kitchen and others, 1997). Pesticides include herbicides, insecticides, and fungicides. In the Midwest, herbicides (including atrazine and alachlor) applied to control weeds in corn and soybean fields constitute most of the pesticide applications. Consequently, the fate and transport of N fertilizer and herbicides using various farming systems is of particular concern.

SELECTED HIGHLIGHTS

- ***Prevailing farming systems affect the quality of surface water, soil, and ground water.***
- ***Fertilizer applied in excess of crop needs often is leached to ground water.***
- ***Pesticide effects on water quality were observed more frequently in surface water than in ground water.***
- ***Rapid transport of agrichemicals from the soil surface to ground water often occurs through preferential flow paths in both sandy and clayey soils.***
- ***Vertical and horizontal flow rates in ground water often are slow enough that the effects of successive agrichemical applications overlap.***
- ***Improvements in sample collection and analytical methods have decreased the cost of future research.***
- ***Stable isotopes are an effective tool to evaluate the movement of agrichemicals through the unsaturated zone.***
- ***Long-term studies (a minimum of 3 to 5 years) are required to fully evaluate the effects of farming systems on ground-water quality.***

Agrichemical behavior in the environment is related to the interaction between hydrology and the method, timing, and persistence of the chemical application. Climate, soil type, geology, and local farm practices affect this interaction. Once in the environment, the potential exists for complex transformations of agrichemicals to occur (fig. 2).

Fertilizers and pesticides behave differently in the environment. Nitrogen fertilizer generally is applied to fields in excess of plant needs to ensure consistently high yields. Consequently, soils have an excess of N for much of the year. If the excess N (that part not used by crops) exists in a mobile phase, such as nitrate (NO_3), some of it can be lost during runoff events or move below the root zone by intense or prolonged infiltration events. However, evapotranspiration often restricts most N fertilizer movement to the root zone during the spring and summer. Excess N fertilizer often is released in the fall and winter when it cannot be used by plants. Infiltration can quickly transport this N into shallow ground water.

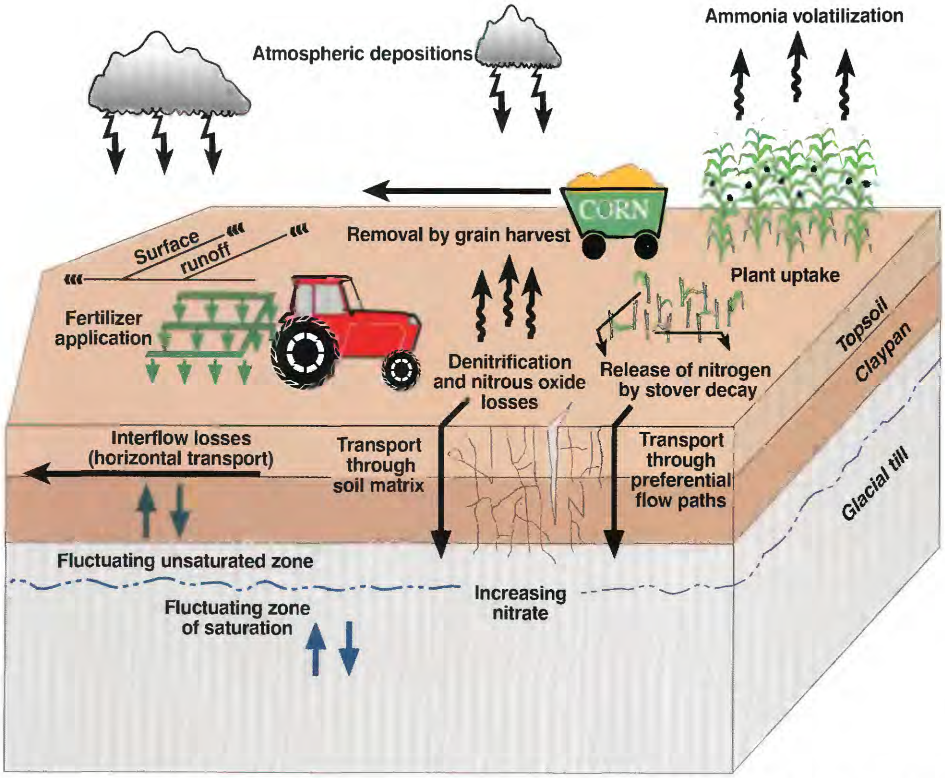

Figure 2. Conceptual model of nitrogen transport through the hydrologic system and plan view of instrumentation designed to measure nitrogen cycle processes at the Centralia, Missouri, site. When nitrogen inputs greatly exceed outputs, nitrogen saturation can occur and leach nitrate to ground water.

Most herbicides, such as atrazine, are applied in the spring and early summer to inhibit weed growth. While herbicides can adsorb to soil organic matter, which tends to limit their downward movement in the soil profile (Komor and Emerson, 1994), they generally are designed to degrade rapidly in soils. Therefore, herbicide losses often occur in runoff events that occur shortly after application, when the concentrations and mobility of herbicides in the soil are still relatively high (Soenksen, 1996). Although concentrations of selected herbicides can be high in these initial events, total herbicide runoff losses typically are only a small fraction of the original application. However, pesticides can move rapidly through soils, especially where soil structure includes preferential flow paths (Tindall and Vencill, 1995).

Desiccation cracks, worm burrows, plant rootlets, and variations in soil structure can all lead to the formation of preferential flow paths in soils. These pathways allow water and dissolved solutes to bypass the soil matrix, thus limiting chemical sorption and degradation opportunities, which might exist if the flow occurred entirely through the soil matrix. Agrichemical movement along preferential flow paths was observed in both sandy and clay soils (Kelly and Pomes, in press; Komor and Emerson, 1994).

NEW TECHNOLOGY

Multiport sampling wells for use in surficial sand and gravel aquifers were designed and tested at the Princeton, Minnesota, site (Delin and Landon, 1996). These wells have numerous stainless steel sample ports that allow for vertical profile sampling of ground water from a single well. Advantages of multiport well design over multiple well nests include reduced construction and installation costs, easier onsite installation, increased flexibility in construction materials, and more discrete aquifer sample intervals. Multiport sampling wells were used to evaluate the effects of various farming systems on ground-water quality at the Minnesota, Nebraska, and Ohio MSEA sites (Delin and others, 1995; Jagucki and others, 1995).

Less expensive, safer, and more efficient onsite and laboratory methods for N isotope analyses were developed and tested (Silva and others, 1996; fig. 3). These methods enabled use of an isotopically labeled (^{15}N) fertilizer to trace N movement through plants, soil, runoff, and the saturated and unsaturated zone (Blevins and others, 1996; Wilkison and others, 1996). The use of isotopically labeled fertilizers is important in hydrologic investigations as tracers of fertilizers. A further modification to this technique is being tested on samples to determine if the isotopic ratios of N ($\delta^{15}N$) and oxygen ($\delta^{18}O$) in NO_3 can reveal the sources of NO_3 that are discharged by the Mississippi River into the Gulf of Mexico (Battaglin and others, 1997).

Figure 3. Field sorbing of nitrogen isotope samples.

RECHARGE RATES THROUGH THE UNSATURATED ZONE

Knowledge of travel times and pathways of agrichemicals in the unsaturated zone is crucial to understanding the effects of farming systems on ground-water quality. Stable isotope values for oxygen ($\delta^{18}O$) and hydrogen (δD) in water were used to trace water sources and NO_3 movement at sites in Minnesota and North Dakota that are underlain by sand and gravel aquifers (Komor and Emerson, 1994). Spring snowmelt (although low in NO_3 concentrations) recharged ground water quickly, in part through preferential flow paths (M.K. Landon, U.S. Geological Survey, written commun., 1998). Although travel times through the unsaturated zone were much longer than in the spring, infiltration that occurred during the summer flushed NO_3 from fertilizer applications into ground water (table 1). Consequently, ground water often is comprised of a mixture of younger and older waters. The most important factors controlling recharge and water movement at the Minnesota MSEA were precipitation amounts and intensities and the initial soil moisture conditions. Runoff directed recharge into lowland areas and caused the increased transport of agrichemicals into ground water (Delin and others, in press).

Table 1. Minimum and maximum travel times in the unsaturated zone for water recharged beneath corn fields at the Princeton, Minnesota, site during 1993–94, based on changes in $\delta^{18}O$ values

[<, less than]

Sample time	Minimum	Maximum
Spring snowmelt, 1993	<1 week–2.5 months	4–7 months
Summer infiltration, 1993	3.5–6 months	7–12 months
Spring snowmelt, 1994	<5 days–1.5 months	1.5–4.5 months
Summer infiltration, 1994	1.5–2.5 months	6–12 months

TRACING FERTILIZER MOVEMENT IN THE ENVIRONMENT

The fate and transport of a single N fertilizer application through plants, soil, runoff, and the unsaturated and saturated zones were determined for four growing seasons at the Centralia, Missouri, site. Claypan soils, which underlie the site, were hypothesized to restrict the movement of agrichemicals from the soil surface to ground water. However, N fertilizer moved rapidly through preferential flow paths in the soil and into the underlying glacial till. Most N transport occurred during the fall and winter when crops were not available to use excess N. Some excess N was retained in the soil and used by successive crops.

Forty months after application, 33 percent of the fertilizer had been removed by grain harvests, 30 percent had been transpired to the atmosphere, and 33 percent had migrated to ground water (fig. 4). Although runoff volumes were 50 percent greater than infiltration, less than 2 percent of the fertilizer was lost to runoff. Small denitrification rates and large dissolved oxygen concentrations in ground water indicate that the fertilizer (in the form of NO_3) would remain stable in ground water (Blevins and others, 1996).

The results for a site with a clayey soil were comparable to those from a sandy soil. As at the Minnesota site, the predominant N transport pathways at the Missouri site appear to be plant uptake and leaching to ground water. However, the peak mass of NO_3 moved to ground water faster under sandy soils (18 months) than for clayey soils (40 months).

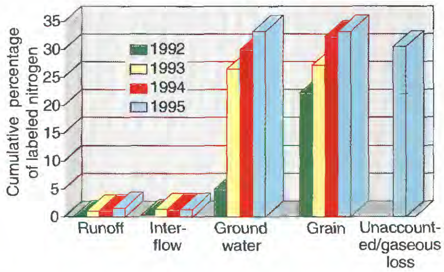

Figure 4. Loss of nitrogen fertilizer at the Centralia, Missouri, site, 1992–95.

HYDROGEOLOGIC AND WATER-QUALITY CHARACTERIZATION

Multi-disciplinary research initiatives such as the MSEA program combine knowledge of agrichemical fate and transport processes with a thorough understanding of the site hydrogeology. Surface and ground water at the Ohio site, for example, was shown to be highly interconnected. Flow paths between the outwash aquifer and adjacent streams often reverse during periods of high stream flow (Jagucki and others, 1995). The periodic inflow of surface water to the aquifer created a zone of oxidation in shallow ground water that was characterized by elevated NO_3 concentrations. At greater depths, the aquifer chemistry changes and naturally consumes and decreases NO_3 contamination.

Research at the Iowa MSEA site demonstrated that most NO_3 in streams at the site originates as ground water, whereas the bulk of the herbicide load is transported by surface runoff (Soenksen, 1996). Herbicides in surface water migrate to ground water as streams lose water to the underlying alluvial aquifer (Buchmiller, 1995).

Current and historical water-level data at the Nebraska site indicated the shallow aquifer (used for crop irrigation) to be in long-term, dynamic equilibrium (Kilpatrick, 1996). A ground-water flow model of the site aided the design and interpretation of ground-water sampling of the aquifer (McGuire and Kilpatrick, 1998). Adequate evaluation of the effects of farming systems on ground-water quality was based on this information.

TECHNOLOGY TRANSFER

The MSEA program brought many Federal and State agencies in a collaborative research partnership to better understand agricultural environmental issues. The length of many of the studies (3 to 5 years) afforded examination of complex issues. One of the cornerstones of the program was education. The USGS scientists worked closely with extension personnel and conveyed interdisciplinary research findings to farmers and resource managers through newsletters, workshops, and farm field days (Cooper and others, 1995).

RESEARCH SIGNIFICANCE AND IMPLICATIONS

Assessment of farming systems requires a thorough understanding of hydrology because agrichemicals affect surface- and ground-water quality differently. Travel times and pathways from the soil surface to ground water vary considerably. Ground water often contains a mixture of recent and older water that makes source analysis difficult. Surface- and ground-water interactions also may occur. The USGS MSEA research identified many of these processes and improved the understanding of the environmental implications of farming systems on water resources.

Nitrogen fertilizer applied in excess of crop needs can reside in soils for several years. Elevated NO_3 concentrations in surface and ground water result from successive fertilizer applications that overlap and saturate ecosystems with N. Chemical conditions in aquifers can favor long-term stability of N in ground water (Missouri site) or can moderate N concentrations through consumptive reactions (Minnesota and Ohio sites). Elevated NO_3 concentrations in ground water can persist from years to decades (Kitchen and others, 1997).

Enhanced N fertilizer management is needed to improve the nutrient efficiency of crops and prevent degradation of water quality. To minimize negative environmental effects, N fertilizer recommendations should incorporate realistic site-specific yield goals; apportion N credits from manure, legumes, or irrigation returns applied to cropland; and account for variations in soil fertility across the landscape. Farming systems that decrease N application rates, split fertilizer applications, increase fertilizer recovery efficiencies, or immobilize N during winter recharge also would help to decrease the risk of N-saturated ecosystems.

Herbicides are most likely to affect runoff that occurs shortly after agrichemical application. Initial concentrations of herbicides in runoff can be high and detections frequent throughout the year. However, the amount of herbicide loss to runoff generally is only a small part of the total amount applied. Herbicides were infrequently detected in ground water beneath crop land. Reduction in the environmental effects associated with herbicide use involves integrated pest management. Integrated strategies include tillage and crop rotation patterns that decrease the need for herbicides or decrease surface runoff, irrigation water management, the use of biological controls and grass buffer strips, crop monitoring to ensure that pest control methods are implemented at key times in the pest life cycle, and employment of control strategies only when crop damage exceeds established economic thresholds.

—By Donald H. Wilkison

REFERENCES

Battaglin, W.A., Kendall, Carol, Goolsby, D.A., and Boyer, L.L., 1997, Plan of study to determine if the isotopic ratios of $\delta^{15}N$ and $\delta^{18}O$ can reveal the sources of nitrate discharged by the Mississippi River into the Gulf of Mexico: U.S. Geological Survey Open-File Report 97–230, 18 p.

Blevins, D.W., Wilkison, D.H., Kelly, B.P., and Silva, S.R., 1996, Movement of nitrate fertilizer to glacial till and runoff from a claypan soil: Journal of Environmental Quality, v. 25, no. 3, p. 584–593.

Buchmiller, R.C., 1995, Hydrogeologic and agricultural-chemical data for the South Skunk River alluvial aquifer at a site in Story County, Iowa, 1992–93: U.S. Geological Survey Water-Resources Investigations Report 94–4244, 29 p.

Cooper, D., Giebink, B., and Olson, K., 1995, Water quality education to protect Minnesota's Sand Plain aquifer, *in* Clean Water-Clean Environment-21st Century, 1995, Proceedings: Kansas City, Missouri, v. III. Practices, Systems, and Adoption.

Delin, G.N., Healy, R.W., Landon, M.K., and Bohlke, J.K., in press, Effects of topography and soil properties on recharge and movement of water through the unsaturated zone at two sites in an agricultural field: Journal of Hydrology.

Delin, G.N., and Landon, M.K., 1996, Multiport well design for sampling of ground water at closely spaced vertical intervals: Groundwater, v. 34, no. 6, p. 1,098–1,104.

Delin, G.N., Landon, M.K., Lamb, J.A., and Dowdy, R.H., 1995, Effects of 1992 farming systems on ground-water quality at the Management Systems Evaluation Area near Princeton, Minnesota: U.S. Geological Survey Water-Resources Investigations Report 95–4104, 18 p.

Jagucki, M.L., Finton, C.D., Springer, A.E., and Bair, E.S., 1995, Hydrogeology and water quality at the Management Systems Evaluation Area near Piketon, Ohio: U.S. Geological Survey Water-Resources Investigations Report 95–4139, 117 p.

Kelly, B.P., and Pomes, M.L., in press, Preferential flow and transport of nitrate and bromide in claypan soil: Groundwater.

Kilpatrick, J.M., 1996, Temporal changes in the configuration of the water table in the vicinity of the Management Systems Evaluation Area site, central Nebraska: U.S. Geological Survey Water-Resources Investigations Report 94–4173, 1 sheet.

Kitchen, N.R., Blanchard, P.E., Hughes, D.F., and Lerch, R.N., 1997, Impact of historical and current farming systems on groundwater nitrate in northern Missouri: Journal of Soil and Water Conservation, v. 52, no. 4, p. 272–277.

Komor, S.C., and Emerson, D.G., 1994, Movements of water, solutes, and stable isotopes in the unsaturated zones of two sand plains in the upper Midwest: Water Resources Research, v. 30, no. 2, p. 253–267.

McGuire, V.L., and Kilpatrick, J.M., 1998, Hydrogeology in the vicinity of the Nebraska Management Systems Evaluation Area site, central Nebraska: U.S. Geological Survey Water-Resources Investigations Report 97–4266, 25 p.

Onstad, C.A., Burkart, M.R., and Bubenzer, G.D., 1991, Agricultural research to improve water quality: Journal of Soil and Water Conservation. v. 46, no. 3, p. 184–188.

Puckett, L.J., 1995, Identifying the major sources of nutrient water pollution: Environmental Science and Technology, v. 29, no. 9, p. 408–414.

Silva, S.R., Chang, C.C., Kendall, Carol, Ging, P.B., and Wilkison, D.H., 1996, A new technique for collection and preparation of dissolved NO_3 for $\delta^{15}N$ and $\delta^{18}O$ analyses and preliminary applications, *in* Puckett, L.J., and Triska, F.J., eds., U.S. Geological Survey Nitrogen-Cycling Workshop: U.S. Geological Survey Open-File Report 96–477, p. 35.

Soenksen, P.J., 1996, Transport of agricultural chemicals in surface flow, tile flow, and stream flow of Walnut Creek watershed near Ames, Iowa, April 1991–September 1993: U.S. Geological Survey Water-Resources Investigations Report 96–4017, 41 p.

Tindall, J.A., and Vencill, W.K., 1995, Transport of atrazine, 2,4-D, and dicamba through preferential flowpaths in an unsaturated claypan soil near Centralia, Missouri: Journal of Hydrology, v. 166, p. 37–59.

Wilkison, D.H., Blevins, D.W., and Pomes, M.L., 1996, Movement of ^{15}N-labeled nitrogen fertilizer and bromide tracers in glacial till and a claypan soil, *in* Puckett, L.J., and Triska, F.J., eds., U.S. Geological Survey Nitrogen-Cycling Workshop: U.S. Geological Survey Open-File Report 96–477, p. 38.

Banner graphic: Karen Lonsdorf

Financial support for Management Systems Evaluation Areas (MSEA) research was provided by the Toxic Substances (Toxics) Program of the U.S. Geological Survey. This program provides unbiased earth-science information on the behavior of toxic substances in the Nation's surface and ground water that is needed to avoid human exposure, to develop effective remedial strategies, and to prevent further contamination. For more information and a bibliography of publications visit Toxics on the World Wide Web at:

http://water.usgs.gov/public/wid/html/toxic.html
or contact:
Coordinator
Toxics Substances Hydrology Program
U.S. Geological Survey, 412 National Center
Reston, VA 22092
(703) 648-6862

For additional information contact:

Don Wilkison, U.S. Geological Survey
Rm 223, 301 W. Lexington
Independence, MO 64050
(816) 254-2942
email: wilkison@usgs.gov

or

Geoff Delin, U.S. Geological Survey
2280 Woodale Drive
Mounds View, MN 55112
(612) 783-3231
email: delin@usgs.gov

For more information on technical reports and hydrologic data related to programs in the Missouri District, please contact:

District Chief
U.S. Geological Survey
1400 Independence Road, MS 100
Rolla, Missouri 65401
(573) 308-3664

Additional information on other U.S. Geological Survey programs in Missouri can be obtained by accessing

http://wwwdmorll.er.usgs.gov

on the World Wide Web.