

**EFFECTS OF 1992 FARMING SYSTEMS ON GROUND-WATER  
QUALITY AT THE MANAGEMENT SYSTEMS EVALUATION AREA  
NEAR PRINCETON, MINNESOTA**

By G.N. Delin<sup>1</sup>, M.K. Landon<sup>1</sup>, J.A. Lamb<sup>2</sup>, and R.H. Dowdy<sup>3</sup>

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1995**

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## Contents

|   | Page |
|---|------|
| Abstract .....  | 1    |
| Introduction .....  | 2    |
| Description of study area .....                               | 2    |
| Methods of study .....  | 4    |
| Effects of 1992 farming systems on ground-water quality ..... | 6    |
| Concentrations of selected agricultural constituents .....    | 6    |
| Bromide .....   | 6    |
| Chloride .....  | 6    |
| Nitrate nitrogen .....  | 10   |
| Herbicides .....  | 11   |
| Masses of chloride and nitrate nitrogen .....                 | 13   |
| 1991 estimates .....  | 13   |
| 1992 estimates .....  | 13   |
| Discussion .....  | 14   |
| Summary .....   | 16   |
| References .....  | 17   |

## Illustrations

|   |   |
|---|---|
| Figure 1. Map showing layout of the Management Systems Evaluation Area near Princeton, Minnesota and example illustrating contouring of chloride concentrations in ground water along a cross-section beneath the potato cropped area, April 1993 .....   | 3 |
| 2. Diagrams showing chloride, nitrate-nitrogen, atrazine, and de-ethylatrazin concentrations in ground water along a section beneath the field corn cropped area during the June 1992 through April 1993 sampling periods at the Management Systems Evaluation Area near Princeton, Minnesota ..... | 7 |
| 3. Diagrams showing chloride, nitrate-nitrogen, atrazine, and de-ethylatrazine concentrations in ground water along a section beneath the potato cropped area during the June 1992 through April 1993 sampling periods at the Management Systems Evaluation Area near Princeton, Minnesota .....    | 8 |
| 4. Diagrams showing chloride, nitrate-nitrogen, atrazine, and de-ethylatrazine concentrations in ground water along a section beneath cropped areas at the Management Systems Evaluation Area near Princeton, Minnesota, April 1993 .....   | 9 |

## Tables

|   | Page |
|---|------|
| Table 1. Application rates of agricultural chemicals at the Management Systems Evaluation Area near Princeton, Minnesota, 1992 .....  | 4    |
| 2. Qualitative detection limits and quantitative reporting limits for gas chromatography/mass spectroscopy analyses of water from the Management Systems Evaluation Area near Princeton, Minnesota .....  | 5    |
| 3. Statistical summary of concentrations of herbicides and herbicide metabolites in 361 ground-water samples collected during the June 1992 through April 1993 sampling periods at the Management Systems Evaluation Area near Princeton, Minnesota ..... | 12   |

**Tables--Continued**

|  | Page |
|--|------|
| 4. Estimated mass of chloride and nitrogen applied in April 1991 at the Management Systems Evaluation Area near Princeton, Minnesota that was detected in the upper 2 meters of the saturated zone as chloride and nitrate nitrogen during April through October 1992..... | 14   |
| 5. Estimated mass of chloride and nitrogen applied in April 1992 at the Management Systems Evaluation Area near Princeton, Minnesota that was detected in the upper 0.5 meters of the saturated zone as chloride and nitrate nitrogen in April 1993.....                   | 15   |

**Conversion Factors**

| <u>Multiply</u>                     | <u>By</u> | <u>To obtain</u> |
|-------------------------------------|-----------|------------------|
| kilometer (km)                      | 0.6214    | mile             |
| meter (m)                           | 3.281     | foot             |
| centimeters (cm)                    | .3937     | inch             |
| centimeter per second (cm/s)        | .03531    | feet per second  |
| hectare (ha)                        | 2.471     | acres            |
| kilograms per hectare (kg/ha) .8924 |           | pounds per acre  |

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

# EFFECTS OF 1992 FARMING SYSTEMS ON GROUND-WATER QUALITY AT THE MANAGEMENT SYSTEMS EVALUATION AREA NEAR PRINCETON, MINNESOTA

by G.N. Delin<sup>1</sup>, M.K. Landon<sup>1</sup>, J.A. Lamb<sup>2</sup>, and R.H. Dowdy<sup>3</sup>

## Abstract

The Management Systems Evaluation Area (MSEA) program was a multiscale, interagency initiative to evaluate the effects of agricultural systems on water quality in the midwest corn belt. The primary objective of the Minnesota MSEA was to evaluate the effects of ridge-tillage practices in a corn and soybean farming system on ground-water quality. The 65-hectare Minnesota MSEA was located in the Anoka Sand Plain near the town of Princeton, Minnesota. Three farming systems were evaluated: corn-soybean rotation with ridge-tillage (areas B and D), sweet corn-potato rotation (areas A and C), and field corn in consecutive years (continuous corn; area E). Water samples were collected four different times per year from a network of 22 multiport wells and 29 observation wells installed in the saturated zone beneath and adjacent to the cropped areas.

Bromide and chloride were used as tracers of water recharged through the cropped areas during 1992. Bromide applied in May 1992 was first detected above background levels between August 1992 and April 1993. Thus, the time of travel of water and bromide moving through the unsaturated zone during 1992 ranged from 3 to 11 months. Chloride applied to area C (sweet corn) in April 1992 was first detected above the residual levels of 1991 chloride applications in April 1993, 12 months after the chemical was applied. Chloride applies to areas A, B, D, and E in April 1992 was not detected above the residual effects from 1991 chloride applications.

Nitrogen (N) fertilizer applied in 1992 on area C (potatoes) was first detected above background concentrations and the residual effects of the 1991 farming practices in April 1993, 12 months after application. Effects of 1992 N fertilizer applications on area E (continuous corn) generally could not be distinguished from the effects of downgradient of area E were consistently greater than background concentrations during August 1992 through April 1993. These concentrations greater than background levels indicate that some N fertilizer applied to the continuous corn crop during 1991 reached the water table. Nitrogen fertilizer applied on areas A, B, and D during 1992 could not be distinguished from the residual effects of the 1991 farming practices but were detected above background concentrations.

Atrazine concentrations beneath the cropped areas were generally indistinguishable from background concentrations. Atrazine was detected in 58 percent of the 361 ground water samples collected beneath cropped and buffer areas during June 1992 through April 1993. Most detections were at trace levels, between the detection limit of 0.01 micrograms per liter ( $\mu\text{g/L}$ ) and the reporting limit of 0.04  $\mu\text{g/L}$ . De-ethylatrazine (DEA) was detected more frequently during June 1992 through April 1993 (78 percent of the 361 samples) and in greater concentrations than any other herbicide or herbicide metabolite, with a median concentration of 0.07  $\mu\text{g/L}$ . The maximum DEA concentration of 0.77  $\mu\text{g/L}$  was detected near the water table in the middle of area E (continuous corn) during April 1993. The likely source of this DEA detection was application of atrazine to area E during 1991-93. Additional data will be needed to conclusively evaluate whether atrazine applied as part of the MSEA farming systems reached the water table.

Results indicate that the effects of the 1992 potassium-chloride and N fertilizer applications were reduced compared to the effects of 1991 applications. The most important factors associated with these differences were

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lower chemical application rates and lower recharge rates during 1992 than during 1991. Some of the chloride and N fertilizer applied to the cropped areas in 1992 likely did not reach the saturated zone in 1993 due to a 60-percent reduction in recharge compared to 1991. Therefore, analysis of data from additional years will be required to fully evaluate the effects of the farming systems on ground-water quality.

## Introduction

The Management Systems Evaluation Area (MSEA) program was a multiscale, interagency initiative to evaluate the effects of agricultural systems on water quality in the midwest corn belt. MSEA's were located in Minnesota, Iowa, Missouri, Nebraska, and Ohio. The research sites were selected to represent a variety of hydrogeologic settings and the geographic diversity of prevailing farming practices in the region. The primary objective of the Minnesota MSEA was to evaluate how ground-water quality is affected by ridge-tillage practices in a corn and soybean farming system in a sand-plain area in Minnesota and at satellite areas in North and South Dakota, and Wisconsin (Anderson and others, 1991). The primary research site was located in the Anoka Sand Plain near the town of Princeton, Minnesota (fig. 1). The MSEA program was a cooperative study between the U.S. Department of Agriculture-Agricultural Research Service, the University of Minnesota Soil Science Department, Minnesota Pollution Control Agency, and the U.S. Geological Survey. The Department of Geology at the University of Minnesota also assisted in the evaluation of ground-water quality at Princeton. This report describes the effects of the 1992 farming systems on ground-water quality at the Princeton site.

## Description Of Study Area

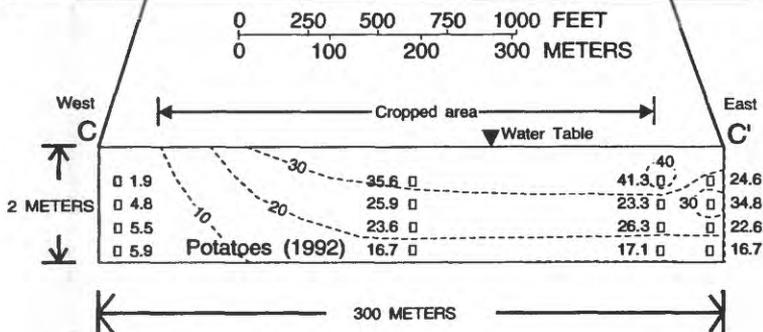
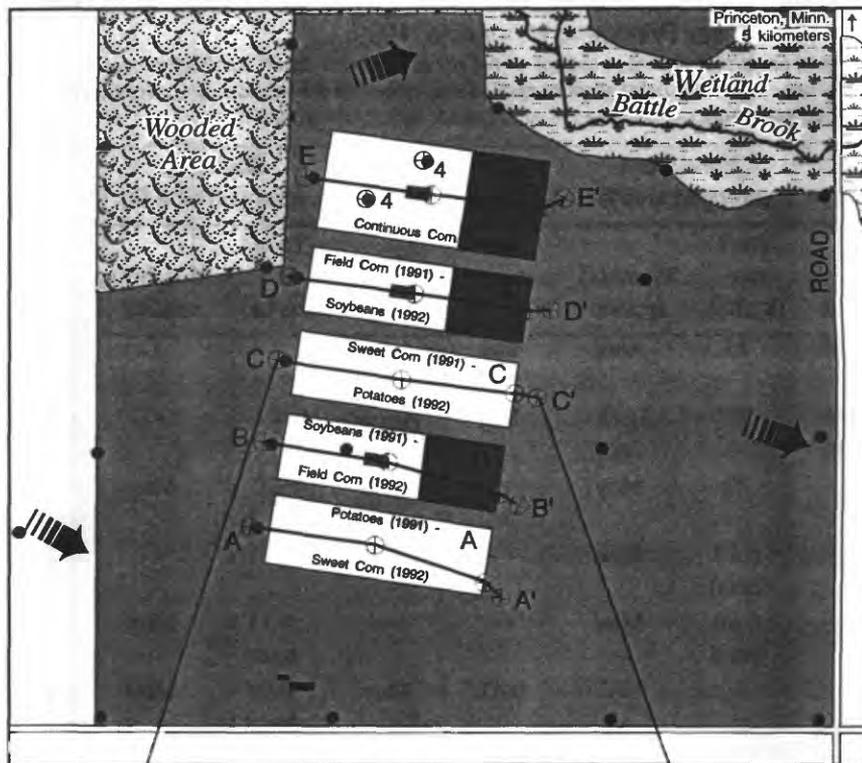
Topographic relief at the 65-hectare (ha) area is less than 3 m over a horizontal distance of about 40 m (Delin and others, 1994). The surficial aquifer consists of an unsaturated zone of fine- to medium-grained sand and a saturated zone of medium- to coarse-grained sand to fine gravel. The unsaturated and saturated zones contain discontinuous layers of silt and very-fine-grained sand up to 20 cm thick. A clayey till underlies the surficial sand and gravel aquifer (the till is less permeable than the sand). During 1992, the average depth to the water table was about 3.3 m below land surface, and the saturated thickness ranged from 4 to 16 m across the study area. The average horizontal hydraulic conductivity is about 0.04 cm/s. Based on this hydraulic conductivity and horizontal hydraulic gradients of 0.0009 to 0.002, ground water generally moved from

west to east (fig. 1) at a rate of 5-18 cm/d. Recharge ranged from 5 to 13 cm during 1991 with a median of 23 cm (Delin and others, 1994). Recharge water displaced older water in the surficial aquifer. The vertical hydraulic gradient at the site was about 0.01 (Delin and others, 1994).

In 1991, crops were planted on five 1.8- to 2.6-ha areas that were oriented parallel to the predominant direction of ground-water flow (fig. 1). These areas were used to evaluate three cropping systems (Anderson and others, 1991): (1) a corn-soybean, two-year rotation under ridge (conservation) tillage, split-nitrogen fertilizer application, nitrogen (N) credit for legumes, and banding of herbicides, which involves application only over the row equivalent to one-third of the broadcast application amount (fig. 1, field corn and soybeans); (2) a sweet corn-potato, two-year rotation with conventional full-width (disk or chisel) tillage, split-N application, banding of herbicides for sweet corn, and broadcast application of herbicides for potatoes (fig. 1, sweet corn and potatoes); and (3) field corn in consecutive years under conventional full-width (disk or chisel) tillage, split-N application, banding of herbicides for sweet corn, and broadcast application of herbicides for potatoes (fig. 1, sweet corn and potatoes); and (3) field corn in consecutive years under conventional full-width tillage, split-N application, and broadcast application of herbicides (fig. 1, continuous corn). Application rates of agricultural chemicals in 1992 are shown in table 1. A buffer area around and between the cropped areas was planted with timothy and smooth brome grass and was not treated with agricultural chemicals.

The research field was planted in alfalfa during 1981-89 and in corn during 1990, prior to the implementation of the MSEA farming systems in spring 1991. Detailed records of farming practices and chemical applications prior to 1991 were not available.

The on-site ground-water-quality monitoring network (fig. 1) consisted of 29 observation wells and 22 multiport wells (Delin and others, 1994). In addition, 14 observation wells were located off the 65-ha field (not shown in fig. 1). Observation wells were used to



The research area is located in the northeast quarter of section 18, township T35N, range R26W.

### EXPLANATION

- Cropped area, identifier, and 1991-92 crop types
- Research area, including cropped areas
- Area where potassium bromide was applied on May 26, 1992
- A—A' Line of section
- 20--- Approximate line of equal chloride concentration -- Contour interval 10 milligrams per liter
- Direction of ground-water flow, January 1992
- Data point -- Number indicates chloride concentration, in milligrams per liter
- Observation well -- Number indicates number of wells, if more than one, at location
- Multiport well
- Building

Figure 1. Layout of the Management Systems Evaluation Area near Princeton, Minnesota and example illustrating contouring of chloride concentrations in ground water along a cross section beneath the potato cropped area, April 1993.

Table 1.--Application rates of agricultural chemicals at the Management Systems Evaluation Area near Princeton, Minnesota, 1992.

[All application rates are broadcast rates except where noted as 'band'; band, application rate where herbicide was applied only over rows (total amount applied was one-third the broadcast application amount); kg/ha, kilograms per hectare; --, not applied; ai, actual ingredient]

| Agricultural chemical or tracer | Sweet Corn (cropped area A) |                  | Field Corn (cropped area B) |                  | Potatoes (cropped area C) |                  | Soybeans (cropped area D) |                  | Continuous Corn (cropped area E) |                  |
|---------------------------------|-----------------------------|------------------|-----------------------------|------------------|---------------------------|------------------|---------------------------|------------------|----------------------------------|------------------|
|                                 | Total rate (kg/ha)          | Month(s) applied | Total rate (kg/ha)          | Month(s) applied | Total rate (kg/ha)        | Month(s) applied | Total rate (kg/ha)        | Month(s) applied | Total rate (kg/ha)               | Month(s) applied |
| Potassium chloride              | 45                          | April            | 45                          | April            | 446                       | April            | --                        | --               | 45                               | April            |
| Nitrogen                        | 168                         | April-June       | 157                         | April-June       | 146                       | April-June       | --                        | --               | 168                              | April-June       |
| Potassium bromide               | --                          | --               | 22                          | May              | --                        | --               | 22                        | May              | 22                               | May              |
| Atrazine (ai)                   | 0.48 band                   | May              | 0.67 band                   | May              | --                        | --               | --                        | --               | 1.68                             | May              |
| Alachlor (ai)                   | 0.64 band                   | May              | 0.90 band                   | May              | --                        | --               | 0.71 band                 | May              | 2.24                             | May              |
| Metribuzin (ai)                 | --                          | --               | --                          | --               | 0.42                      | May              | 0.09 band                 | May              | --                               | --               |
| Metolachlor (ai)                | --                          | --               | --                          | --               | 1.68                      | May              | --                        | --               | --                               | --               |

measure monthly water levels and selected wells were used to determine background concentrations of agricultural chemicals. These wells were constructed of 5.1-cm inside-diameter (i.d.) galvanized-steel or polyvinylchloride (PVC) casing with 0.6-m-long screens located at the water table or 0.15-m-long screens installed deeper in the aquifer. The multiport wells were located 21 m upgradient, in the middle, at the downgradient edge, and 25 m downgradient of each cropped area (fig. 1). Each multiport well consisted of six, 0.6-cm i.d. stainless-steel tubes housed in a 5.1-cm i.d. PVC casing; each tube had a 3-cm-long screened interval (port) external to the PVC casing. The observation wells and multiport wells were installed through 10.2-cm i.d. hollow-stem augers. The sampling ports were installed at 0.5-m intervals with the uppermost port 0.5 m above the water table to allow sample collection if the water table rose. Delin and others (1994) provides a more detailed description of the ground-water-quality monitoring network.

### Methods of Study

Water samples were collected four times per year from all multiport wells and selected on-site observation wells (fig. 1). These samples were collected in April

before agricultural chemicals were applied, in June and August during the growing season, and in October after crops were harvested. Delin and others (1994) describe the sample-collection and laboratory-analysis quality-assurance/quality-control protocols. Specific conductance, pH, temperature, dissolved-oxygen concentration, and oxidation-reduction potential of ground water were measured during pumping at each sampling site. Water samples were collected once these properties stabilized. Alkalinity titrations were performed in the field within 4 hours of sample collection. Water samples were collected and analyzed for: dissolved major cations and anions; the nutrients nitrite-plus-nitrate nitrogen (hereinafter referred to as nitrate-N), ammonia nitrogen, total kjeldahl nitrogen, and total phosphorus; the herbicides atrazine, alachlor, metolachlor, and metribuzin; atrazine metabolites de-ethylatrazine (DEA) and de-isopropylatrazine (DIA); gas chromatography/mass spectroscopy (GC/MS) was used to determine herbicide concentrations (P.D.Capel,U.S. Geological Survey, written commun.,1991). The U.S. Geological Survey herbicide laboratory in Navarre, Minnesota developed compound-specific reporting and detection limits for each of the analytes. The qualitative detection limit was defined as the minimum concentration at which the analyte could

Table 2.--Qualitative detection limits and quantitative report limits for gas chromatography/mass spectroscopy analyses of water from the Management Systems Evaluation Area near Princeton, Minnesota  
[µg/L, micrograms per liter]

| Herbicide or herbicide metabolite | Qualitative detection limit (µg/L) | Quantitative reporting limit (µg/L) |
|-----------------------------------|------------------------------------|-------------------------------------|
| Atrazine                          | 0.01                               | 0.04                                |
| De-ethylatrazine                  | .03                                | .06                                 |
| De-isopropylatrazine              | .06                                | .08                                 |
| Alachlor                          | .01                                | .04                                 |
| 2,6-diethylaniline                | .01                                | .04                                 |
| Chloralachlor                     | .06                                | .08                                 |
| Metolachlor                       | .01                                | .04                                 |
| Metribuzin                        | .03                                | .06                                 |

be detected by GC/MS. The quantitative reporting limit was defined as the concentration at which there was a 99 percent confidence in the reported concentrations. Concentrations greater than or equal to the qualitative detection limit but less than the quantitative reporting limit indicated trace concentrations of the analytes, or concentrations that could not be reliably assigned a quantitative value but indicated that the analytes were present.

Effects of the 1992 farming systems were evaluated in part by comparing the concentrations of agricultural chemicals beneath the cropped areas to background concentrations in the buffer areas. Background concentrations were estimated by calculating the average concentration of the agricultural chemicals in samples from multiport wells upgradient (west) of cropped areas A, B, and C and from observation wells located in the buffer areas. Particular emphasis was placed on concentrations in the upper meter of the saturated zone because this interval was expected to be most greatly affected by MSEA farming practices. Concentrations of most agricultural chemicals upgradient of areas D and E were less than other background concentrations due to the close proximity of these multiport wells to the wooded area (fig. 1), where chemical use had not occurred. Therefore, the concentrations of agricultural chemicals in these multiport wells were not considered in estimating background concentrations.

Where concentrations of the agricultural chemicals were greater beneath a cropped area than upgradient, contours were drawn to reflect the interpretation that the source of these greater concentrations was recharge from the overlying cropped area. For example, because potassium chloride fertilizer applied to area C was determined to be the source of the elevated chloride

concentrations shown in figure 1, the 10-mg/L chloride contour was extended to near the upgradient (west) end of the area.

Bromide was used as a tracer of water recharged through selected cropped areas during 1992 because it moves conservatively with ground water. Potassium bromide was applied on May 26, 1992 at a rate of 22 kg/ha (table 1) to the eastern end of areas B, D, and E (fig. 1). Potassium bromide was also applied to a 24- by 15-m area upgradient of the multiport well in the middle of these cropped areas (fig. 1). Potassium bromide was not applied to areas A and C as a precautionary measure to avoid possible human health risks of consuming sweet corn and potatoes containing trace levels of bromide.

The masses of chloride and nitrate-N that reached the saturated zone as a result of applications during 1991-92 were estimated using the following equation:

$$M = (V \times C)/A \quad (1)$$

where

M = mass of chemical applied that reached the saturated zone [ $M/l^2$ ] (kg/ha),

V = volume of water in upper 2 m (or 0.5 m) of saturated zone beneath the cropped area [ $l^3$ ] ( $m^3$ ),

C = average concentration beneath the cropped area in excess of average background concentration [ $M/l^3$ ] ( $kg/m^3$ ), and

A = area covered by MSEA crop [ $l^2$ ] (ha).

An aquifer porosity of 0.40 (Delin and others, 1994) was used in estimating the volume (V) of water in the upper 2 m of the saturated zone beneath the cropped areas. The masses of chloride and nitrate-N that reached the saturated zone were estimated using average

concentrations from the sampling period during which the greatest concentrations were first detected following the year of application. For example, data from June 1992 were used in making some of the estimates for 1991 applications. In these cases, the greatest concentrations were first detected in June 1992 following application of the chemical in 1991. It was assumed that these detections resulted from 1991 applications and that none of the chemicals applied during 1992 reached the water table by June 1992. Chloride and nitrate-N in the upper 2 m of the saturated zone beneath the cropped areas that exceeded background concentrations were assumed to have recharged through the overlying cropped areas. It was also assumed that contributions of N from precipitation were the same beneath the background areas as beneath the cropped areas.

## Effects of 1992 Farming Systems on Ground-Water Quality

Effects of the 1992 farming systems are reflected to varying degrees in 1993 water-quality data. Therefore, water-quality data from April 1993 are included in figures 2-4 because they generally reflect the maximum effects of 1992 agricultural practices. Agricultural chemicals for the 1993 growing season were applied after the April 1993 sampling period was completed. When interpreting the June 1992 through April 1993 water-quality data shown in figures 2-4 it is important to keep in mind that areas A, B, C, and D were farmed with two-year crop rotations (fig. 1). Consequently, the effects of chemical applications to the 1991 crops were reflected to varying degrees in the 1992 water-quality data beneath these areas.

### Concentrations of Selected Agricultural Constituents

Concentrations of selected agricultural constituents in ground water were contoured along a section representing the upper 2 m of the saturated zone extending beneath each cropped area (figs. 1-4). The contouring is somewhat subjective due to the wide horizontal spacing of the data points. Contour intervals were selected that best emphasized contrasts in constituent concentrations along each cross section.

Most of the closed contours in figures 1-4 are artifacts of the contour intervals selected. The closed contour around the 41.3 mg/L chloride concentration in figure 1, for example, likely represents a volume of water that was recharged through the overlying cropped area. This volume of water could have become isolated within, or experienced limited mixing with, water having lower

chloride concentrations due to temporal and spatial variations in the flux of water and chemicals to the saturated zone. Other closed contours in figures 1-4, primarily for the herbicides, were caused by mixing of ground water in the saturated zone. For atrazine and DEA, the contour intervals selected are the reporting and detection limits for each compound. Because there was uncertainty associated with the reproducibility of the herbicide analyses near their detection limits, there is also uncertainty associated with the locations of the contour lines (figs. 2-4).

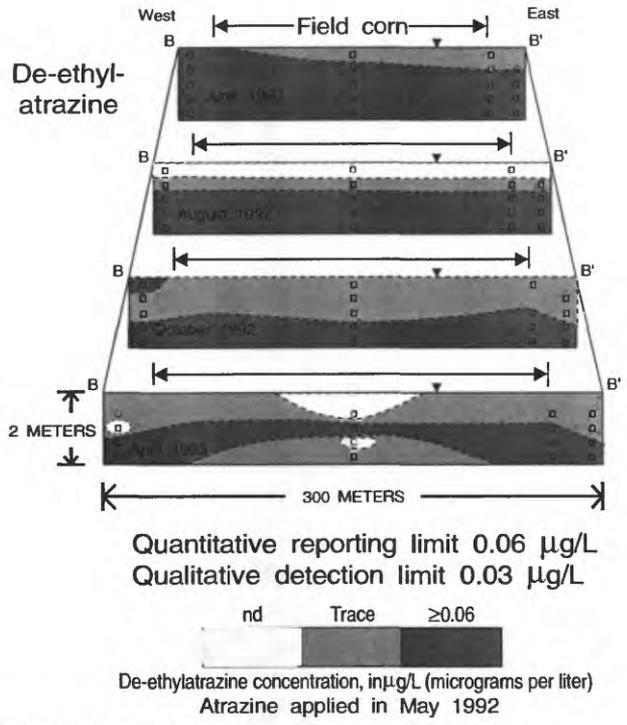
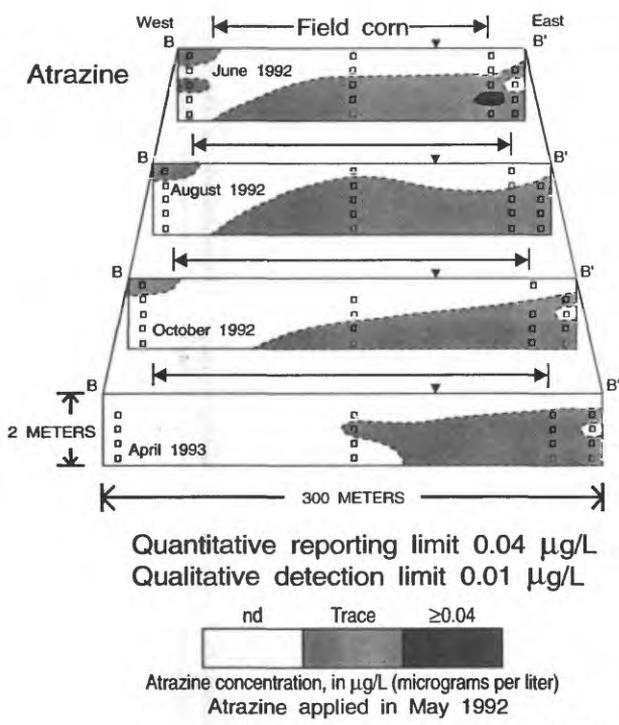
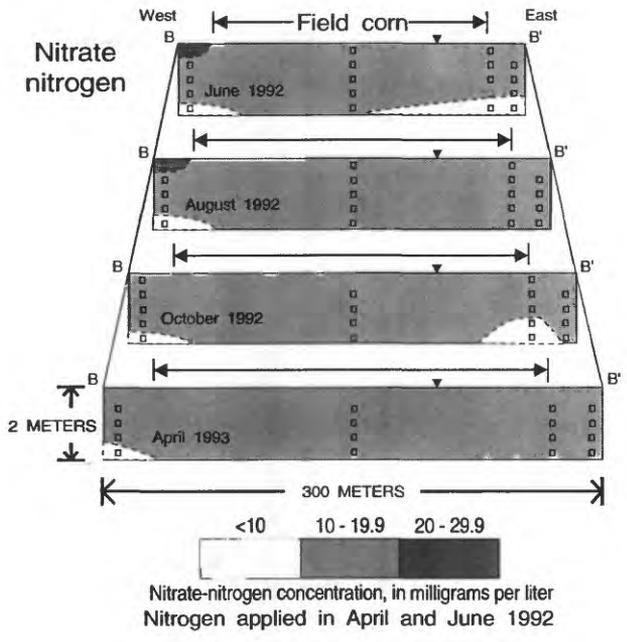
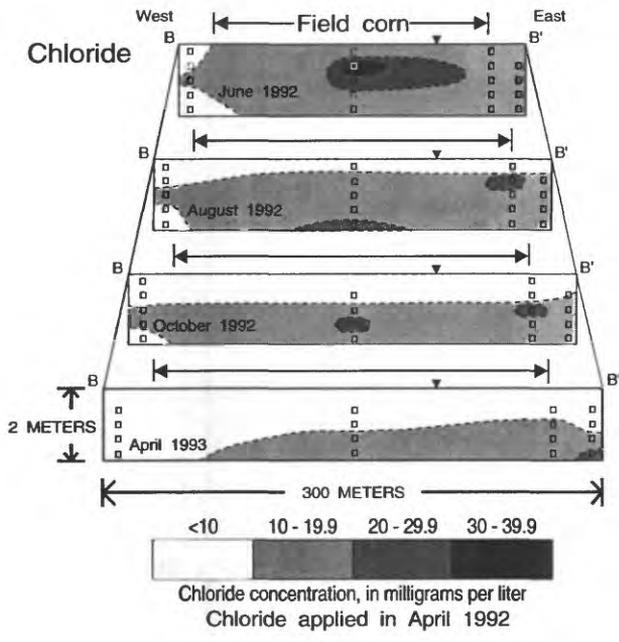
### Bromide

Although bromide concentrations, prior to bromide application, generally were below the reporting limit of 0.03 mg/L, some concentrations as great as 0.06 mg/L were detected before May 1992. The likely source of these low-level detections was application of potassium chloride fertilizer that contained trace levels of bromide (E.C. Alexander, University of Minnesota, written commun., 1992).

Bromide applied to the MSEA cropped areas was first detected above background levels beneath area B in August 1992, about 3 months after application. The first detections of bromide beneath areas D and E were in October 1992 and April 1993, respectively. Based on these results, the time of travel of water and bromide moving through the unsaturated zone during 1992 ranged from 3 to 11 months. These are maximum travel times, however, because the quarterly sampling periods were not frequent enough to more accurately identify first arrival of the tracer. The 1992 bromide travel times were similar to the travel time of 2.5 months determined for a dye study completed in 1991 (Delin and others, 1992) and to travel times of 1-7.5 months estimated using chloride as a tracer (Landon and others, 1995).

### Chloride

Chloride was used as a tracer of water recharged through the cropped areas because potassium chloride fertilizer was applied only to the cropped areas and because chloride moves conservatively with ground water. During April 1993, concentrations beneath the cropped areas generally ranged from 7 to 41 mg/L compared to concentrations of 1-16 mg/L in the buffer areas and deeper in the saturated zone (fig. 4). By comparison, chloride concentrations during April 1992 beneath the cropped areas ranged from 20 to 50 mg/L and in the buffer areas ranged from 2 to 19 mg/L (Landon and others, 1995). Thus, chloride concentrations beneath the cropped areas decreased substantially from 1991 to 1992, whereas concentrations

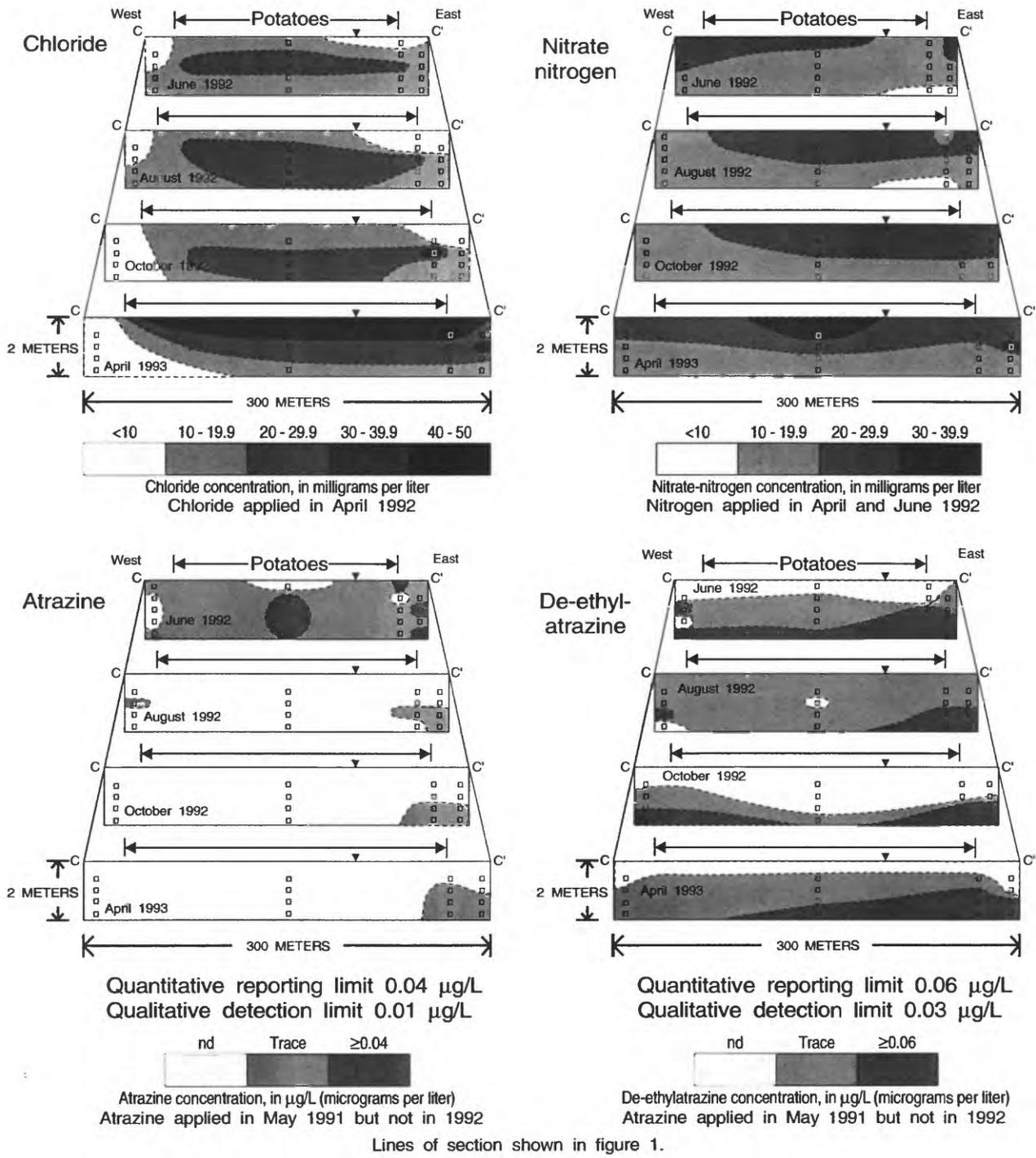


Lines of section shown in figure 1.

**EXPLANATION**

- ▼— Water table
- Approximate line of equal chemical concentration
- ◄—► Cropped area
- August 1992 Sampling period
- nd Below the detection limit
- Trace Compound detected but not quantified
- Data point

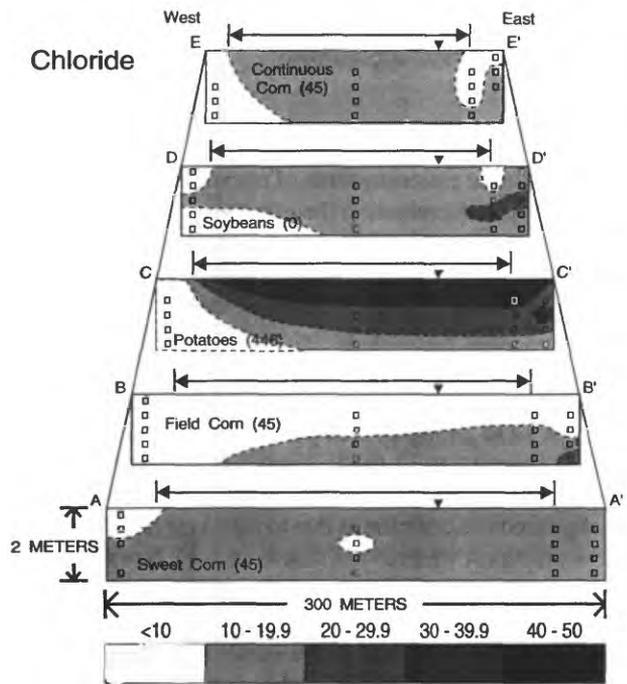
**Figure 2. Chloride, nitrate-nitrogen, atrazine, and de-ethylatrazine concentrations in ground water along a section beneath the field corn cropped area during the June 1992 through April 1993 sampling periods at the Management Systems Evaluation Area near Princeton, Minnesota.**



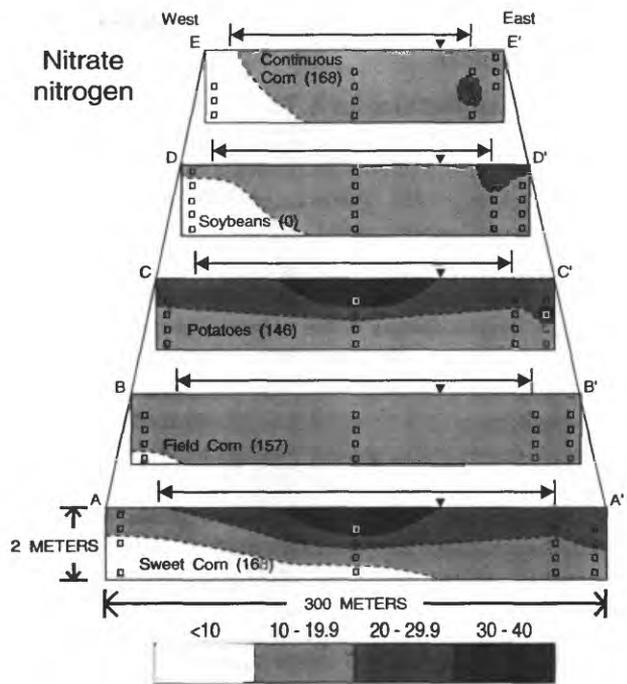
**EXPLANATION**

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- Approximate line of equal chemical concentration
- ↔ Cropped area
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- nd Below the detection limit
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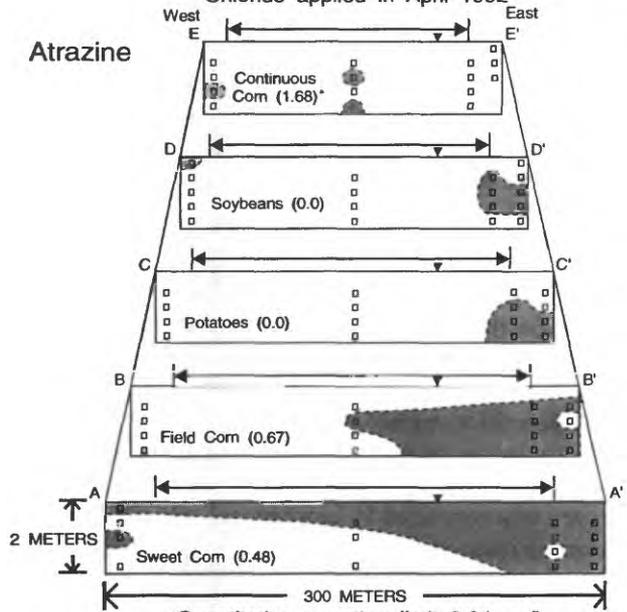
**Figure 3. Chloride, nitrate-nitrogen, atrazine, and de-ethylatrazine concentrations in ground water along a section beneath the potato cropped area during June 1992 through April 1993 sampling periods at the Management Systems Evaluation Area near Princeton, Minnesota.**



Chloride concentration, in milligrams per liter  
Chloride applied in April 1992

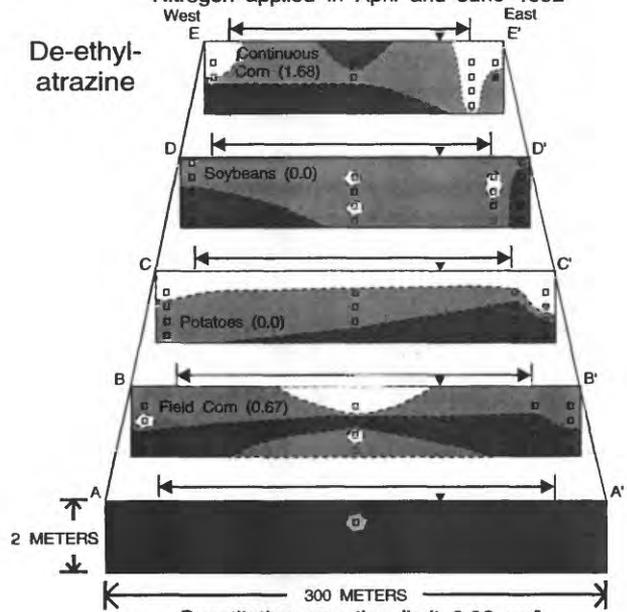


Nitrate-nitrogen concentration, in milligrams per liter  
Nitrogen applied in April and June 1992



Quantitative reporting limit 0.04 µg/L  
Qualitative detection limit 0.01 µg/L

Atrazine concentration, in µg/L (micrograms per liter)  
Atrazine applied to areas A, B, and E in May 1992



Quantitative reporting limit 0.06 µg/L  
Qualitative detection limit 0.03 µg/L

De-ethylatrazine concentration, in µg/L (micrograms per liter)  
Atrazine applied to areas A, B, and E in May 1992

Lines of section shown in figure 1.

**EXPLANATION**

- 
- 

**Figure 4. Chloride, nitrate-nitrogen, atrazine, and de-ethylatrazine concentrations in ground water along a section beneath cropped areas at the Management Systems Evaluation Area near Princeton, Minnesota, April 1993.**

in the buffer areas remained relatively constant or decreased slightly.

Chloride applied to areas A, B, D, and E in April 1992 was not detected above the residual effects from 1991 applications and concentrations generally decreased during 1992. For example, maximum concentrations beneath area B decreased from 38 mg/L in June 1992 to 18 mg/L in April 1993 (fig. 2). Ground water having the greatest chloride concentrations gradually moved deeper in the saturated zone during this period of time. The greater concentrations beneath areas A, B, and E early in 1992 were residuals from application of 11.2, 2.5, and 2.5 times more chloride to the areas, respectively, during 1991 than during 1992 (Landon and others, 1995, table 1). Therefore, residual chloride concentrations from 1991 were greater than, and thus concealed, any increases in chloride concentrations that would have resulted from 1992 applications.

Chloride concentrations remained relatively constant beneath area C during June through October 1992 and ranged from 9 to 29 mg/L (fig. 3). Ground water having the greatest chloride concentrations gradually moved deeper in the saturated zone during this period of time. The relatively constant chloride concentrations, and gradual downward migration of the greatest concentrations, indicates that these chloride detections were residuals from applications during 1991. The 1992 application rate for chloride to area C was 4 times more than the 1991 rate (table 1); and Landon and others, 1995, table 1).

Chloride applied to area C in 1992 was first detected above the residual effects of 1991 applications in April 1993 (fig. 3). This 12-month time of travel for water and chloride moving through the unsaturated zone was longer than the 1991 estimate of from 1-7.5 months (Landon and others, 1995). These time-of-travel estimates are maximum values because the quarterly sampling periods were not frequent enough to identify first arrival of the chloride tracer. The most likely reason for the longer time of travel was that 1992 recharge of 9 cm was 60 percent less than 1991 recharge of 23 cm. The 12-month time of travel also may have been longer than earlier estimates because residual chloride from 1991 applications partially concealed increases in chloride concentrations from 1992 applications.

The range of chloride concentrations beneath area C decreased from 17-41 mg/L in April 1993 (fig. 3), decreased to 14-33 mg/L in June, before increasing to 15-48 mg/L during August through November 1993. Although most of the August through November 1993 increases were likely due to chloride applications during

April 1993, some of the increases may have been residuals from 1992 applications.

## Nitrate Nitrogen

Background concentrations of nitrate-N in the buffer areas hampered evaluating the effects of the MSEA farming systems on water quality. Background concentrations of nitrate-N during 1992 typically ranged from 5 to 25 mg/L with a median of about 13 mg/L. Nitrate-N concentrations in the multiport wells upgradient of each cropped area ranged as follows: area A, from 5 to 19 mg/L; area B, from 6 to 25 mg/L; area C, from 10 to 24 mg/L; area D, from 2 to 17 mg/L; and area E, from 0.1 to 11 mg/L. Nitrate-N concentrations upgradient of areas D and E were less than other background concentrations due to the close proximity of these multiport wells to the woods (fig. 1). Nitrate-N concentrations beneath the woods generally were less than 0.3 mg/L (Delin and others, 1994). Because N fertilizer was not applied to the buffer areas, nitrate-N concentrations near the water table during 1992 resulted from the residual effects of land use prior to implementation of the MSEA farming systems in 1991. The most likely sources of background nitrate-N in the shallow ground water include decomposition of alfalfa roots and N residues in the soil from cropping with alfalfa during 1981-89 or application of N fertilizer to corn grown during 1990.

Nitrate-N concentrations beneath the cropped areas during 1992 typically were 15-30 mg/L near the water table and decreased to less than 0.2 mg/L at depths of 5-7 m below the water table, similar to results from 1991 (Landon and others, 1995). Similarly, dissolved-oxygen concentrations typically decreased from more than 8 mg/L near the water table to less than 0.5 mg/L at depths of 5-7 m below the water table. This decrease in dissolved-oxygen concentration with depth implies that oxygen was consumed by biochemical oxidation-reduction reactions faster than it could be replenished by advection of oxygen-rich water from the water table (Ronen and others, 1987; Champ and others, 1979). This decline in dissolved oxygen and nitrate-N concentrations is consistent with nitrate-N being denitrified at depth within the aquifer (Postma and others, 1991; Trudell and others, 1986). Isotopic, chemical, and dissolved-gas data from other research at the Princeton site provide supporting evidence for denitrification occurring at depth in the aquifer (Böhlke and others, 1994).

Nitrogen fertilizer applied to area A (sweet corn) during 1992 was not detected above the residual effects of the 1991 farming practices or above background

concentrations. Nitrate-N concentrations beneath area A during 1992 ranged from 8 to 41 mg/L. These relatively high concentrations were residuals from N fertilizer applications to the area during 1991. Although the relatively large nitrate-N concentrations during April 1993 (fig. 4) may include inputs of nitrate-N from 1992, these detections may also reflect continued inputs as a result of 1991 N fertilizer applications. The 1991 N fertilizer application rate to area A was 1.3 times greater than the 1992 rate (table 1; Landon and others, 1995, table 1).

Nitrogen fertilizer applied to area B (field corn) during 1992 was not detected above the residual effects of the 1991 farming practices or above background concentrations. Landon and others (1994) similarly found that the effects of the field-corn crop (area D in 1991) could not be distinguished from background concentrations of nitrate-N. Concentrations of nitrate-N beneath area B remained relatively constant during 1992, were similar to background concentrations, and ranged from 9 to 19 mg/L (fig. 2). The relatively large existing concentrations of nitrate-N (fig. 2) may have concealed any small increases in nitrate-N concentrations resulting from N fertilizer applications during 1992. Nitrogen fertilizer was not applied to area B during 1991 but may have been fixed from the atmosphere and mineralized by the soybeans.

Nitrogen fertilizer applied to area C (potatoes) during 1992 was first detected above the residual effects of the 1991 farming practices in April 1993, 12 months after application (fig. 3). Nitrate-N concentrations beneath area C ranged from 7 to 29 mg/L during June through October 1992 (fig. 3). During August and October 1992 concentrations of nitrate-N beneath area C exceeded the background concentrations of 12-19 mg/L (fig. 3). Based in part on chloride concentrations during the same time period, the excessive nitrate-N concentrations during August and October 1992 were residuals from N fertilizer applications to area C during 1991. By April 1993, nitrate-N concentrations beneath area C generally increased from 7-29 mg/L to 13-30 mg/L. These elevated concentrations were within the part of the saturated zone affected by 1992 chemical applications, as delineated by the chloride data (fig. 3).

Nitrate-N concentrations beneath area D (soybeans) generally exceeded background concentrations and increased by 2-8 mg/L during June through October 1992. These slight increases in nitrate-N concentrations resulted primarily from N fertilizer applications during 1991 of 168 kg/ha compared to none in 1992 (table 1; Landon and others, 1995, table 1).

Bromide detections showed that 1992 recharge through area D during 1992 first reached the water table

by October 1992. Some of the increased nitrate-N concentrations near the water table in October 1992 may have resulted from leaching of nitrate-N from the 1992 soybean crop, a legume that fixes N from the atmosphere.

Effects of N fertilizer applications to area E (continuous corn) during 1992 could not be distinguished from the effects of applications during 1991. Concentrations of nitrate-N beneath area E during June 1992 through April 1993 ranged from 9 to 33 mg/L and were similar to or slightly greater than background levels. Concentrations of nitrate-N at the downgradient end of area E (23 to 33 mg/L) were consistently greater than background concentrations during August 1992 through April 1993. These concentrations greater than background levels indicate that some N fertilizer applied to the continuous corn crop during 1991 reached the saturated zone.

## Herbicides

Background concentrations of herbicides and herbicide metabolites in the buffer areas, where herbicides were not applied during this study, hampered evaluating the effects of the MSEA farming systems on ground-water quality. The median concentration of atrazine and DEA beneath the buffer areas during 1992 was 0.01 µg/L (range from 0.01 to 0.14 µg/L) and 0.07 µg/L (range from 0.01 to 0.36 µg/L), respectively (table 3). Similar concentrations of atrazine and atrazine metabolites were detected in the buffer areas during 1991 (Landon and others, 1995). These detections in the buffer areas indicate a source of atrazine unrelated to the MSEA farming systems. Assuming atrazine was not applied to the alfalfa crop during 1981-89, possible sources of atrazine and atrazine metabolites in the buffer areas are: (1) deposition in precipitation, (2) application of atrazine to the research area before 1980, or (3) application of atrazine to the field corn grown on the research area during 1990, one year prior to implementation of the MSEA (Delin and others, 1994).

Atrazine was detected in 58 percent of the 361 ground-water samples collected beneath cropped and buffer areas during June 1992 through April 1993 (table 3). Most detections were at trace levels, between the detection limit of 0.01 µg/L and the reporting limit of 0.04 µg/L.

Atrazine concentrations beneath the cropped areas were generally indistinguishable from background concentrations. Atrazine was detected at trace levels beneath all of the cropped areas within the region of the saturated zone affected by 1991-92 recharge, as delineated using the chloride data (figs. 2, 3, and 4). The maximum concentrations of atrazine beneath the

cropped areas were as follows: area A - 0.08 µg/L; area B - 0.05 µg/L; area C - 0.11 µg/L; area D - 0.09 µg/L; and area E - 0.11 µg/L. Because none of these detections exceeded the maximum of 0.14 µg/L in the buffer areas, a source unrelated to the MSEA farming systems is the most likely origin of atrazine detected beneath the cropped areas. Because these detections are within the

region of the saturated zone affected by 1991-92 recharge, however, it cannot be totally discounted that some of the detections may have been related to applications of atrazine to areas C, D, and E during 1991-92. If any trace-level inputs did result from MSEA atrazine applications, they could not be

distinguished above the existing concentrations of atrazine.

DEA was detected beneath the research area more frequently during June 1992 through April 1993 (78 percent of the 361 samples) and in greater concentrations (median 0.07 µg/L; range from <0.03 to 0.77 µg/L) than any other herbicide or metabolite (table 3), similar to results from 1991 (Landon and others, 1995; table 2). DEA was detected in low concentrations (median 0.01 µg/L; range from 0.03 to 0.08 µg/L) beneath all of the cropped areas within the region of the saturated zone affected by 1991-92 recharge (figs. 2, 3, and 4).

Table 3.--Statistical summary of concentrations of herbicides and herbicide metabolites in 361 ground-water samples<sup>1</sup> collected during the June 1992 through April 1993 sampling periods at the Management Systems Evaluation Area near Princeton, Minnesota.

[DEA, de-ethylatrazine; DIA, de-isopropylatrazine; µg/L, micrograms per liter; <, less than; >, more than]

|  | Atrazine<br>(µg/L) | DEA<br>(µg/L) | DIA<br>(µg/L) | Alachlor<br>(µg/L) | 2,6-<br>Diethyl-<br>aniline<br>(µg/L) | Chloro-<br>alachlor<br>(µg/L) | Metol-<br>achlor<br>(µg/L) | Metri-<br>buzin<br>(µg/L) |
|--|--------------------|---------------|---------------|--------------------|---------------------------------------|-------------------------------|----------------------------|---------------------------|
| Median <sup>2</sup>                                    | 0.01               | 0.07          | <0.06         | <0.01              | <0.01                                 | <0.06                         | <0.01                      | <0.03                     |
| Maximum  | .14                | .77           | .15           | .02                | .01                                   | .31                           | .08                        | .11                       |
| Minimum  | <.01               | <.03          | <.06          | <.01               | <.01                                  | <.06                          | <.01                       | <.03                      |
| Greater Than Qualitative Detection Limit <sup>3</sup>  |                    |               |               |                    |                                       |                               |                            |                           |
| Number of<br>detections                                | 211                | 281           | 47            | 3                  | 2                                     | 3                             | 6                          | 3                         |
| Percentage of<br>samples<br>collected                  | 58                 | 78            | 13            | 1                  | 1                                     | 1                             | 2                          | 1                         |
| Greater Than Quantitative Reporting Limit <sup>4</sup> |                    |               |               |                    |                                       |                               |                            |                           |
| Number of<br>detections                                | 42                 | 212           | 22            | 0                  | 0                                     | 1                             | 2                          | 1                         |
| Percentage of<br>samples<br>collected                  | 12                 | 59            | 6             | 0                  | 0                                     | 0                             | 1                          | 0                         |

<sup>1</sup> The samples were collected from beneath the cropped areas and beneath the buffer areas.

<sup>2</sup> Some of these values are less than the reporting limit and should be considered approximate.

<sup>3</sup> The qualitative detection limit for atrazine, DEA, DIA, alachlor, 2,6-diethylaniline, chloralachlor, metolachlor, and metribuzin analyses were 0.01, 0.03, 0.06, 0.01, 0.01, 0.06, 0.01, and 0.03 µg/L, respectively. 0000

<sup>4</sup> The quantitative reporting limit for atrazine, DEA, DIA, alachlor, 2,6-diethylaniline, chloralachlor, metolachlor, and metribuzin analyses were 0.04, 0.06, 0.08, 0.04, 0.04, 0.08, 0.04, and 0.06 µg/L, respectively.

Concentrations of DEA generally increased with depth from about 0.03 µg/L near the water table to about 0.10 µg/L or greater between the 1- and 2-m depths. This trend with depth was present beneath the buffer areas as well as beneath the cropped areas. The trend with depth was first detected in April 1992 and could indicate that water recharging through the cropped areas during 1991 generally had lower DEA concentrations than older ground water. However, the maximum DEA concentration of 0.77 µg/L was detected near the water table in the middle of area E during April 1993, prior to application. The source of this DEA detection likely was application of atrazine during 1991-92 to the continuous corn crop on area E. Additional data would be needed to conclusively evaluate whether atrazine applied as part of the MSEA farming systems reached the saturated zone.

DIA was detected in 13 percent of the 361 samples collected during 1992 (table 3). About half of these detections were above the reporting limit of 0.08 µg/L. Fourteen of the 22 detections above the reporting limit were from beneath the cropped areas. The maximum DIA concentration of 0.15 µg/L was detected 2 m below the water table in the middle of area D during August 1992, which is within the region of the saturated zone affected by 1991 recharge. Thus, this detection could possibly be related to application of atrazine to area D during 1991.

Metolachlor, metribuzin, alachlor, and alachlor metabolites chloroalachlor and 2,6-diethylalanine were detected in only several samples at trace concentrations or just at the reporting limit (table 3). These detections were in areas where the herbicides were applied and in areas where they were not applied. Metolachlor was detected above the reporting limit of 0.04 µg/L in only one sample beneath area D, where the chemical was not applied in 1992. Thus, the source of some or all of these herbicide detections is unrelated to the MSEA farming systems. There were no clear spatial or temporal trends in the distribution of any of these herbicides or metabolites in ground water during June 1992 through April 1993.

### **Masses of Chloride and Nitrate Nitrogen**

The masses of chloride and nitrate-N that reached the saturated zone as a result of applications during 1991-92 were estimated using equation 1. Results for each year are discussed separately in the following sections of the report.

### **1991 Estimates**

The masses of chloride and nitrate-N that reached the saturated zone as a result of applications during 1991 were estimated previously (Landon and others, 1995) under the assumption that the maximum effects occurred during April 1992. However, concentrations of chloride and nitrate-N continued to increase beneath some of the cropped areas after this sampling period as a result of 1991 applications. The revised 1991 estimates described herein were based on data collected during the sampling period when the maximum concentrations occurred during April through October 1992. Mass estimates were estimated separately for each cropped area because recharge rates varied in the research area.

About 72 percent of the chloride applied to area A during 1991 reached the saturated zone by June 1992 (table 4). This estimate significantly exceeds the previous estimate of 32 percent (Landon and others, 1995). About 71 percent of the chloride applied to areas B, C, D, and E during 1991 reached the upper 2 m of the saturated zone by April 1992 (table 4). These revised estimates are unchanged from those of Landon and others (1994).

About 51 percent of the N fertilizer applied to area A during 1991 reached the upper 2 m of the saturated zone by October 1992 (table 4). This estimate exceeds the previous estimate of 21 percent (Landon and others, 1995). An estimate was not made for area B because N was not applied during 1991 and nitrate-N concentrations beneath this area were largely indistinguishable from background concentrations. About 28 percent of the N fertilizer applied to area C during 1991 reached the upper 2 m of the saturated zone by October 1992 (table 3). This estimate significantly exceeds the previous estimate of 9 percent (Landon and others, 1995). About 6 percent of the N fertilizer applied to area D during 1991 reached the upper 2 m of the saturated zone by October 1992. Landon and others (1994) did not estimate the mass for area D because nitrate-N concentrations in April 1992 were indistinguishable from background concentrations. An estimate could not be made for area E because nitrate-N concentrations beneath this area were largely indistinguishable from background concentrations. Less than one percent of the N fertilizer applied to area E likely reached the saturated zone, however, based on estimates for the other areas.

### **1992 Estimates**

Because concentrations of chloride and nitrate-N beneath most areas during 1992 were largely

Table 4.-- Estimated mass of chloride and nitrogen applied in April 1991 at the Management Systems Evaluation Area near Princeton, Minnesota that was detected in the upper 2 meters of the saturated zone as chloride and nitrate nitrogen during April through October 1992.

[kg/ha, kilograms per hectare; --, could not be estimated because concentrations were indistinguishable from background levels; na, not applicable because chemical was not applied]

| Cropped area and crop type, 1991 | Applied chloride, (kg/ha) | Mass of applied chloride in upper 2 meters of saturated zone, (kg/ha) | Percent of applied chloride in upper 2 meters of saturated zone | Applied nitrogen, (kg/ha) | Mass of applied Nitrogen as nitrate in upper 2 meters of saturated zone, (kg/ha) | Percent of applied Nitrogen in upper 2 meters of saturated zone |
|----------------------------------|---------------------------|---|---|---------------------------|--|---|
| Area A, potatoes                 | 380                       | 272   | 72  | 224                       | 114  | 51  |
| Area B, soybeans                 | 84                        | 60  | 71  | 0                         | na   | na  |
| Area C, sweet corn               | 84                        | 60  | 71  | 157                       | 44   | 28  |
| Area D, field corn               | 84                        | 60  | 71  | 157                       | 10   | 6   |
| Area E, continuous corn          | 84                        | 60  | 71  | 157                       | --   | --  |

indistinguishable from the effects of 1991 applications, the masses that reached the saturated zone as a result of 1992 applications could only be estimated for area C (table 5). The same procedures described in the Methods of Study section were used in making the 1992 estimates with the exception that only the upper 0.5 m of the saturated zone was used to calculate the volume of aquifer with excess chloride and nitrate-N concentrations. Chloride from 1992 applications was only distinguishable from 1991 applications in the upper 0.5 m of the saturated zone as of April 1993 (fig. 3). The 60-percent reduction in recharge from 1992 to 1991 was the likely cause of the smaller thickness of aquifer being affected by 1992 applications compared to 1991 applications. Thus, about a 400-percent smaller volume of water was affected by the chloride applied to area C during 1992 than during 1991.

About 16 percent of the chloride applied as potassium fertilizer to area C (potatoes) during 1992 reached the upper 0.5 m of the saturated zone by April 1993 (table 5). This mass was about two percent less than the mass of chloride that reached the upper 0.5 m of the saturated zone beneath the potato crop (area A) in 1991. About one percent of the N fertilizer applied to area C in 1992 reached the upper 0.5 m of the saturated zone by April 1993 (table 5). This mass is about 12 percent less than the mass of N fertilizer that reached the upper 0.5 m of the saturated zone beneath the potato crop (area A) in 1991. The reduced transport of chemicals to the water table during 1992 likely resulted primarily from 60 percent less ground-water recharge compared to 1991.

## Discussion

Results indicate that the effects of the 1992 potassium chloride and N fertilizer applications were reduced compared to the effects from 1991 applications. The primary factors associated with these reduced effects were: (1) lower chemical application rates in 1992 than in 1991, (2) lower recharge rates in 1992 (9 cm) than in 1991 (23 cm), and (3) varying depths to the water table.

Chemical application rate was an important factor affecting ground-water concentrations, with the greatest concentrations generally occurring beneath areas with the greatest chloride and N fertilizer application rates. During April 1993, chloride concentrations were greater beneath area C (potatoes) than beneath any other cropped area (fig. 4) because the 1992 application rate for potassium chloride on area C was about 10 times more than on any other area (table 1). Similarly, nitrate-N concentrations were greatest beneath area A (sweet corn) during April 1993 primarily because the total amount of N fertilizer applied to area A during 1991 and 1992 was 1.2 to 2.5 times the total amount applied to the other areas (table 1; Landon and others, 1995, table 1). However, nitrate-N concentrations beneath area C were greater than beneath area E (continuous corn) even though more N was applied to area E than to area C and the depth to the water table is similar beneath both areas. Similarly, nitrate-N concentrations were not elevated beneath area E compared to areas B and D (corn-soybean rotation) even though the N fertilizer application rate was about two times more to area E during 1991-92 than on the other two areas.

Table 5.--Estimated mass of chloride and nitrogen applied in April 1992 at the Management Systems Evaluation Area near Princeton, Minnesota that was detected in the upper 0.5 meters of the saturated zone as chloride and nitrate nitrogen in April 1993.

[kg/ha, kilograms per hectare; --, could not be estimated because concentrations were indistinguishable from background levels; na, not applicable because chemical was not applied]

| Cropped area and crop type, 1992 | Applied chloride, (kg/ha) | Mass of applied chloride in upper 0.5 meters of saturated zone, (kg/ha) | Percent of applied chloride in upper 0.5 meters of saturated zone | Applied nitrogen, (kg/ha) | Mass of applied Nitrogen as nitrate in upper 0.5 meters of saturated zone, (kg/ha) | Percent of applied Nitrogen as nitrate in upper 0.5 meters of saturated zone |
|----------------------------------|---------------------------|---|---|---------------------------|--|--|
| Area A, sweet corn               | 34                        | --  | --  | 168                       | --   | --   |
| Area B, field corn               | 34                        | --  | --  | 157                       | --   | --   |
| Area C, potatoes                 | 336                       | 54  | 16  | 146                       | 1  | 1  |
| Area D, soybeans                 | 0                         | na  | na  | 0                         | na   | na   |
| Area E continuous corn           | 34                        | --  | --  | 168                       | --   | --   |

Less chloride and nitrate-N was transported to the water table beneath the potato crop (area C) during 1992 than during 1991 (area A), partly due to lower application rates during 1992. Twelve percent less potassium chloride was applied on the potato crop in 1992 than in 1991. Similarly, about 35 percent less N fertilizer was applied on the potato crop in 1992 than in 1991.

The 60-percent reduction in ground-water recharge from 1991 to 1992 was an important factor that affected the transport of agricultural chemicals to the water table. For example, the greatest nitrate-N concentrations from 1991 applications were present beneath area A in part because the relatively large N fertilizer applications of 224 kg/ha coincided with relatively large recharge of 23 cm. In contrast, lower N fertilizer applications of 168 kg/ha on area A in 1992 coincided with a much lower recharge rate of 9 cm. The lower amount of recharge in 1992 than in 1991 may be a contributing factor in explaining why nitrate-N concentrations beneath area B did not increase during 1992 despite the application of N fertilizer on the field corn, after being cropped in soybeans during 1991. The percentage of chloride applied to the potatoes in 1992 that reached the saturated zone as of April 1993 was much smaller than in 1991 in part because of reduced recharge.

Varying depths to the water table beneath the cropped areas was another factor that contributed to measured differences in chloride and nitrate-N concentrations. For example, the depth to the water table during 1991-92 was less beneath area A (2.5 to 3.6 m) than beneath area B (3.1 to 3.9 m) or area C (3.7 to 4.3 m) (Delin and others, 1994). Thus, the distance for water and agricultural chemicals to travel to the water table was less beneath area A than beneath the other areas. The shallower depth to the water table resulted in a shorter transport time through the unsaturated zone because the recharge had a shorter distance to travel, assuming the unsaturated-zone hydraulic properties were uniform beneath the cropped areas. Concentrations of nitrate-N beneath topographic depressions in areas D and E, for example, were 2 to 10 mg/L greater than the concentrations elsewhere. Other research (Delin and Landon, 1995) indicates that increased recharge of water and agricultural chemicals occurs in topographic depressions, which may have caused these locally increased nitrate-N concentrations.

Advective displacement and mixing of ground water also affected concentrations of the agricultural chemicals. Water recharged in 1992, having lower concentrations of chloride and nitrate-N, displaced older ground water having higher chemical concentrations,

forcing it deeper into the saturated zone and laterally downgradient of the cropped areas. In addition to this advective displacement, the 1992 recharge water mixed with and diluted concentrations of the chemicals in ground water beneath the cropped areas. Because ground-water quality in 1993 reflected this mixing of water recharged in 1992 and earlier, it was difficult to differentiate between ground water affected by the 1991 and 1992 farming systems. Therefore, analysis of data from additional years would be required to fully evaluate the effects of the farming systems on ground-water quality.

## Summary

The Management Systems Evaluation Area (MSEA) program was a multiscale, interagency initiative to evaluate the effects of agricultural systems on water quality in the midwest corn belt. The primary objective of the Minnesota MSEA was to evaluate the effects of ridge-tillage practices in a corn and soybean farming system on ground-water quality. The 65-ha Minnesota MSEA was located in the Anoka Sand Plain near the town of Princeton. Three farming systems were evaluated: corn-soybean rotation with ridge-tillage (areas B and D), sweet corn-potato rotation (areas A and C), and field corn in consecutive years (continuous corn; area E). Water samples were collected during 1992 at four different times from a network of 22 multipoint wells and 29 observation wells installed in the saturated zone beneath and adjacent to the cropped areas.

Bromide was used as a tracer of water recharged through selected cropped areas during 1992 because it moves conservatively with ground water. Potassium bromide was applied to selected parts of areas B, D, and E on May 26, 1992 at a rate of 22 kg/ha. Bromide was first detected above background levels beneath area B in August 1992, about 3 months after application. The first detections of bromide beneath areas D and E were in October 1992 and April 1993, 5 and 11 months after application, respectively. Based on these results, the time of travel of water and bromide moving through the unsaturated zone during 1992 ranged from 3 to 11 months.

Chloride was used as a tracer of water recharged through the cropped areas because potassium chloride fertilizer was applied only to the cropped areas and because chloride moves conservatively with ground water. Chloride applied to area C in 1992 was first detected above the residual effects of 1991 applications in April 1993. This 12-month time of travel for water and chloride moving through the unsaturated zone was longer than the 1991 estimate of from 1 to 7.5 months.

These time-of-travel estimates, however, do not identify the first arrival of the chloride tracer. Chloride applied to areas A, B, D, and E in 1992 was not detected above the residual effects from 1991 applications and concentrations generally decreased during 1992.

Nitrate-N concentrations beneath the cropped areas during 1992 typically ranged from 15 to 30  $\mu\text{g/L}$  near the water table and decreased to less than 0.2 mg/L at depths of 5-7 m below the water table. Similarly, dissolved-oxygen concentrations decreased from more than 8 mg/L near the water table to less than 0.5 mg/L at depths of 5-7 m below the water table. This decline in dissolved-oxygen and nitrate-N concentrations indicates that nitrate-N was denitrified at depth within the aquifer.

Nitrogen fertilizer applied on area A (sweet corn) and on area B (field corn) during 1992 was not detected above the residual effects of the 1991 farming practices. Nitrogen fertilizer applied on area C (potatoes) was first detected above the residual effects of the 1991 farming practices in April 1993, about 12 months after application. Nitrate-N concentrations beneath area D (soybeans) increased by 2-8 mg/L during June through October 1992. These slight increases in nitrate-N concentrations resulted primarily from N fertilizer applications during 1991 because N fertilizer was not applied to the soybean crop during 1992. However, some of the increased nitrate-N concentrations near the water table in October 1992 may have resulted from the 1992 soybean crop. The effects of N fertilizer applications on area E (continuous corn) in 1992 generally could not be distinguished from the effects of N fertilizer applications during 1991. However, concentrations of nitrate-N at the downgradient end of area E were consistently greater than background concentrations during August 1992 through April 1993. These concentrations greater than background levels indicate that some N fertilizer applied to the continuous corn crop during 1991 reached the saturated zone.

Background concentrations of herbicides and herbicide metabolites in the buffer areas hampered evaluating the effects of the MSEA farming systems on ground-water quality. The median concentration of atrazine and DEA beneath the buffer areas during 1992 was 0.01  $\mu\text{g/L}$  (range from 0.01 to 0.14  $\mu\text{g/L}$ ) and 0.07  $\mu\text{g/L}$  (range from 0.01 to 0.36  $\mu\text{g/L}$ ), respectively. These detections in the buffer areas indicate a source of atrazine unrelated to the MSEA farming systems.

Atrazine concentrations beneath the cropped areas were generally indistinguishable from background concentrations. Atrazine was detected at trace levels beneath all of the cropped areas within the region of the saturated zone affected by 1991-92 recharge, as

delineated using the chloride data. The maximum concentrations of atrazine beneath the cropped areas were as follows: area A - 0.08 µg/L; area B - 0.05 µg/L; area C - 0.11 µg/L; area D - 0.09 µg/L; and area E - 0.11 µg/L. Because none of these detections exceed the maximum of 0.14 µg/L in the buffer areas, a source unrelated to the MSEA farming systems is the most likely origin of atrazine detected beneath the cropped areas. Because these detections are within the region of the saturated zone affected by 1991-92 recharge, however, it cannot be totally discounted that some of the detections may have been related to applications of atrazine to areas C, D, and E during 1991-92. If any trace-level inputs did result from MSEA atrazine applications, they could not be distinguished above the existing concentrations of atrazine.

DEA was detected more frequently during June 1992 through April 1993 (78 percent of the 361 samples) and in greater concentrations (median 0.07 µg/L; range from 0.03 to 0.77 µg/L) than any other herbicide or metabolite. DEA was detected in low concentrations (median 0.01 µg/L; range from 0.03 to 0.08 µg/L) beneath all of the cropped areas within the region of the saturated zone affected by 1991-92 recharge. The maximum DEA concentration of 0.77 µg/L was detected near the water table in the middle of area E during April 1993. The source of this DEA detection likely was application of atrazine during 1991-92 to the continuous corn crop on area E. However, additional data will be needed to conclusively evaluate whether atrazine applied as part of the MSEA farming systems reached the saturated zone.

The transport of agricultural chemicals to the water table from 1991 applications was greater than from 1992 applications. About 16 percent of the chloride applied to area C (potatoes) during 1992 reached the upper 0.5 m of the saturated zone by April 1993. This mass was about 2 percent less than the mass of chloride that reached the upper 0.5 m of the saturated zone beneath area A (potatoes) in 1991. About one percent of the N fertilizer applied to area C in 1992 reached the upper 0.5 m of the saturated zone by April 1993. This mass is about 12 percent less than the mass of N fertilizer that reached the upper 0.5 m of the saturated zone beneath area A (potatoes) in 1991. The reduced transport of chemicals to the water table during 1992 likely resulted primarily from 60 percent less ground-water recharge compared to 1991.

Results indicate that the effects of the 1992 potassium chloride and N fertilizer applications were reduced compared to the effects from 1991 applications. The primary factors associated with these reduced effects

were: (1) lower application rates in 1992 than in 1991, (2) lower recharge rates in 1992 (9 cm) than in 1991 (23 cm), and (3) varying depths to the water table. Chloride and nitrate-N concentrations were generally greatest beneath areas where the total amount of N fertilizer applied during 1991-92 were greatest. However, some of the chloride and N fertilizer applied to the cropped areas in 1992 may not have reached the saturated zone in 1993 due to a 60-percent reduction in recharge compared to 1991. Analysis of data from additional years will be required to fully evaluate the effects of the farming systems on ground-water quality.

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