ESTIMATION OF AGRICULTURAL CHEMICAL MASS IN GROUND WATER BY VOLUME MODELING TECHNIQUES

by

William A. Battaglin
A thesis submitted to the Faculty and Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Engineering (Geological Engineer).

Golden, Colorado
Date 8/21/92

Signed: [Signature]
William A. Battaglin

Approved: [Signature]
Dr. A. Keith Turner
Thesis Advisor

Golden, Colorado
Date ______________

[Signature]
Dr. Roger Slatt
Professor and Head, Department of Geology and Geological Engineering
ABSTRACT

Agricultural chemicals may occur in ground water beneath areas of agricultural activity as a result of the leaching of those chemicals from the land surface. Farming management systems may have an effect on the mass of agricultural chemicals that reach an aquifer system. At the Rosholt Research Farm in Westport, Minnesota, three farming management systems were implemented on six test plots by University of Minnesota researchers to determine if the management systems affected the movement of agricultural chemicals to the ground water.

Two techniques were developed to estimate the mass of agricultural chemicals in ground water from the sample data. Both techniques: (1) developed models that characterized the three-dimensional distribution of chemical concentrations; (2) calculated the volume of the saturated zone between concentration increments for the range of concentrations determined on each date; and (3) calculated agricultural chemical mass estimates by multiplying volumes between concentration increments by the porosity of the aquifer and the average value of the increment, and summing for all increments.

Volumetric modeling of agricultural chemical distributions at the Rosholt Research farm has demonstrated that: (1) farming management systems do affect the quality of ground water; (2) effective techniques exist for estimating the mass of agricultural chemicals in the saturated zone; (3) powerful workstations have the ability to handle the large amounts of data, large number of calculations, and high resolution of graphics required to work effectively with three-dimensional data sets; and (4) there are advantages to visualizing all sample data for a given date in one graphic display.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>ix</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>x</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Purpose</td>
<td>2</td>
</tr>
<tr>
<td>Objective</td>
<td>2</td>
</tr>
<tr>
<td>Background</td>
<td>2</td>
</tr>
<tr>
<td>Study Area Geohydrology</td>
<td>3</td>
</tr>
<tr>
<td>Site Design</td>
<td>5</td>
</tr>
<tr>
<td>Well Network</td>
<td>7</td>
</tr>
<tr>
<td>Well Design and Location Information</td>
<td>8</td>
</tr>
<tr>
<td>Well Numbering System</td>
<td>8</td>
</tr>
<tr>
<td>Previous Investigations</td>
<td>10</td>
</tr>
<tr>
<td>Approach</td>
<td>10</td>
</tr>
<tr>
<td>WELL DATA</td>
<td>15</td>
</tr>
<tr>
<td>Water-level Measurements</td>
<td>15</td>
</tr>
<tr>
<td>Nitrate Concentrations</td>
<td>15</td>
</tr>
<tr>
<td>Atrazine Concentrations</td>
<td>16</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

1. Location of observation wells, test plots, and site polygon at the Rosholt Research Farm, Minnesota ........................................ 4

2. Observation wells and well identification numbers at the Rosholt Research Farm .................................................................................................................. 9

3. Example of an IVM generated three-dimensional display of a nitrate concentration model on--
   a. August 17, 1988 ..................................................................................... 13
   b. September 9, 1989 .................................................................................. 14

4. Three-dimensional representation techniques and associated methods for calculating integral properties of solid models ....................................................... 24

5. -17. IVM generated three-dimensional display of a nitrate concentration model on--
   5. July 21, 1988 .......................................................................................... 34
   6. August 17, 1988 .................................................................................... 35
   7. April 18, 1989 ....................................................................................... 36
   8. May 5, 1989 .......................................................................................... 37
   9. May 25, 1989 ....................................................................................... 38
  11. August 9, 1989 ..................................................................................... 40
  12a. September 9, 1989 ............................................................................... 41
  12b. September 9, 1989, alternative view .................................................. 42
  13a. September 13, 1989 ........................................................................... 43
  13b. September 13, 1989, alternative view ................................................ 44
  14. October 11, 1989 ................................................................................ 45
  15. November 30, 1989 ............................................................................. 46
  16. March 22, 1990 ................................................................................... 47
  17. May 3, 1990 ......................................................................................... 48

18. Example volume report generated by IVM .................................................. 49
19. GMS generated two-dimensional display of three-dimensional nitrate concentration model on August 17, 1988, view from the-
   a. top, approximately one meter below the water-table . . . . . 53
   b. side, looking north, approximately 30 meters north of the south end of the test plots . . . . . . . . . . . . . . . 54
20. Example volume report generated by GMS . . . . . . . . . . 56
21. Boxplots of IVM generated nitrate mass estimates under each of the test plots 60
22. Boxplots of IVM generated nitrate mass estimates for the three farming management systems . . . . . . . . . . . . . . . . . . . . 62
23. Boxplots of IVM generated atrazine mass estimates for the three farming management systems . . . . . . . . . . . . . . . . . . . . 70
24. IVM generated three-dimensional display of a atrazine concentration model on September 13, 1989 . . . . . . . . . . . . . . . . . . . . 71
25. Boxplots of GMS generated nitrate mass estimates under each of the test plots. 75
26. Boxplots of GMS generated nitrate mass estimates for the three farming management systems . . . . . . . . . . . . . . . . . . . . 76
27. Regression plot of IVM generated nitrate mass estimates verses GMS generated nitrate mass estimates. . . . . . . . . . . . . . . . 78
LIST OF TABLES

Table 1. Estimated mass of --
   a. nitrogen fertilizer applied to the six test plots and within the site polygon, at the Rosholt Research Farm, Minnesota ..............................................6
   b. atrazine applied to the six test plots and within the site polygon, at the Rosholt Research Farm, Minnesota ......................................................6
Table 2. Summary statistics on water-level measurements from wells at the Rosholt Research Farm, Minnesota ..................................................17
Table 3. Summary of nitrate and atrazine concentration data from wells sampled at the Rosholt Research Farm, Minnesota .......................................18
Table 4. IVM generated estimates of nitrate mass in the saturated zone beneath the six test plots and the site polygon, at the Rosholt Research Farm, Minnesota ..............................................59
Table 5. Mean sub-plot nitrate mass estimated using IVM and GMS, and mean sub-plot atrazine mass estimated using IVM, for the three farming management systems ..............................................63
Table 6. IVM generated estimates of nitrate mass beneath the six test plots and the site polygon in the upper fifteen feet of the saturated zone ..............................................64
Table 7. Effects of the Z-influence factor on IVM generated estimates of nitrate mass in the saturated zone on September 9, 1989, beneath the six test plots and the site polygon, at the Rosholt Research Farm, Minnesota ..............................................67
Table 8. IVM generated estimates of atrazine mass in the saturated zone beneath the six test plots and the site polygon, at the Rosholt Research Farm, Minnesota ..............................................69
Table 9. GMS generated estimates of nitrate mass in the saturated zone beneath the six test plots and the site polygon, at the Rosholt Research Farm, Minnesota ..............................................74
ACKNOWLEDGMENTS

The author extends thanks to Jeff Stoner and Geoffrey Delin (U. S. Geological Survey, WRD, Minnesota) for providing technical assistance necessary for the completion of this study, to those at the University of Minnesota who did most of the analytical work and provided permission to analyze the water-quality data they collected, and to Mike Crane (U. S. Geological Survey, NMD) and Bob Bruce, Gina Boice and Dr. Keith Turner (Colorado School of Mines) for providing guidance and access to computer software and hardware required for the completion of this study.
INTRODUCTION

Two techniques for estimating the mass of agricultural chemical in ground water are compared in this report. The techniques utilize two volume modeling systems: (1) Interactive Volume Modeling\(^1\) (IVM) a proprietary software package distributed by Dynamic Graphics Inc., and (2) LYNX Geoscience Modeling System\(^1\) (GMS) a proprietary software package distributed by LYNX Geosystems Inc. The IVM and GMS systems are used in conjunction with the ARC/INFO\(^1\) geographic information system (GIS) to construct three-dimensional volume models that represent agricultural chemical concentration distributions. IVM characterizes three-dimensional concentration distributions using a minimum tension gridding algorithm which applies iterative solutions to a biharmonic cubic spline function to sample data to create a three-dimensional gridded model. GMS applies either a geostatistical (kriging), or an inverse distance technique to produce estimates of three-dimensional sample concentration distributions.

The two techniques were used to estimate the mass of either nitrate or atrazine in ground water beneath six test plots at the Rosholt Research Farm in west-central Minnesota. The Rosholt farm overlies an unconfined glacial outwash aquifer with approximately 20 feet of saturated, and 10 feet of unsaturated thickness. Data collected from 42 observation wells, for thirteen dates between July 1988 and May 1990, are used to generate three-dimensional models depicting nitrate concentration distributions. Atrazine concentration data for five dates between April 1989 and September 1989, were also modeled.

---

\(^{1}\)Use of brand names in this paper is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey or the Colorado School of Mines.
**Purpose**

The purpose of this research is to demonstrate how volumetric modeling of the occurrence of agricultural chemicals in ground water can be used to evaluate the effects of farming management systems on shallow ground-water quality. Volumetric modeling of nitrate and atrazine concentration data demonstrate: (1) two techniques for estimating the mass of nitrate and atrazine occurring as aqueous solutions in ground water, and (2) the advantages of being able to visualize the three-dimensional concentration distributions of agricultural chemicals in ground water.

**Objective**

The objective of this study is to compare two techniques for estimating the mass of nitrate and atrazine occurring in ground water beneath six test plots at the Rosholt Research Farm in west-central Minnesota. IVM and GMS volume modeling systems have been used to: (1) develop three-dimensional volume models of the concentration distributions of nitrate and atrazine in ground water, (2) develop three-dimensional displays of the volume models, and (3) perform volumetric calculations on the computed three-dimensional concentration distributions to estimate the mass of agricultural chemicals beneath six test plots at the Rosholt Research Farm. Similarities and differences between the results of the two techniques are discussed, and the two software systems are critically evaluated.

**Background**

The Rosholt Research Farm was established to evaluate the impact on ground-water quality of agricultural management systems used for corn and soybean farming (Anderson, 1989). The University of Minnesota and Pope County Soil and Water Conservation District (SWCD) have established six test plots (each about one acre in area) on the south-western side of the Rosholt farm (See Figure 1). The Rosholt Farm site has been instru-
mented to monitor agricultural chemicals in the saturated zone. Forty-two observation wells (See Figure 1) were periodically sampled for nutrients (nitrate), and triazine herbicides (atrazine). Water-level measurements were also collected at the time of sampling.

**Study Area Geohydrology**

The Rosholt farm is located on an unconfined glacial outwash sand-plain aquifer with approximately 20 feet of saturated, and 10 feet of unsaturated thickness. The near surface material at the site is characterized by hydrologic properties that tend to allow rapid movement of contaminants into the aquifer. These properties include: high hydraulic conductivity (soil, unsaturated and saturated zones), shallow depth to water-table (ten feet or less), flat topography (hence low runoff), high rates of ground-water recharge (9 inches per year), high base flow to surface-water bodies, sandy aquifer matrix (low organic and clay content), and large annual temperature fluctuations. Aquifer porosity and hydraulic conductivity at the Rosholt Farm were estimated from analysis of a 31-hour aquifer test to be 0.27, and 1250 feet per day, respectively (Anderson and Stoner, 1989). Analysis of well logs collected during the installation of the observation wells indicate that some local variability in grain size distributions occurs at the site, but no consistent or site-wide stratification is evident that may affect the movement of agricultural chemicals. The aquifer was modeled as being homogeneous and isotropic.

The unconfined glacial outwash sand-plain aquifer overlies a glacial till. This till is an unstratified, unsorted mixture of clay, silt, sand, and gravel (Van Voast, 1971). Glacial tills that are high in clay and silt content generally have low permeability and act as aquitards (Freeze and Cherry, 1979). The soil in the study area is a sandy loam that is generally less than two feet thick (Anderson and Stoner, 1989).
Figure 1.--Location of observation wells, test plots, and site polygon at the Rosholt Research Farm, Minnesota
Site Design

The Rosholt Research Farm was originally designed to accommodate five major areas of water-quality research: (1) water movement in soils and the vadose zone, (2) nitrogen fate and management, (3) pesticide fate and management, (4) tillage and movement of agricultural chemicals to ground water, and (5) land application of incinerator ash (Anderson, 1989). Six test plots, each about 1 acre in area, were established on the southwestern side of the farm to evaluate three common corn and soybean agricultural management systems. The three farming management systems were implemented on the test plots as follows: (1) continuous cropping of corn using 160 pounds of nitrogen fertilizer and 454 grams of atrazine per acre, on plots 1 and 3; (2) continuous cropping of corn using 214 pounds of nitrogen fertilizer and 454 grams of atrazine per acre, on plots 2 and 5; and (3) a corn-soybeans crop rotation sequence (corn on even years) with 160 pounds of nitrogen fertilizer and 454 grams of atrazine per acre applied on corn, and 15 pounds nitrogen fertilizer per acre (no atrazine) applied on soybeans, on plots 4 and 6 (Anderson and Stoner, 1989). Estimates of the mass of nitrate and atrazine applied to the six test plots for the years 1986 through 1990 are given in Tables 1a and 1b. Rates of application for nitrogen fertilizer on soybeans, and atrazine on corn, were estimated using average usage rates for Minnesota (Agricultural Statistics Board, 1991).

A total of forty-six observation wells were installed at the site between 1986 and 1988. The wells were installed so that the screens were at one of three depth levels: (1) near the top of the saturated zone, (2) near the middle of the saturated zone, and (3) near the bottom of the saturated zone. More detailed information about the observation wells is given in the next section.
Table 1a.--Estimated mass of nitrogen fertilizer applied to the six test plots and within the site polygon, at the Rosholt Research Farm, Minnesota

<table>
<thead>
<tr>
<th>Year</th>
<th>Plot 1</th>
<th>Plot 2</th>
<th>Plot 3</th>
<th>Plot 4</th>
<th>Plot 5</th>
<th>Plot 6</th>
<th>Site Polygon</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986</td>
<td>134</td>
<td>177</td>
<td>134</td>
<td>124</td>
<td>214</td>
<td>165</td>
<td>938</td>
</tr>
<tr>
<td>1987</td>
<td>134</td>
<td>177</td>
<td>134</td>
<td>12</td>
<td>214</td>
<td>17</td>
<td>688</td>
</tr>
<tr>
<td>1988</td>
<td>134</td>
<td>177</td>
<td>134</td>
<td>124</td>
<td>214</td>
<td>165</td>
<td>938</td>
</tr>
<tr>
<td>1989</td>
<td>134</td>
<td>177</td>
<td>134</td>
<td>12</td>
<td>214</td>
<td>17</td>
<td>688</td>
</tr>
<tr>
<td>1990</td>
<td>134</td>
<td>177</td>
<td>134</td>
<td>124</td>
<td>214</td>
<td>165</td>
<td>938</td>
</tr>
</tbody>
</table>

Table 1b.--Estimated mass of atrazine applied to the six test plots and within the site polygon at the Rosholt Research Farm, Minnesota

<table>
<thead>
<tr>
<th>Year</th>
<th>Plot 1</th>
<th>Plot 2</th>
<th>Plot 3</th>
<th>Plot 4</th>
<th>Plot 5</th>
<th>Plot 6</th>
<th>Site Polygon</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986</td>
<td>381</td>
<td>376</td>
<td>381</td>
<td>349</td>
<td>454</td>
<td>467</td>
<td>2,409</td>
</tr>
<tr>
<td>1987</td>
<td>381</td>
<td>376</td>
<td>381</td>
<td>0</td>
<td>454</td>
<td>0</td>
<td>1,592</td>
</tr>
<tr>
<td>1988</td>
<td>381</td>
<td>376</td>
<td>381</td>
<td>349</td>
<td>454</td>
<td>467</td>
<td>2,409</td>
</tr>
<tr>
<td>1989</td>
<td>381</td>
<td>376</td>
<td>381</td>
<td>0</td>
<td>454</td>
<td>0</td>
<td>1,592</td>
</tr>
<tr>
<td>1990</td>
<td>381</td>
<td>376</td>
<td>381</td>
<td>349</td>
<td>454</td>
<td>467</td>
<td>2,409</td>
</tr>
</tbody>
</table>
Three features of the site design have an effect on the results of the experiment. First, the fields are oriented north-south, and the direction of ground-water flow is to the northeast (See Figure 1). This results in cross-contamination between the plots, a problem that was identified by earlier researchers and confirmed by visualization of three-dimensional nitrate models generated using IVM (Geoffery Delin, USGS-WRD, personal commun.). In particular, test plots that received high rates of the nitrogen fertilization (2 and 5) contaminated ground water beneath test plots 3 and 6 that were downgradient and that received lower rates of nitrogen fertilization. Second, the plots were separated by narrow grass strips less than 25 feet across. Even if the plots were oriented in the direction of ground-water flow, it is unclear that this amount of separation would be adequate to eliminate problems of cross-contamination between plots. Third, other agricultural experiments, some that included the application of agricultural chemicals, took place at the Rosholt farm in the area to the North of the six test plots (See Figure 1), and other farming (not at the research farm) took place to the east the site. Thus, concentrations of agricultural chemicals measured in wells to the north and east of the test plots (See Figure 1) may not solely reflect effects resulting from activities on the test plots, and have limited use in defining background conditions at the site.

**Well Network**

A network of 46 observation wells were installed at the Rosholt Research Farm between 1986 and 1988. Most of the wells were clustered around the six test plots in the southwestern portion of the research farm. Other wells were located up and down gradient from the test plots (See Figure 1). Forty-two of the 46 wells were periodically sampled for concentrations of atrazine and nitrate. Water-level measurements were usually collected at the time of sampling. Of the forty-two regularly sampled wells, 25 were screened near the top of the saturated zone, 12 were screened near the middle of the saturated zone, and 5 were screened near the bottom of the saturated zone. The remaining 4 of the 46 wells that were not sampled for ground-water quality were installed to monitor drawdown resulting...
from the pumping of an irrigation well located in the northwest corner of the research farm (See Figure 2).

**Well Design and Location Information**

All observation wells were constructed using two-inch diameter galvanized-steel casing completed with 2- or 3-foot-long screens (Anderson and Stoner, 1989). All wells were installed by personnel from the Minnesota district office of the U.S. Geological Survey, WRD. Well location information for the 46 observation wells including land-surface and screen-midpoint altitudes are given in Appendix A.

**Well Numbering System**

The well numbering system provides information on well location, depth, and relative position with regard to the test plots. All well identification numbers (WIDs) begin with the letter ‘W’ and a number where 0 means the well is upgradient, 9 means the well is downgradient, and 1-6 means the well is associated with test plot 1-6. The second character denotes the depth of the well where L means the well is screened in the lower portion of the saturated zone, M means the well is screened in the middle of the saturated zone, and U means the well is screened in the upper portion of the saturated zone. The final four numbers of the well identification represent the relative location of the well in feet south of the northern boundary of the research farm. The WIDs of the wells at the research farm are shown on Figure 2.
Figure 2. Observation wells and well identification numbers at the Rosholt Research Farm.
Previous Investigations

The geology and hydrology of the glacial-outwash sand-plain aquifers of southern Minnesota were first described in a report by Hall and others, 1911. Two more recent reports by Cotter and others, 1968, and Van Voast, 1971, provided more detail on the size and hydrologic characteristics of the sand-plain aquifers. The report by Van Voast includes plates summarizing surficial and sub-surficial materials, depth to water-table, saturated thickness, transmissivity, and theoretical maximum yields for individual wells, for an area that includes the study area.

Approach

The techniques developed are based on the assumption that the mass of an agricultural chemical in the saturated zone beneath test plots can be related to the farming management systems used on the test plots. By converting concentrations at discrete locations (observation wells) to estimates of agricultural chemical mass within areas immediately beneath test plots, biases that result from looking at concentrations in individual wells are eliminated, resulting in a more quantitative means of assessing the impacts that farming management systems have on shallow ground-water quality.

Two techniques, utilizing the IVM and GMS systems respectively, were used to estimate the mass of nitrate in aqueous solution in the ground-water beneath the six test plots. For both techniques, the available concentration data from the 42 observation wells were used to simulate thirteen three-dimensional models depicting nitrate concentrations from July 21, 1988 to May 3, 1990. The IVM technique was also used to simulate five three-dimensional models depicting atrazine concentrations from April 18, 1989 to September 13, 1989.

The IVM technique produced three-dimensional grids containing estimated values of the concentration of an agricultural chemical from scattered data points (sampling locations) using a minimum tension gridding algorithm (iterative solutions to a biharmonic
cubic spline function). The three-dimensional grids can be contoured in a manner similar to two-dimensional contour maps, in this case producing a display file consisting of a series of isovalue surfaces that show the three-dimensional concentration distribution of the substance (See Figures 3a and 3b). The volume of a region between two isovalue surfaces (or shells) can be calculated from the three-dimensional grid.

Agricultural chemical mass estimates were calculated using IVM by multiplying volumes between concentration increments (isovalue surfaces) by the porosity of the aquifer and the average value of the increment, and then summing for all increments. The region where the volumes were calculated was limited laterally by test plot boundary polygons (See Figure 1), and vertically by two-dimensional surfaces representing the altitude of the water-table (the upper limit), and the altitude of the base of the sand-plain aquifer (the lower limit).

The LYNX Geoscience Modeling System (GMS) was also used to produce three-dimensional grids containing estimated values of the concentration of an agricultural chemical from scattered data points. GMS uses either geostatistical (kriging) techniques or an inverse distance technique to produce gridded estimates of concentration values. Once gridded estimates are developed, GMS applies a method of successive slices to calculate volumes of the model above and below a specified threshold value. This procedure is repeated for a number of thresholds, covering the range of concentrations observed in the model. The mass estimates were then calculated by multiplying volumes between concentration thresholds by the porosity of the aquifer and the average value of the thresholds, and then summing for all thresholds. The region where the volumes were calculated was bounded laterally by the test plot boundaries, and vertically by planes representing the mean water-table altitude (upper limit), and the mean altitude of the base of the sand-plain aquifer (lower limit).

More detail on the procedures used for the two techniques are given later in the report. Once the masses were calculated statistical tests were used to determine the relations between farming management systems on the test plots, and agricultural chemical
masses in the saturated zone beneath the test plots.

All geographic, geologic, and water-quality data used for this study were managed using the ARC/INFO GIS. Programs were written that extract data from this GIS and convert it into forms that could be read by the volume modeling computer programs. All methods development and computer analysis were performed using computer resources that were made available by either the U.S. Geological Survey’s Central Region Geographic Information System laboratory, the Center for Geoscience Computing at the Colorado School of Mines, or the Water-Resources Division Central Region Office of the U.S. Geological Survey.
Nitrate concentrations on 8/17/88 at the Rosholt Research Farm

Figure 3a.—Example of an IVM generated three-dimensional display of a nitrate concentration model on August 17, 1988
Nitrate Concentrations on 9/7/89 at the Rosholt Research Farm

Figure 3b.—Example of an IVM generated three-dimensional display of a nitrate concentration model on September 9, 1989
WELL DATA

Water-level measurements, and nitrate and atrazine concentration data have been collected periodically from observation wells at the Rosholt Research Farm since October, 1986. This study used data collected between July 21, 1988 and May 3, 1990. These dates were chosen because they represent the time period with the most complete three-dimensional distribution of data. Prior to the summer of 1988 less than 20 observation wells had been installed and sampled on a regular basis at the Rosholt Research Farm.

Water-level Measurements

Water-level measurements were generally collected on the same day that water-quality sampling was done. In some cases, water-levels measurements were not collected on a sampling date. For these dates, water-level measurement from the date closest to the sampling date were used to generate the water-table surfaces or mean water-table altitudes. Water-level measurements were collected to the hundredth of an inch. Water-level data collected with this level accuracy can be used to indicate how hydrologic conditions have changed between measurement dates. Changes in mean water-levels altitudes can be used as a indication of when recharge has occurred, or when stream baseflow levels have risen or fallen. Table 2 shows summary statistics for the water-level data that was used in this study. The actual water-level measurements are given in Appendix B.

Nitrate Concentrations

Nitrate concentration data were collected on thirteen dates during the study period. All nitrate concentration data were reported in milligrams per liter (mg/L) of nitrate as nitrogen. All nitrate analysis used for this study were done at the University of Minnesota’s Center for Agricultural Impacts on Water Quality Laboratory (Anderson, 1989). On
several dates duplicate samples were collected and analyzed at the United States Geological Survey’s National Water Quality Laboratory in Arvada, Colorado. Based on results of comparisons between the duplicate samples, the QA/QC at the University of Minnesota laboratory was excellent and the data are representative of field conditions (Geoffery Delin, USGS-WRD, personal commun.). The number of wells sampled, and mean, median, and maximum nitrate concentration for each sampling date are shown in Table 3. The actual nitrate concentration data used for this study are shown in Appendix C.

**Atrazine Concentrations**

Atrazine concentration data were collected on five dates between April 1989 and September 1989. All atrazine concentration data were reported in micrograms per liter (ug/L). All atrazine analysis used for this study were done at the University of Minnesota’s Center for Agricultural Impacts on Water Quality Laboratory (Anderson, 1989). On several dates duplicate samples were collected and analyzed at the United States Geological Survey’s National Water Quality Laboratory in Arvada, Colorado, and in the field using immunoassay techniques. Based on results of comparisons between the duplicate samples, the QA/QC at the University of Minnesota laboratory was excellent and the data are representative of field conditions (Geoffery Delin, USGS-WRD, personal commun.). The number of wells sampled, and mean, median, and maximum atrazine concentration for each sampling date are shown in Table 3. The actual atrazine concentration data used for this study are shown in Appendix D.
Table 2.—Summary statistics on water-level measurements from wells at the Rosholt Research Farm, Minnesota

<table>
<thead>
<tr>
<th>Date</th>
<th>Wells Measured</th>
<th>Mean Water-level (feet above sea level)</th>
<th>Median Water-level (feet above sea level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>07/28/88</td>
<td>39</td>
<td>1,322.38</td>
<td>1,322.40</td>
</tr>
<tr>
<td>08/16/88</td>
<td>39</td>
<td>1,322.91</td>
<td>1,322.88</td>
</tr>
<tr>
<td>04/18/89</td>
<td>41</td>
<td>1,324.53</td>
<td>1,324.52</td>
</tr>
<tr>
<td>05/03/89</td>
<td>42</td>
<td>1,324.41</td>
<td>1,324.40</td>
</tr>
<tr>
<td>05/25/89</td>
<td>40</td>
<td>1,324.06</td>
<td>1,324.03</td>
</tr>
<tr>
<td>07/12/89</td>
<td>41</td>
<td>1,323.67</td>
<td>1,323.64</td>
</tr>
<tr>
<td>08/08/89</td>
<td>42</td>
<td>1,323.13</td>
<td>1,323.08</td>
</tr>
<tr>
<td>09/07/89</td>
<td>42</td>
<td>1,323.71</td>
<td>1,323.66</td>
</tr>
<tr>
<td>09/13/89</td>
<td>42</td>
<td>1,323.76</td>
<td>1,323.71</td>
</tr>
<tr>
<td>10/12/89</td>
<td>42</td>
<td>1,323.66</td>
<td>1,323.61</td>
</tr>
<tr>
<td>11/30/89</td>
<td>42</td>
<td>1,323.42</td>
<td>1,323.43</td>
</tr>
<tr>
<td>03/22/90</td>
<td>42</td>
<td>1,323.39</td>
<td>1,323.40</td>
</tr>
<tr>
<td>05/03/90</td>
<td>42</td>
<td>1,324.03</td>
<td>1,324.04</td>
</tr>
</tbody>
</table>
Table 3.--Summary of nitrate and atrazine concentration data from wells sampled at the Rosholt Research Farm, Minnesota

<table>
<thead>
<tr>
<th>Date</th>
<th>Sampled Wells</th>
<th>Nitrate Concentration (mg/L)</th>
<th>Atrazine Concentration (ug/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Median</td>
<td>Mean</td>
<td>Maximum</td>
</tr>
<tr>
<td>07/21/88</td>
<td>42</td>
<td>6.45</td>
<td>6.11</td>
</tr>
<tr>
<td>08/17/88</td>
<td>43</td>
<td>7.80</td>
<td>8.31</td>
</tr>
<tr>
<td>04/18/89</td>
<td>42</td>
<td>5.25</td>
<td>5.36</td>
</tr>
<tr>
<td>05/03/89</td>
<td>42</td>
<td>7.55</td>
<td>6.27</td>
</tr>
<tr>
<td>05/25/89</td>
<td>40</td>
<td>7.55</td>
<td>5.99</td>
</tr>
<tr>
<td>07/07/89</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>07/10/89</td>
<td>41</td>
<td>7.20</td>
<td>6.65</td>
</tr>
<tr>
<td>08/09/89</td>
<td>42</td>
<td>7.35</td>
<td>7.74</td>
</tr>
<tr>
<td>09/07/89</td>
<td>42</td>
<td>7.25</td>
<td>9.67</td>
</tr>
<tr>
<td>09/13/89</td>
<td>42</td>
<td>6.95</td>
<td>10.46</td>
</tr>
<tr>
<td>10/11/89</td>
<td>40</td>
<td>5.75</td>
<td>11.68</td>
</tr>
<tr>
<td>11/30/89</td>
<td>42</td>
<td>6.80</td>
<td>9.64</td>
</tr>
<tr>
<td>03/22/90</td>
<td>39</td>
<td>5.70</td>
<td>7.51</td>
</tr>
<tr>
<td>05/03/90</td>
<td>42</td>
<td>5.85</td>
<td>7.65</td>
</tr>
</tbody>
</table>
GEOGRAPHIC INFORMATION SYSTEM

The ARC/INFO geographic information system was used to manage and store all geographic, geologic, and water-quality data used for this study. Initially ARC/INFO executed on a Prime 9955 microcomputer. Later, applications were transferred to and executed on a Data General Aviion 300 Unix workstation. ARC/INFO was an excellent tool for storing and managing the data used in this study. ARC/INFO was used to create numerous applications for analyzing and displaying data, and for converting data into forms that could be read by the volume modeling computer programs.

GIS Data Base

The database used for this study contained three basic types of information: water-quality data, geohydrologic data, and map data. Water-quality data, specifically nitrate and atrazine concentration data, were stored as ARC/INFO point coverages where each well was represented by a point. Items (columns of attribute values) containing the concentration values for each sampling date were added to the point coverages. Other attributes stored in the water-quality point coverage included the well identification number, landsurface altitude, screen-midpoint altitude, and x- and y-coordinates (in meters) of the well projected in an Alber’s equal area map projection. Documentation for the coverages WELLS.NIT (nitrate data) and WELLS.ATR (atrazine data) are in Appendix E.

Geohydrologic data were stored in both ARC/INFO point and line coverages. The altitude of the basal till, used during the mass calculation procedure, was estimated for the site in a two step process. First, the altitude of the till surface was determined from well-log data for 10 wells at the site. This data was augmented by digitizing and attributing a portion of a till surface structure contour map (Van Voast, 1971, Figure 3). Together these two sources of till surface altitude data were used to generate a triangulated irregular network (TIN) representation of the till surface. Second, the TIN was resampled at regularly spaced points (every 25 meters) to produce a grid of till altitudes that extended beyond the
immediate study area. This grid of points was then imported into the Interactive Surface Modeling (ISM) software which used the points to generate a two-dimensional surface that could be used to bound volume models in IVM.

A similar procedure was used to define water-table surfaces for each of the sampling dates. First, a generalized water-level map was digitized (Van Voast, 1971, pl. 1, map C) and used to estimate the water-level at 6 control points surrounding the study area. These water-level estimates, and the actual water-level measurements for a given date, were used to generate TIN’s representing the altitude of the water-table. Second, the TIN’s were resampled on a regular grid of points (25 meter spacing) and the data were imported into ISM and used to generate two-dimensional surfaces representing the water-table. The water-table surfaces were used to bound volume models in IVM. The surfaces representing the top of the till, and the individual water-table for a given date, defined the extent of the saturated zone for a given date. Documentation for the coverage WELLS.WL (water-level data) is in Appendix E.

Map data were stored as ARC/INFO line and polygon coverages. These coverages include a line coverage of the general basemap, and polygon coverages of the test plot boundaries, the site polygon, and the Minnesota state boundary (See Figure 1). The polygon coverages of the test plot and site boundaries were used in the analysis of agricultural chemical mass. These coverages were converted into ASCII files of sets of x-y coordinate pairs by use of the ARC/INFO “ungenerate” command. Header information was edited onto these files and they were imported into IVM and made into polygon files. The polygons described in these files were used to bound volume models horizontally during volume calculations in IVM. The x-y coordinate pairs defining the outlines of the test plots and site polygon were also used to define the horizontal extent of geologic models in GMS.
**Interface With Volume Modeling Systems**

A series of ARC/INFO macro language programs (AMLs) acted as an interface between the GIS and the volume modeling systems. AMLs were written that extracted nitrate or atrazine concentration data and water-level data from the point coverages and formatted the data for importing into IVM. The AML codes are listed in Appendix F. While not a true interactive interface, these programs automated the procedure for converting data in the database to the ASCII data files that could be imported by the volume modeling systems. C-shell scripts (Shown in Appendix G) were used to run IVM and ISM. The input data format for GMS was more complex and manual editing of a template file (Appendix I) was required to make new ASCII well-log files that could be imported into GMS.
VOLUME MODELING

Introduction

The ability to estimate the volume and other integral properties of three-dimensional solid objects is a fundamental requirement of volume modeling systems (also referred to as geoscientific information systems (GSIS)) (Bak and Mill, 1989, Turner, 1991). Without this ability, and the ability to perform Boolean type operations between one or more three-dimensional models, existing volume modeling software (i.e. IVM, or GMS) would be little different from three-dimensional rendering software systems.

True three-dimensional representations of data have numerous advantages over two-dimensional representations. These advantages include the ability to: (1) visualize large and complex three-dimensional data sets (i.e. site geology), (2) visualize an entire data set at once (i.e. contaminant plume data), (3) determine integral properties of the modeled area (i.e. volume) accurately, and (4) provide input to three-dimensional simulation programs (Jones and Leonard, 1990). These advantages allow the three-dimensional model builder to better interact with their data, and to perhaps gain the creative insight that is needed to correctly interpret their data. In the past, computers that were available to the general user were unable to handle the volume of data, the number of calculations, or the resolution of graphics required to work effectively with three-dimensional data sets (Turner, 1990). Flynn (1990) estimates that manipulation of three-dimensional solids requires 20,000 times the computing power required to manipulate two-dimensional wire-frame models. The advent of modern graphics-oriented workstations, such as the Silicon Graphics and IBM RS/6000 workstations, has put the power required to handle three-dimensional data within reach of a larger number of scientists (Turner, 1990).

The methods for calculating integral properties from solid models is largely dependent upon the method used for representing those objects. Five solid model representation methods are summarized by Lee and Requicha (1982), and are discussed further in the fol-
lowing section. Associated with each representation method is a method for calculating the integral properties of the solid model (See Figure 4).

All of the methods for calculating the integral properties of a solid model are attempting to evaluate the triple (volumetric) integral shown in Equation 1, were \( I \) is volume; \( S \) is a solid; \( F(P) \) is a function of \( X, Y, \) and \( Z \); and \( dV \) is the volume differential.

\[
I = \int_S F(P) \, dV
\]  

(1)

It should be noted that most commonly studied applications of multiple integration deal with situations were \( S \) is geometrically simple and the function \( F \) is complex. In the mass property calculations the inverse is true: \( F \) is a simple function and \( S \) is a complex shape (Lee and Requicha, 1982). The accuracy of the methods used for volume estimation are largely controlled by errors in approximating the solid, and not to more traditional sources of numerical error such as round-off, truncation, numerical cancellation, or approximate integration formulas (Lee and Requicha, 1982).

**Basic Methods for Three-Dimensional Representation and Associated Volume Calculation Techniques**

Lee and Requicha (1982) define five methods of solid model representation, namely: (1) primitive instances, (2) quasidisjoint decomposition, (3) simple sweeps, (4) boundary representations, and (5) constructive solid geometry representations. The volume estimation techniques which are most commonly associated with these representation techniques are respectively: (1) special formula, (2) spatial separability, (3) dimensional separability, (4) surface to surface integration, and (5) divide and conquer.
Figure 4.—Three-dimensional representation techniques and associated methods for calculating integral properties of solid models
**Primitive Instancing**

The primitive instancing representation method describes an object as one or more instances of geometric primitives. Primitives are simple geometric forms such as cubes or prisms. Instances are individual realizations of primitives, for example, a cube with sides each 1 meter long. To compute integral properties of objects represented by primitive instancing, a special formula is required for each primitive. For example, Equation 2 is the formula for calculating the volume of a cube were $L$ is the length of a side of the cube. This formula is valid for any instance of the cube primitive.

$$Volume = L^3$$

(2)

Primitive instancing works well for situations were the solid being modeled is relatively simple. Man-made or “designed objects” would generally fit into this category, but “revealed” or “geo-objects” generally would not (Fried and Leonard, 1990). A disadvantage of primitive instancing is that coding overhead and software size increases with increased numbers of, and complexity of primitives (Lee and Requicha, 1982).

**Quasidisjoint Decomposition**

A quasidisjoint decomposition representation of a solid is a segmentation of the solid into smaller solid cells that have no holes and disjoint interiors (Lee and Requicha, 1982). Cells can be a variety of shapes but are commonly tetrahedral or cubic. When all cells are identical in shape and size, the decomposition is referred to as spatial enumeration (Brunet, 1991). When cell sizes are power-of-two multiples of a minimum size cube, the decomposition is referred to as an octree. To compute integral properties of objects represented by decomposition, a technique referred to as spatial separability is applied. The object is first decomposed or separated spatially into component cells with simple shapes. Then the integral properties of the individual shapes are calculated in a manner similar to that used for primitive instancing. The disadvantages of this method are similar to those for primitive instancing; many complex shapes can not be well represented by simple
building blocks. In addition, the methods for decomposing complex shapes into simple components are not fully automated (Lee and Requicha, 1982).

**Simple Sweeps**

A simple sweep representation of a solid is based upon the idea that a solid can be generated by translating or rotating a two-dimensional shape. In general, the domain of useful objects that can be represented by simple sweeping is limited to those objects that exhibit translational or rotational symmetry (Requicha and Voelcker, 1982). This implies that simple sweep representations are best suited for designed objects. Integral properties of swept objects are computed by taking advantage of the dimensional separability of the swept object. The volume triple integral can be broken down into an area double integral that is then solved over a planar set. The methods for calculating integral properties of objects defined by more complex sweeping operations are not known (Lee and Requicha, 1982).

**Boundary Representation**

A boundary representation of a solid is perhaps the most commonly used representation technique in computer graphics applications today. The solid is represented by segmenting its surface into non-overlapping “patches” for which information about the edges of the patch and the surface on which the patch lies are known (Lee and Requicha, 1982). Boundary representations are difficult and time consuming to construct. Most systems that use boundary representation for display purposes construct them from other representations via conversion algorithms (Requicha and Voelcker, 1982). Integral properties of objects defined by boundary representations are calculated either by direct integration, or by applying the divergence theorem of vector calculus. Both methods provide accurate results for polyhedral objects, but irregular geo-objects cause some difficulty. Curved objects can be accommodated either through polyhedral approximation of the object (a method similar to primitive instancing), or by approximate integration over surface
patches. The magnitude of error introduced by these two “fixes” has not been extensively studied (Lee and Requicha, 1982).

**Constructive Solid Geometry**

A constructive solid geometry (CSG) representation of a solid is a tree whose nonterminal nodes represent operators and whose leaves represent primitive solids (Lee and Requicha, 1982). A CSG representation of a solid is constructed by adding or subtracting simple primitive “blocks”. The integral properties of solids represented by CSG are calculated using a “divide and conquer” strategy, were integrals for the primitive components to be added or subtracted are solved individually. Calculation of integral properties of CSG solids suffers from the same problems encountered when performing volumetric calculations on models generated by decomposition or primitive instancing. As the solids become more natural and less regular, the computation time required to solve for integral properties increases, and the accuracy of the solution becomes more difficult to evaluate (Lee and Requicha, 1982). Currently, the best means of solving for integral properties of solids represented by CSG involves converting those CSG models to either boundary representations or quasidisjoint cuboid cell decompositions, and then solving for integral properties (Lee and Requicha, 1982).

**Other Methods for Calculating Integral Properties of Solid Models**

Two other methods for calculating the integral properties of a solid are discussed in the literature. The simplest of these involves conversion of one of the five representation types to another type and then solving for the integral properties using the method commonly applied to the converted solid representation type. Conversions of this type are commonly done with solids represented by quasidisjoint decomposition, and constructive solid geometry (See Figure 4). Such conversions are often performed to avoid problems associated with constructive solid geometry representation such as exponential growth of the number of primitives required to portray complex solids (Lee and Requicha, 1982).
A second method for calculating the integral properties of a solid is to apply a Monte Carlo type method of integral approximation. For this type of solution the solid is enclosed in a bounding cuboid. Then Equation 3 is solved were \( I_e \) is the desired volume, \( V_b \) is the volume of the cuboid, \( N \) is the number of points, and \( F(P_i) \) is a characteristic function equal to one if the point is within the solid, and zero if the point is outside the solid. The major drawback of this method is that the value for \( I_e \) converges to the correct value for \( I \) only as \( N \) increases to a very large number. Thus to acquire accurate results, large computation times may be required (Lee and Requicha, 1982).

\[
\begin{align*}
(I_e) &= \left( \frac{(V_b)}{N} \right) \sum_i F(P_i)
\end{align*}
\] (3)

**Volumetric Modeling Using Commercially Available Software**

A number of software systems are able to perform some volumetric modeling. It should be noted that volumetric modeling is still a very new technology. Hardware, and in particular software, for modeling and rendering of three-dimensional data was essentially unavailable prior to the 1990's (Flynn, 1990).

In order to address three-dimensional problems, software should meet three basic requirements; modeling of source information, visualization of modeled results, and analysis of modeled results (Belcher and Paradis, 1991). Modeling of the data involves the transformation of measured or calculated three-dimensional property data into a continuous representation of that information within the area to be modeled. This process is similar to contouring of scattered data in two dimensions. Visualization of three-dimensional data allows the user to see the results of the modeling process. Visualizations of three-dimensional data are important because of the way they appeal to our brains and to our eyes (Van Driel, 1989). Although the ability to model data and perform calculations on the modeled results may have more scientific application, it is visualization of the models that
can provide critical insight into the behavior of the modeled parameter, and it is often visualization of the models that removes ambiguity in communication of scientific results among researchers. Three-dimensional visualization techniques are also required for validation of complex three-dimensional models (Turner, 1991). The ability to perform volumetric analysis or boolean operations on three-dimensional models is one feature that separates volume modeling systems from three-dimensional rendering software. It is this ability that enables the researcher to go beyond the creation of “pretty pictures” and to do quantitative analysis of three-dimensional models. In the following sections of this report, two volume modeling software systems, IVM and GMS, are described.

**IVM**

Interactive Volume modeling software (IVM) is a proprietary software package sold by Dynamic Graphics, Inc. IVM software models, displays, and analyzes properties or characteristics that vary continuously in three dimensions (Dynamic Graphics, Inc., 1990). IVM software is being used for a broad range of applications including petroleum resource analyses, environmental assessments, atmospheric studies, and oceanographic studies (Belcher and Paradis, 1991). For this research IVM was used to model the distribution of nitrate and atrazine concentrations in the saturated zone beneath the Rosholt Research Farm.

**Software Design**

The primary functions of IVM are executed in three main programs. The IVMCalc program performs all data-related calculations including gridding, volumetrics, and grid related operations. IVMCalc is also used for data management operations such as data import, export, and file deletion, and to prepare display files for later visualization. Starting the IVMCalc program initiates a dialogue of questions which are answered by the user in order to perform specific tasks (Dynamic Graphics Inc., 1990). All data used by IVM for this research were imported from ASCII data files (Shown in Appendix I). All calcula-
tions and analysis performed for this research were done using version 4.0 of the IVMCalc program.

Interactive surface modeling software (ISM) by Dynamic Graphic Inc., must be installed for IVM to work. ISM is a two-dimensional or surface modeling package that serves as a companion to IVM. ISM generates two-dimensional surfaces that can be used to bound display files for visualization, and three-dimensional gridded models for volumetric calculations. Starting the ISM program initiates a dialogue of questions which are answered by the user in order to perform specific tasks. All calculations and analysis performed for this research were done using version 7.0 of the ISM software.

The IVMDraw program displays three-dimensional models after they have been converted into display files, and allows the user to interact with those displays. Starting the IVMDraw program initiates a graphical user interface (GUI) through which the user selects, displays, modifies, and in other ways interacts with a representation of the three-dimensional model. The user has control over most aspects of the display including: color of isovalue shells, point of view, z-exaggeration, various cuts into the model, and the range of isovalue shells displayed. All displays shown in this document were generated using either version 4.0 of IVMDraw, or a test release of version 5.0 of IVMDraw.

**Data modeling - Gridding Algorithm**

IVM software models data by applying an extension of the minimum tension gridding algorithm to create three-dimensional grids of estimated property values from scattered data points (Belcher and Paradis, 1991). The minimum tension algorithm (also called minimum curvature) has been used by geoscientists to produce machine contoured maps of bathymetry (National Geophysical Data Center, 1988), and magnetic and gravity anomalies (Geological Society of America Map Committees, 1987), largely because of the algorithm’s ability to generate results that are an adequate substitute to hand drafted maps (Briggs, 1974). The minimum tension gridding algorithm in its unaltered form honors the data at constrained points, but may have oscillation (loops or excessive curvature)
between widely spaced points or in unconstrained areas (Smith and Wessel, 1990). These oscillations can be reduced by either relaxing the requirement that source data be honored exactly, or by relaxing the constraint that total curvature be minimized by adding some tension to the splines (Smith and Wessel, 1990). IVM may utilize one of these techniques, but the precise details of the IVM gridding algorithm are proprietary.

The initial step in the minimum tension gridding procedure is to estimate parameter values at each grid node from the input scattered data. This initial solution is iteratively reevaluated using a biharmonic cubic spline function. The scattered input data are used as feedback to guide the iteration process. The minimum tension gridding technique has the effect of distributing the curvature of isovalue surfaces, rather than concentrating that curvature at sample points.

IVM also allows the user to generate gridded data models in other applications and import those gridded data sets into IVM. Once data are imported into IVM, volumetric calculations can be performed on the data, and display files of the modeled data can be generated.

**Visualization**

Model display files (called ‘filename’.faces file in IVM) are generated by the IVM-Calc program. Dynamic visualization of model results is accomplished by viewing these display files with the IVMDraw program. The display files show isovalue surfaces of the data at a user specified contour interval (See Figure 3). The isovalue surfaces are interpolated throughout the gridded model using a three-dimensional equivalent of two-dimensional isovalue line threading. The isovalue surfaces are displayed as color-filled, Gouraud shaded bodies (Belcher and Paradis, 1991).

Figures 3, and 5 through 17, demonstrate some of the functionality that is available in controlling three-dimensional displays in IVM. All the model displays have been truncated with a surface representing the water-table, and a surface representing the top of the underlying till. Some of the views shown have been cut by either the test plot boundaries
(See Figure 3), or by a polygon that enclosed the immediate area of interest at the Rosholt Research Farm (See Figures 5 through 17). Some of the controls on the displayed image must be done prior to visualization (by IVMCalc). However, once built, the user can modify the displayed image in many ways. IVM contains an interactive color table editor used to generate custom color tables to highlight important concepts or thresholds. For example, in Figures 5 through 17, the change in color between blues and greens occurs at 10 mg/L, which is the drinking water standard for nitrate. The internal portions of the model can be revealed by cutting away portions of the model along the X,Y, or Z axes; or successive concentration shells can be peeled away; or, by using the chair mode, which removes a volume bounded by the X, Y, and Z axis from the front corner of the model view (Belcher and Paradis, 1991)(See Figure 3).

**Data Analysis - Method of Volume Calculation**

The IVM software can estimate the volume between two isovalue surfaces (shells) from a previously defined gridded model. IVM uses a unique method for calculating volumes that is similar to both the divide and conquer technique and a decomposition technique (Lee and Requicha, 1982). To calculate volumes, IVM first creates a boundary representation defining two isovalue surfaces from the gridded model. Then each cell in the gridded three-dimensional model is divided into subcells. The thickness between the isovalue surfaces is then calculated from the boundary representation at the centroid of each subcell. The thickness for each subcell with a positive thickness is averaged and multiplied by the area of positive thickness within the grid cell to get the volume between the isovalue surfaces within each grid cell. The volumes are then summed for all grid cells.

The term “volume container” refers to a geometric solid that defines the region in which a volume is calculated. IVM is very flexible in allowing the user to specify constraints to the volume container. The volume container can be restricted by two-dimensional surfaces above and below, or by maximum/minimum values in the Z direction. The container can be further constrained by polygons in the X-Y plane which cut vertically.
through the solid. Yield factors, and conversion factors, can be incorporated into the volumetric calculations, so that estimates for the volume of water in an aquifer, for example, can be made if the aquifer porosity is known (Paradis and Belcher, 1990).

Results of the volume calculation procedure are given in a volume report (See Figure 18). For this research, a separate volume report was generated quantifying the volume of the saturated zone between 1 mg/L concentration increments beneath each of the six test plots for the range of concentrations observed on each sampling date. Shell scripts (Shown in Appendix G) were written that extracted the necessary information from each volume report, totaled the amounts, and calculated the estimates of nitrate or atrazine mass shown in this report.
Figure 5.--IVM generated three-dimensional display of a nitrate concentration model on July 21, 1988
Figure 6—IVM generated three-dimensional display of a nitrate concentration model on August 17, 1988.
Figure 7. IVM generated three-dimensional display of a nitrate concentration model on April 18, 1989.
Figure 8.--IVM generated three-dimensional display of a nitrate concentration model on May 5, 1989.
Figure 9.—IVM generated three-dimensional display of a nitrate concentration model on May 25, 1989.
Nitrate concentrations on 07/10/89

Figure 10.—IVM generated three-dimensional display of nitrate concentration model on July 10, 1989.
Figure 11.—IVM generated three-dimensional display of a nitrate concentration model on August 9, 1989.
Figure 12b.--IVM generated three-dimensional display of a nitrate concentration model on September 9, 1989, alternative view.
Figure 13a.—IVM generated three-dimensional display of a nitrate concentration model on September 13, 1989
Figure 13b.—IVM generated three-dimensional display of a nitrate concentration model on September 13, 1989, alternative view.
Nitrate concentrations on 11/30/89

Figure 15.—IVM generated three-dimensional display of a nitrate concentration model on November 30, 1989
Nitrate concentrations on 03/22/90

Figure 16.--IVM generated three-dimensional display of a nitrate concentration model on March 22, 1990
Figure 17: IVM generated three-dimensional display of nitrate concentration model on May 3, 1990.
VOLUMETRICS REPORT

Run by: bill
Version: 4.0
Date: 05/27/92
Time: 14:11:59

Volumetrics file: vf19.n090789
3-D grid file: nit.090789.grid
Polygon file: fields.poly
Sorted by: Natural polygon order
Volumetrics conversion factor: .3048000037

Top grid name: wl.090789.grid
Bottom grid name: till.grid
Yield factor: Constant per polygon
Minimum thickness: 0.0000000000
Volume for shell from: 18.0000000000
to: 19.0000000000

volumetrics report nitrate model on 090789 18 - 19 mg/L
field Class field area volume of water (m3)
--------------------------------- -------------- ------------- ---------------
FIELD 1 TEST PLOTS 3,388.57031 58.773647
FIELD 2 TEST PLOTS 3,359.58593 71.286674
FIELD 3 TEST PLOTS 3,393.14062 67.841430
FIELD 4 TEST PLOTS 3,126.36718 74.569679
FIELD 5 TEST PLOTS 4,031.09375 110.708068
FIELD 6 TEST PLOTS 4,163.82812 85.315917
WHOLE SITE AT ROSHOL SITE 29,178.02539 612.055847
Totals for Shell 1 50,640.61132 1,080.551265

Figure 18.--Example volume report generated by IVM
GMS

The LYNX Geoscience Modelling System (GMS) is a proprietary software package sold by LYNX Geosystems Inc. GMS software is designed to address any situation in which three-dimensional, qualitative, quantitative, and visual appreciation of the geological subsurface is required (LYNX Geosystems Inc., 1992). GMS was designed for use in the mining industry, but has also been used for other geological, hydrological, and environmental applications. For this research, GMS was used to model the distribution of nitrate concentrations in the saturated zone beneath the Rosholt Research Farm.

Software Design

The primary functions of GMS are executed by a set of modules (programs) which are accessed by the user through both a menu system and a graphical interface (LYNX Geosystems Inc., 1992). Starting the GMS program initiates the menu system and allows the user to proceed in one of four major applications: data management, data analysis, geological modeling, or geostatistical modeling.

The purpose of the data management programs is to provide tools for data entry, storage, retrieval, and manipulation. Data can be introduced into GMS in one of two formats, a drill-log data format, or a map data format (LYNX Geosystems Inc., 1992). All sample data used for this research were imported into GMS from ASCII files in the drill-log format (Shown in Appendix I).

The purpose of the data analysis programs is to provide tools for visual, statistical, and geostatistical inspection of the project data. With these programs the user can plot data, perform simple statistics, (i.e. correlations), and do some data analysis in preparation for future geostatistical analysis (i.e. semivariogram analysis) (LYNX Geosystems Inc., 1992).

The purpose of the geological modeling programs is to provide an interactive means for defining geological interpretations in three dimensions, and to build three-dimensional
models of the geological subsurface. Once built, these models can be visualized, analyzed volumetrically, used to control the modeling of parameters within the volume, and intersected with other volume models (LYNX Geosystems Inc., 1992).

The purpose of the geostatistical modeling programs is to predict and represent the three-dimensional variation of a numerical attribute within a geological model, based on isolated attribute observations within and/or around the geological model. GMS provides the user with two primary algorithms for attribute interpolation: kriging and inverse distance. The definition of the three-dimensional grid model and the intersection of geological models with grid models are also performed by the geostatistical modeling programs (LYNX Geosystems Inc., 1992).

**Data Modeling - Gridding Algorithm**

GMS software models data by applying either an inverse-distance or kriging gridding algorithm. Inverse distance gridding uses an average of adjacent data values to estimate the value at a grid node. Weights are assigned to the data values according to the distances between a grid node the data values (Davis, 1986). The inverse-distance algorithm used in GMS first divides the search volume into plan quadrants in the X-Y plane of the search ellipsoid, and then determines which points fall within each quadrant. The distance weighted average value and a quadrant weight are then calculated for each quadrant. The cell value is then calculated as the sum of the product of the average quadrant values and quadrant weights, divided by the sum of the quadrant weights (LYNX Geosystems Inc., 1992). The user can define the size and orientation of the search ellipsoid. All inverse-distance gridded estimates generated for this study used a third order distance weight.

Kriging is a geostatistical technique for generating estimates of parameter values. The kriging estimate is a linearly weighted combination of the known data where the weights are determined by analyzing the spatial distribution of the observations, and are defined such that estimation variance is minimized, and the best linear unbiased estimator
is produced (Karlinger and Skrivan, 1981, Brooker, 1980). Prior to kriging of a data set, a
semivariogram must be defined. This semivariogram summarizes the behavior of the sam-
ple variables spatially. The form of the semivariogram is dependent upon the assumption
that the distribution of the differences in parameter values between two point samples is
the same over the entire modeled area (Clark, 1980). Once defined by the user, informa-
tion from the semivariogram is used to define weights used in the estimation of values at
grid nodes.

An advantage of kriging over other interpolation techniques is that kriging provides
a measure of the statistical uncertainty associated with each estimated value. LYNX Geo-
systems Inc., recommends using kriging for the interpolation of all parameters for which
an acceptable semivariogram can be obtained (LYNX Geosystems Inc., 1992).

**Visualization**

Three-dimensional visualization of geological models is possible using GMS. How-
ever, with the software versions available during this project, the displays generated are
not dynamic and some features, such as Z-exaggeration, cannot be controlled. Three-
dimensional visualization of grid models cannot be accomplished using GMS. An option
exists to produce a file that is compatible with the Data Visualizer from Wavefront Tech-
nologies Inc. (LYNX Geosystems Inc., 1992), but the Wavefront Technologies Inc. soft-
ware was not accessible at the time this research was done. The only other way to
visualize results of data modeling was to view two-dimensional planes or cross-sections
showing data values (See Figures 19a and 19b). For this research three perpendicular sec-
tions cutting each grid model were viewed to ensure that no obvious gridding errors
occurred.
Figure 19a.—GMS generated Two-dimensional display of three-dimensional nitrate concentration model on August 17, 1988, view from the top, approximately one meter below the water-table
Figure 19b.--GMS generated Two-dimensional display of three-dimensional nitrate concentration model on August 17, 1988, view from the side, looking north, approximately 30 meters north of the south end of the test plots.
Data Analysis - Method of Volume Calculation

The GMS software can be used to estimate the volume of a previously defined object (geological model), the volume of intersection between two or more objects, or the volumes above and below specified parameter thresholds within a geological model (LYNX Geosystems Inc., 1992). GMS applies a form of dimensional separability to calculate volume estimates. The process involves using area integration to calculate the areas of intersection between a geologic or parameter model and a set of equally spaced parallel planes that pass through the model. The volume is then equal to the sum of the products of the areas of intersection and the thickness of each plane (LYNX Geosystems Inc., 1992). The integration increment controls the thickness of the planes and is specified by the user. The volume container in GMS is a geological model specified by the user. Geological models can be defined to represent essentiality any three-dimensional shape. The volume calculations done for this report used the “attribute analysis for model volumes” option in GMS. This option allows the user to overlay selected volume model components (geological models) with a three-dimensional grid model. GMS then calculates the volumes within the volume models containing attribute values which are above and below a set of user specified threshold values (LYNX Geosystems Inc., 1992).

Results of the volume calculation procedure are given in a volume report (See Figure 20). This report indicates the volume within the selected set of geological models that fall above and below a set of user specified thresholds. A FORTRAN program (Shown in Appendix H) was written that reads a tabular version of this report and calculates the estimates of nitrate masses beneath each of the six test plots and the site polygon that are shown in this report.
LYNX GMS VOLUMETRICS - ATTRIBUTE ANALYSIS OF MODEL VOLUMES

PROJECT : WBATTAGL
ANALYSIS : N7 volumes I, 4/18/89

3D GRID MODEL : N2A
PRIMARY ATTRIBUTE : Nitrate
THRESHOLD VALUE : 1.000
ATTRIBUTE SCALING FACTOR : 1.0
VOLUME MODEL SELECTION : G,RH,N7,*,*
VOLUME INTEGRATION INCREMENT : 1.00
DENSITY : 1.000
VOLUME/TONS SCALING FACTOR : 1.0

|-- VOLUME IDENTITY--|--TOTAL--|--GREATER THAN THRESHOLD--|
|--LESS THAN THRESHOLD--|--UNDEF--|--SECONDARY--|

UNIT COMPONENT CODE VOL TON VOL TON PRIMARY VOL TON PRIMARY (%) TON ATT(1) ATT(2) ATT(3)
N7 F1 3 21058. 21058. 20042. 20042. 7.65 0. 0. .00 5. 1015.
N7 F2 3 21064. 21064. 19616. 19616. 5.65 430. 430. .58 5. 1017.
N7 F3 3 21349. 21349. 14192. 14192. 4.69 6129. 6129. .59 5. 1028.
N7 F4 3 19181. 19181. 12110. 12110. 6.45 6164. 6164. .41 5. 907.
N7 F5 3 24922. 24922. 15779. 15779. 8.72 7945. 7945. .37 5. 1197.
N7 F6 3 26058. 26058. 16487. 16487. 6.59 8230. 8230. .20 5. 1341.
N7 S2 1 181563. 181563. 133072. 133072. 6.66 39475. 39475. .38 5. 9017.

-----------------------------------------------
TOTAL 315194. 315194. 231299. 231299. 6.66 68373. 68373. .38 5. 15523.

Figure 20.--Example volume report generated by GMS
ESTIMATING AGRICULTURAL CHEMICAL MASS

In order to meet the objectives of this study, the masses of nitrate occurring in ground water beneath each of the six test plots, and the site polygon at the Rosholt Research Farm, were estimated using both IVM and GMS volume modeling systems. The masses of atrazine occurring in ground water at the Rosholt Research Farm were also estimated using IVM. The specific procedures used and the results of the analysis for both systems are discussed in the following sections of this report. A comparison of the results from the two systems, and a discussion of the usability of the two software systems is also included.

Method Using IVM

The general method used to generate agricultural chemical mass estimate using IVM was summarized in the approach section of this report. Because IVM can be run through a command file, most of the steps in creating the mass estimates in IVM could be automated. The steps used to produce mass estimates for nitrate on a given date are listed below (the procedure for atrazine was similar, but used modified versions of the programs listed):

1. run the AML's MAKE_NIT_SCAT and MAKE_WL_SCAT (Shown in Appendix F) which create scattered data files of nitrate concentrations measurements and water-table altitudes, respectively;
2. transfer the scattered data files to the Silicon Graphics workstation;
3. run the C-shell script 3DMODEL.SC (Shown in Appendix G) that makes the two-dimensional water-table surface in ISM and the three-dimensional grid of estimated nitrate concentrations in IVM;
4. run the C-shell script VOLIMG.SC (Shown in Appendix G) that generates volume reports indicating the volume of the saturated zone between two isovalue surfaces for the range of concentration values observed in the grid model beneath each test plot and the site polygon;
5. run the C-shell script MASS_CALC.SC (Shown in Appendix G) that uses UNIX
grep and awk commands to read the volume reports and calculate the mass of nitrate beneath each test plot,

(6) run the C-shell script SITEVOL.SC (Shown in Appendix G) that generates volumes reports indicating the volume of the saturate zone beneath the entire site polygon between two isovalue surfaces for the range of concentration values observed in the grid model;

(7) run the C-shell script MASS_SITE.SC (Shown in Appendix G) that uses UNIX grep and awk commands to read the volume reports and calculate the mass of nitrate beneath the entire site,

(8) run the C-shell script 3DDISPLAY.SC (Shown in Appendix G) to make the display file used to visualize the grid model, and

(9) delete and deactivate the volume report files,

The elaspsed time require to create a model and calculate the mass estimates for one date was about 2 hours.

**Results - IVM**

The results of the nitrate mass estimation procedure using IVM are listed in Table 4. Recall that the three farming management systems implemented on the test plots are as follows: (1) continuous cropping of corn using 160 pounds of nitrogen fertilizer and 454 grams of atrazine per acre, on plots 1 and 3; (2) continuous cropping of corn using 214 pounds of nitrogen fertilizer and 454 grams of atrazine per acre, on plots 2 and 5; and (3) a corn-soybeans crop rotation sequence (corn on even years) with 160 pounds of nitrogen fertilizer and 454 grams of atrazine per acre applied on corn, and 15 pounds nitrogen fertilizer per acre (no atrazine) applied on soybeans, on plots 4 and 6 (Anderson and Stoner, 1989).

Figure 21 shows boxplots (Velleman and Hoaglin, 1981) of the nitrate mass estimates for the thirteen sampling dates under each test plot. These boxplots indicate that there is not a simple and consistent relation between farming management system and nitrate mass occurring in the saturated zone beneath the test plots. It is important to note that, in general, lower nitrate masses occur beneath plots 3 and 4, and higher nitrate masses occur beneath plots 1, 2, 5, and 6.
Table 4.--IVM generated estimates of nitrate mass in the saturated zone beneath the six test plots and the site polygon, at the Rosholt Research Farm, Minnesota

<table>
<thead>
<tr>
<th>Date of Sampling</th>
<th>Plot 1</th>
<th>Plot 2</th>
<th>Plot 3</th>
<th>Plot 4</th>
<th>Plot 5</th>
<th>Plot 6</th>
<th>Site Polygon</th>
</tr>
</thead>
<tbody>
<tr>
<td>07/21/88</td>
<td>77.1</td>
<td>58.1</td>
<td>40.5</td>
<td>30.5</td>
<td>37.0</td>
<td>29.6</td>
<td>372.6</td>
</tr>
<tr>
<td>08/17/88</td>
<td>65.5</td>
<td>70.3</td>
<td>49.8</td>
<td>41.0</td>
<td>79.4</td>
<td>59.3</td>
<td>497.5</td>
</tr>
<tr>
<td>04/18/89</td>
<td>78.5</td>
<td>51.7</td>
<td>34.1</td>
<td>38.8</td>
<td>62.7</td>
<td>49.4</td>
<td>426.5</td>
</tr>
<tr>
<td>05/03/89</td>
<td>83.1</td>
<td>68.9</td>
<td>46.4</td>
<td>37.7</td>
<td>55.4</td>
<td>59.0</td>
<td>475.6</td>
</tr>
<tr>
<td>05/25/89</td>
<td>84.7</td>
<td>72.3</td>
<td>49.3</td>
<td>35.3</td>
<td>51.5</td>
<td>51.1</td>
<td>467.0</td>
</tr>
<tr>
<td>07/10/89</td>
<td>89.5</td>
<td>80.9</td>
<td>51.3</td>
<td>32.8</td>
<td>47.3</td>
<td>45.0</td>
<td>471.0</td>
</tr>
<tr>
<td>08/09/89</td>
<td>76.6</td>
<td>74.1</td>
<td>58.2</td>
<td>38.5</td>
<td>51.1</td>
<td>47.2</td>
<td>470.7</td>
</tr>
<tr>
<td>09/07/89</td>
<td>80.5</td>
<td>88.2</td>
<td>75.9</td>
<td>60.7</td>
<td>118.2</td>
<td>101.6</td>
<td>710.3</td>
</tr>
<tr>
<td>09/13/89</td>
<td>98.1</td>
<td>121.6</td>
<td>103.1</td>
<td>66.4</td>
<td>136.2</td>
<td>108.3</td>
<td>850.1</td>
</tr>
<tr>
<td>10/11/89</td>
<td>109.5</td>
<td>110.3</td>
<td>99.6</td>
<td>69.6</td>
<td>136.6</td>
<td>108.9</td>
<td>859.5</td>
</tr>
<tr>
<td>11/30/89</td>
<td>79.6</td>
<td>70.0</td>
<td>85.4</td>
<td>53.1</td>
<td>58.6</td>
<td>86.0</td>
<td>588.0</td>
</tr>
<tr>
<td>03/22/90</td>
<td>68.2</td>
<td>49.0</td>
<td>52.5</td>
<td>40.9</td>
<td>57.5</td>
<td>58.4</td>
<td>449.0</td>
</tr>
<tr>
<td>05/03/90</td>
<td>78.5</td>
<td>63.8</td>
<td>50.3</td>
<td>48.2</td>
<td>87.7</td>
<td>73.7</td>
<td>544.3</td>
</tr>
</tbody>
</table>
Figure 21.—Boxplots of IVM generated nitrate mass estimates under each of the test plots
In Figure 22, the nitrate mass estimates have been grouped by farming management system. Figure 22 indicates that nitrate mass is consistently lower under plots using management system 3 (corn-soybean rotation) than under plots using either management systems 1 or 2 (continuous corn). A Kruskal-Wallis test (Iman and Conover, 1983) on the nitrate mass estimates associated with the three farming management systems indicates that the null hypothesis of equal population means is rejected at the 0.05 significance level.

The mean nitrate masses associated with the three management systems are listed in Table 5. Table 5 indicates that nitrate mass beneath test plots using farming management 3 was 25 percent less than nitrate mass beneath test plots using farming management system 2, and 21 percent less that nitrate mass beneath test plots using farming management system 1.

The saturated zone was divided into three 5-foot thick zones and mass estimates were calculated beneath the test plots and beneath the entire site for each zone (See Table 6). Kruskal-Wallis test results for the lower and middle parts of the saturated zone again indicate that nitrate mass estimates are consistently smaller under plots using a corn-soybean rotation management system. The null hypothesis of equal population means for the three management systems is not rejected at the 0.05 significance level for nitrate mass estimates from the upper part of the saturated zone.

Estimates of sub-field nitrate mass can also be compared with estimates of nitrogen fertilizer applied to test plots shown in Table 1a. It appears that a significant percentage of the nitrate applied is reaching the aquifer at the Rosholt Research Farm.
IVM Generated Nitrate Mass Estimates
by Farming Management System

Figure 22.—Boxplots of IVM generated nitrate mass estimates for the three farming management systems.
Table 5.—Mean sub-plot nitrate mass estimated using IVM and GMS, and mean sub-plot atrazine mass estimated using IVM, for the three farming management systems

<table>
<thead>
<tr>
<th>Farming Management System</th>
<th>Mean Sub-field Nitrate Mass IVM (pounds)</th>
<th>Mean Sub-field Nitrate mass GMS (pounds)</th>
<th>Mean Sub-field Atrazine mass IVM (grams)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Continuous Corn</td>
<td>71.9</td>
<td>97.2</td>
<td>0.063</td>
</tr>
<tr>
<td>N applied at</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>160 pounds per acre</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atrazine applied at</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>454 grams per acre</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2) Continuous Corn</td>
<td>75.4</td>
<td>107.5</td>
<td>0.039</td>
</tr>
<tr>
<td>N applied at</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>214 pounds per acre</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atrazine applied at</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>454 grams per acre</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(3) Corn-Soybean Rotation</td>
<td>56.6</td>
<td>77.6</td>
<td>0.014</td>
</tr>
<tr>
<td>N applied at</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>160 pounds per acre to corn,</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 pounds per acre to soybeans</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atrazine applied at</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>454 grams per acre to corn</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 grams per acre to soybeans</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 6.—IVM generated estimates of nitrate mass beneath the six test plots and the site
polygon in the upper fifteen feet of the saturated zone

[U - portion of saturated zone from water-table surface to five feet below the median
water-level, M - portion of saturated zone from five to ten feet below the median
water-level, L - portion of saturated zone from ten to fifteen feet below the median
water-level]

<table>
<thead>
<tr>
<th>Date of Sampling</th>
<th>Portion of Water-Entire Site</th>
<th>Median(^1) Mass of Nitrate (pounds) in Groundwater beneath Plot 1</th>
<th>Plot 2</th>
<th>Plot 3</th>
<th>Plot 4</th>
<th>Plot 5</th>
<th>Plot 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>07/21/88</td>
<td>U</td>
<td>1322.4</td>
<td>32.0</td>
<td>29.4</td>
<td>24.5</td>
<td>20.7</td>
<td>26.3</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>1322.4</td>
<td>25.6</td>
<td>18.8</td>
<td>12.2</td>
<td>8.3</td>
<td>8.9</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>1322.4</td>
<td>15.0</td>
<td>8.4</td>
<td>3.0</td>
<td>1.4</td>
<td>1.8</td>
</tr>
<tr>
<td>08/17/88</td>
<td>U</td>
<td>1322.9</td>
<td>27.0</td>
<td>34.9</td>
<td>33.0</td>
<td>30.4</td>
<td>59.0</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>1322.9</td>
<td>21.2</td>
<td>22.4</td>
<td>12.8</td>
<td>9.2</td>
<td>18.4</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>1322.9</td>
<td>13.3</td>
<td>10.9</td>
<td>3.1</td>
<td>1.3</td>
<td>1.9</td>
</tr>
<tr>
<td>04/18/89</td>
<td>U</td>
<td>1324.5</td>
<td>29.3</td>
<td>21.7</td>
<td>18.5</td>
<td>23.2</td>
<td>37.8</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>1324.5</td>
<td>26.4</td>
<td>18.7</td>
<td>12.0</td>
<td>13.0</td>
<td>20.8</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>1324.5</td>
<td>16.2</td>
<td>8.7</td>
<td>2.3</td>
<td>1.9</td>
<td>3.3</td>
</tr>
<tr>
<td>05/03/89</td>
<td>U</td>
<td>1324.4</td>
<td>33.0</td>
<td>31.4</td>
<td>27.5</td>
<td>24.6</td>
<td>35.3</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>1324.4</td>
<td>26.2</td>
<td>22.2</td>
<td>13.9</td>
<td>10.9</td>
<td>16.7</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>1324.4</td>
<td>16.9</td>
<td>11.9</td>
<td>3.7</td>
<td>1.7</td>
<td>2.6</td>
</tr>
<tr>
<td>05/25/89</td>
<td>U</td>
<td>1324.3</td>
<td>33.7</td>
<td>31.7</td>
<td>28.0</td>
<td>22.8</td>
<td>33.1</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>1324.3</td>
<td>26.6</td>
<td>23.5</td>
<td>15.2</td>
<td>10.4</td>
<td>15.6</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>1324.3</td>
<td>17.4</td>
<td>13.4</td>
<td>4.8</td>
<td>1.5</td>
<td>2.1</td>
</tr>
<tr>
<td>07/10/89</td>
<td>U</td>
<td>1323.6</td>
<td>39.6</td>
<td>42.2</td>
<td>30.5</td>
<td>21.7</td>
<td>32.2</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>1323.6</td>
<td>28.7</td>
<td>25.9</td>
<td>16.0</td>
<td>9.3</td>
<td>12.8</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>1323.6</td>
<td>15.8</td>
<td>10.4</td>
<td>3.7</td>
<td>1.4</td>
<td>1.8</td>
</tr>
<tr>
<td>08/09/89</td>
<td>U</td>
<td>1323.1</td>
<td>43.2</td>
<td>46.3</td>
<td>40.3</td>
<td>27.3</td>
<td>36.9</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>1323.1</td>
<td>22.3</td>
<td>20.4</td>
<td>14.5</td>
<td>9.6</td>
<td>12.2</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>1323.1</td>
<td>9.0</td>
<td>6.0</td>
<td>2.5</td>
<td>1.4</td>
<td>1.8</td>
</tr>
</tbody>
</table>
Table 6.--IVM generated estimates of nitrate mass beneath the six test plots and the site polygon in the upper fifteen feet of the saturated zone--continued

[U - portion of saturated zone from water-table surface to five feet below the median water-level, M - portion of saturated zone from five to ten feet below the median water-level, L - portion of saturated zone from ten to fifteen feet below the median water-level]

<table>
<thead>
<tr>
<th>Date of Sampling</th>
<th>Portion of Water-Whole Nitrate Level</th>
<th>Median(^1)</th>
<th>Mass of Nitrate (pounds) in Groundwater beneath</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Plot 1</td>
<td>Plot 2</td>
</tr>
<tr>
<td>09/07/89</td>
<td>U</td>
<td>40.7</td>
<td>49.2</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>23.7</td>
<td>25.3</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>12.7</td>
<td>11.2</td>
</tr>
<tr>
<td>09/13/89</td>
<td>U</td>
<td>51.6</td>
<td>72.8</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>30.1</td>
<td>35.3</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>13.5</td>
<td>11.4</td>
</tr>
<tr>
<td>10/11/89</td>
<td>U</td>
<td>60.7</td>
<td>71.0</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>32.7</td>
<td>30.4</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>13.3</td>
<td>7.1</td>
</tr>
<tr>
<td>11/30/89</td>
<td>U</td>
<td>50.7</td>
<td>48.1</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>21.6</td>
<td>18.0</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>5.5</td>
<td>2.2</td>
</tr>
<tr>
<td>03/22/90</td>
<td>U</td>
<td>33.9</td>
<td>29.6</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>21.0</td>
<td>14.3</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>10.4</td>
<td>3.4</td>
</tr>
<tr>
<td>05/03/90</td>
<td>U</td>
<td>40.3</td>
<td>35.7</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>23.8</td>
<td>19.3</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>11.0</td>
<td>6.8</td>
</tr>
</tbody>
</table>

\(^1\)Median water-level is calculated as the median of measured water-levels on the date of, or the date closest to the sampling date, for wells screened in the upper portion of the aquifer, with identification numbers containing 726 or 926 (see figure 2).
A time series of the thirteen nitrate models is shown in Figures 5 through 17. A date by date interpretation of the nitrate models is given in Appendix J. By looking at both visual representations of the nitrate models and the nitrate mass estimates (See Tables 4 and 6) one can observe that:

(1) nitrate concentrations decreased with depth in the saturated zone,
(2) nitrate concentrations tended to increase after recharge events,
(3) the highest nitrate concentrations tended to occur near the water-table surface,
(4) the highest concentrations and masses of nitrate occurred in the fall,
(5) cross-contamination may be occurring between plots with high nitrate application rates (plot 5) and plots with low nitrate applications rates (plot 6) on some dates (See Figures 6, 9, 11, 12, 13, and 14), and
(6) nitrate may be moving on site from off site sources (See Figures 5, 9, 10, and 15).

When calculating grids of estimated parameter values in IVM, the user can define a value for a variable called the Z-influence factor. The Z-influence factor controls the vertical influence during gridding, with a factor of 1 indicating normal three-dimensional minimum tension gridding; a factor less than one gives data in the Z direction less influence, and factors greater than one gives data in the Z direction more influence (Dynamic Graphics Inc., 1990). The results shown in Tables 4, 5, 6, and 8 were calculated using a Z-influence factor of one. Table 7 shows nitrate mass estimates for one model date and a set of Z-influence factors. These results indicate that the nitrate mass estimates were not particularly sensitive to the Z-influence factor.
Table 7.—Effects of the Z-influence factor on IVM generated estimates of nitrate mass in the saturated zone on September 9, 1989, beneath the six test plots and the site polygon, at the Rosholt Research Farm, Minnesota

<table>
<thead>
<tr>
<th>Z-influence Factor</th>
<th>Plot 1</th>
<th>Plot 2</th>
<th>Plot 3</th>
<th>Plot 4</th>
<th>Plot 5</th>
<th>Plot 6</th>
<th>Site Polygon</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>82.4</td>
<td>84.3</td>
<td>72.5</td>
<td>64.0</td>
<td>122.2</td>
<td>106.6</td>
<td>718.7</td>
</tr>
<tr>
<td>0.5</td>
<td>80.7</td>
<td>87.2</td>
<td>74.5</td>
<td>61.0</td>
<td>119.1</td>
<td>103.4</td>
<td>710.9</td>
</tr>
<tr>
<td>1.0</td>
<td>80.5</td>
<td>88.2</td>
<td>75.9</td>
<td>60.7</td>
<td>118.2</td>
<td>101.6</td>
<td>710.3</td>
</tr>
<tr>
<td>2.0</td>
<td>80.9</td>
<td>89.0</td>
<td>77.2</td>
<td>60.7</td>
<td>117.4</td>
<td>99.8</td>
<td>710.7</td>
</tr>
</tbody>
</table>
The results of the atrazine mass estimation procedure using IVM are listed in Table 8. The results for atrazine are difficult to interpret due to the limited number of atrazine detections from any one sampling date. A Kruskal-Wallis test on the atrazine mass estimates associated with the three management systems indicates that the population means are not significantly different at the 0.05 significance level. However, Figure 23 and Table 5 both indicate that the mass of atrazine is about 50 percent lower under plots using a corn-soybean rotation than under plots using continuous corn management systems. Figure 24 shows the atrazine model for September 13, 1989. Estimates of atrazine applications are listed in Table 1b. It appears that only a very small percentage of the applied atrazine is reaching the aquifer at the Rosholt Research Farm.
Table 8.--IVM generated estimates of atrazine mass in the saturated zone beneath the six test plots and the site polygon, at the Rosholt Research Farm, Minnesota

<table>
<thead>
<tr>
<th>Date of Sampling</th>
<th>Plot 1</th>
<th>Plot 2</th>
<th>Plot 3</th>
<th>Plot 4</th>
<th>Plot 5</th>
<th>Plot 6</th>
<th>Site Polygon</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/18/89</td>
<td>0.0773</td>
<td>0.0692</td>
<td>0.0486</td>
<td>0.0186</td>
<td>0.0154</td>
<td>0.0058</td>
<td>0.350</td>
</tr>
<tr>
<td>05/03/89</td>
<td>0.0917</td>
<td>0.0871</td>
<td>0.0870</td>
<td>0.0535</td>
<td>0.0179</td>
<td>0.0090</td>
<td>0.518</td>
</tr>
<tr>
<td>05/25/89</td>
<td>0.0060</td>
<td>0.0055</td>
<td>0.0052</td>
<td>0.0043</td>
<td>0.0053</td>
<td>0.0057</td>
<td>0.044</td>
</tr>
<tr>
<td>07/07/89</td>
<td>0.0057</td>
<td>0.0056</td>
<td>0.0062</td>
<td>0.0065</td>
<td>0.0599</td>
<td>0.0804</td>
<td>0.260</td>
</tr>
<tr>
<td>09/13/89</td>
<td>0.2118</td>
<td>0.2356</td>
<td>0.1531</td>
<td>0.0755</td>
<td>0.0694</td>
<td>0.0394</td>
<td>1.086</td>
</tr>
</tbody>
</table>
Figure 23.--Boxplots of IVM generated atrazine mass estimates for the three farming management systems
Figure 24.—IVM generated three-dimensional display of atrazine concentration model on September 13, 1989
Method Using GMS

The general method used to generate nitrate mass estimate using GMS is summarized in the approach section of this report. It was hoped that GMS could be used to generate kriged estimates of nitrate concentration distributions. However, a satisfactory semivariogram could not be generated. After developing numerous unsatisfactory models, it was concluded that the data were not amenable to kriging, so the inverse-distance gridding algorithm was used.

Because GMS cannot be run with a command file or shell script, most of the steps in generating the mass estimates in GMS could not be automated. The steps used to generate mass estimates for nitrate on a given date using GMS are listed below:

(1) from INFO generate an ASCII output a file of nitrate concentrations for the desired date,
(2) edit the ASCII drill-log file (Shown in Appendix I) adding the correct nitrate values and eliminating missing data,
(3) transfer the ASCII drill-log file to an IBM RS6000 running GMS software,
(4) start GMS and import the drill-log data,
(5) go to the data analysis modules and make a “.DAT” file for statistical and visual inspection of the data,
(6) edit the “.DAT” file changing -333.33 to -380000.00, so GMS statistical routines do not think that all the data is missing,
(7) check the imported well-data by plotting X vs. Y, and Z vs. nitrate concentration,
(8) define the geology models which represent the six test plot, and the entire site on the specified date,
(9) intersect the geology models with a previously defined three-dimensional grid model,
(10) define the inverse-distance gridding parameters,
(11) start the inverse-distance gridding,
(12) check the results of the gridding by viewing perpendicular planes of gridded results using the geological modeling modules,
(13) calculate volumes above and below threshold values using the attribute analysis for model volumes modules (the thresholds used were 1, 3, 5, 10, 15, 20, 25, 30,
35, 40, and 45 mg/L), and

(14) run the mass_lynx.f program (Shown in Appendix H) to convert volumes and threshold values to estimates of nitrate mass beneath the test plots and the entire site.

The elapsed time require to create a model and calculate the mass estimates for one date was about 4 hours.

Results - GMS

The results of the nitrate mass estimation procedure using GMS are listed in Table 9. Figure 25 shows boxplots of the nitrate mass estimates for the thirteen sampling dates under each test plot. These boxplots indicate that there is not a simple and consistent relation between farming management system and nitrate mass occurring in the saturated zone beneath the test plots. Note that in general lower nitrate masses occur beneath plots 3 and 4, and higher masses occur beneath plots 1, 2, 5, and 6.

In Figure 26, the mass estimates have been grouped by farming management system. Figure 26 indicates that the mass of nitrate is consistently lower under plots using management system 3 (corn-soybean rotation) than under plots using either management systems 1 or 2 (continuous corn). A Kruskal-Wallis test (Iman and Conover, 1983) on the nitrate mass estimates associated with the three management systems indicates that the null hypothesis of equal population means is rejected at the 0.05 significance level. The mean nitrate masses associated with the three management systems are listed in Table 5. The numbers in Table 5 indicate that nitrate mass beneath test plots using farming management 3 was 28 percent less than nitrate mass beneath test plots using farming management system 2, and 20 percent less than nitrate mass beneath test plots using farming management system 1. Estimates of sub-field nitrate mass can also be compared with estimates of nitrogen as fertilizer applied to the test plots shown in Table 1a.
Table 9.—GMS generated estimates of nitrate mass in the saturated zone beneath the six test plots and the site polygon, at the Rosholt Research Farm, Minnesota

<table>
<thead>
<tr>
<th>Date of Sampling</th>
<th>Plot 1</th>
<th>Plot 2</th>
<th>Plot 3</th>
<th>Plot 4</th>
<th>Plot 5</th>
<th>Plot 6</th>
<th>Site Polygon</th>
</tr>
</thead>
<tbody>
<tr>
<td>07/21/88</td>
<td>89.8</td>
<td>83.9</td>
<td>53.7</td>
<td>41.9</td>
<td>52.5</td>
<td>51.2</td>
<td>505.4</td>
</tr>
<tr>
<td>08/17/88</td>
<td>90.6</td>
<td>101.9</td>
<td>80.0</td>
<td>65.6</td>
<td>135.6</td>
<td>88.6</td>
<td>759.2</td>
</tr>
<tr>
<td>04/18/89</td>
<td>96.9</td>
<td>67.2</td>
<td>45.8</td>
<td>46.5</td>
<td>88.5</td>
<td>66.4</td>
<td>556.5</td>
</tr>
<tr>
<td>05/03/89</td>
<td>103.2</td>
<td>90.4</td>
<td>60.6</td>
<td>47.7</td>
<td>82.9</td>
<td>79.1</td>
<td>627.6</td>
</tr>
<tr>
<td>05/25/89</td>
<td>105.3</td>
<td>92.5</td>
<td>63.9</td>
<td>42.5</td>
<td>69.9</td>
<td>71.4</td>
<td>602.5</td>
</tr>
<tr>
<td>07/10/89</td>
<td>104.2</td>
<td>109.4</td>
<td>67.7</td>
<td>39.4</td>
<td>67.4</td>
<td>67.7</td>
<td>613.4</td>
</tr>
<tr>
<td>08/09/89</td>
<td>110.5</td>
<td>111.2</td>
<td>84.3</td>
<td>52.6</td>
<td>80.6</td>
<td>72.8</td>
<td>693.0</td>
</tr>
<tr>
<td>09/07/89</td>
<td>116.7</td>
<td>123.4</td>
<td>107.3</td>
<td>77.2</td>
<td>171.5</td>
<td>138.9</td>
<td>994.9</td>
</tr>
<tr>
<td>09/13/89</td>
<td>132.4</td>
<td>164.1</td>
<td>146.3</td>
<td>76.7</td>
<td>198.0</td>
<td>142.2</td>
<td>1153.1</td>
</tr>
<tr>
<td>10/11/89</td>
<td>147.2</td>
<td>153.3</td>
<td>142.9</td>
<td>83.0</td>
<td>202.2</td>
<td>150.7</td>
<td>1184.8</td>
</tr>
<tr>
<td>11/30/89</td>
<td>115.7</td>
<td>91.2</td>
<td>127.4</td>
<td>70.4</td>
<td>94.4</td>
<td>142.7</td>
<td>862.9</td>
</tr>
<tr>
<td>03/22/90</td>
<td>86.6</td>
<td>64.9</td>
<td>73.0</td>
<td>52.3</td>
<td>83.2</td>
<td>90.7</td>
<td>614.1</td>
</tr>
<tr>
<td>05/03/90</td>
<td>106.5</td>
<td>85.1</td>
<td>68.9</td>
<td>62.9</td>
<td>128.7</td>
<td>95.9</td>
<td>741.4</td>
</tr>
</tbody>
</table>
Figure 25.--Boxplots of GMS generated nitrate mass estimates under each of the test plots
GMS Generated Nitrate Mass Estimates by Farming Management System

Figure 26.--Boxplots of GMS generated nitrate mass estimates for the three farming management systems
Comparison of IVM and GMS Results

Both GMS and IVM produced models of nitrate concentration distributions and estimates of the nitrate mass that were realistic and indicative of conditions observed in the sub-surface at the Rosholt Research Farm. The sample correlation coefficient (Iman and Conover, 1983) between all nitrate mass estimates generated using IVM and all nitrate mass estimates generated using GMS was 0.975. Sample correlation coefficients between mass estimates by farming management system were 0.964, 0.984, and 0.967 for systems 1, 2, and 3, respectively. The strength of these correlations validates both the method as executed using either software system, and the strength of the relation between nitrate mass in the saturated zone and farming management system at the land surface, at the Rosholt Research Farm.

Nitrate mass estimates generated by IVM were in general lower than nitrate mass estimates generated by GMS (See Tables 4, 5, and 9). Figure 27 shows a regression plot comparing the nitrate mass estimates generated using the two volume modeling systems. The slope of this highly significant regression equation (multiple R-square = 0.95) indicates that nitrate mass estimates generated using IVM were about 67 percent as large as nitrate mass estimates generated using GMS.

One of the reasons for the differences between the mass estimates generated by IVM and GMS can be observed by comparing Figures 19a and 19b with Figures 3a and 6: in the IVM model concentrations dropped off more rapidly from an isolated high value than in the GMS model. Comparing Figures 21 and 22 with Figures 24 and 25, it may be seen that, although the magnitudes of the mass estimates differed, the associations observed between farming management systems and nitrate mass estimates were the same for both systems.
Regression of Nitrate Mass Estimates

\[ Y = 4.442755 + 0.6743613 \times X \]

Figure 27.--Regression plot of IVM generated nitrate mass estimates verses GMS generated nitrate mass estimates
Comparison of IVM and GMS Software

Both IVM and GMS software were able to produce gridded estimates of nitrate concentration distributions and estimates of volume from those models that could be used to estimate the mass of nitrate in the saturated zone at the Rosholt Research Farm. Both systems worked well mathematically and produced results in a similar amount of time. In the following paragraphs IVM and GMS are compared in terms of ease of use, software design, the ability to handle complex situations, and visualization functionality.

IVM software is easier to use than GMS both as a first time user and as a frequent operator. One reason why IVM is easier to use for the first time user is that the IVM program operates by initiating an interactive dialogue that leads the user through commonly performed actions. During this dialogue, the user always has options to: ask for additional help in explaining the question, back up to the last question, or get a listing of possible answers (i.e. when a file name is asked for). Also, IVM documentation was clearly written, well organized, and concise. In contrast, GMS was difficult to use for the first time user because to accomplish a task the user needed to navigate through a series of menus which were not organized in manor which made it obvious what the next step in a procedure should be. Unlike IVM, there was seldom on line help available to the user, and the software documentation (volume 1) discussed how the software operated conceptually, but failed to provide examples, or adequate guidance for commonly attempted procedures.

Several features of IVM made it easier to use for the frequent operator. The most important of these feature was that IVM (and ISM) could be run in batch mode via a command file, or shell script. IVM software automatically saved the responses to question given by the user in a file. These file were easily converted to shell scripts (Appendices F and G) which saved the user hours of typing (and sitting at the terminal waiting for the computer) when new models were made. IVM also operated smoothly when run across a network. GMS can not be run via a command file or shell script, and it’s operation across a network is at best cumbersome, largely because of the software’s use of function keys.
IVM software was more integrated and had a better overall design than GMS. The software design of IVM, and in particular the user interface, result in it being easier than GMS to use. Several features of IVM also make the software more useful for the type of environmental modeling demonstrated in the report. One of the most important of these features is that IVM can read gridded data files that were generated on other software systems for subsequent rendering, and can write files containing results of the gridding procedure that can be accessed by the user. In addition to three-dimensional gridded data, the user of IVM can make files containing the X, Y, and Z coordinates of a specified isovalue shell, or the X, Y, and P (property value) values of a specified model layer. GMS will not produce a table or file listing the P values of a model in a controlled fashion.

The GMS system was better suited for modeling complex geological situations than IVM. This is in part because GMS is more oriented towards modeling discrete bodies whereas IVM is more oriented towards modeling continuously varying properties. GMS can be used to generate gridded models in faulted terrain, something that IVM can not easily do. GMS also offers the user the choice of more than one gridding algorithm, and the ability to do some statistical analysis of input data.

In terms of visualization, the IVM software was far superior. IVM’s smooth renderings of three-dimensional grid models were excellent for gaining insight into model results, and for communicating ideas and results generated by this study to other researchers and non-researchers. Output from the IVM system could be used directly to produce high quality visual displays suitable for presentation at scientific meetings (Battaglin, 1990). In contrast, visualizations of three-dimensional grid models using GMS were barely adequate for model validation.
DISCUSSION AND CONCLUSIONS

This study demonstrates how volumetric modeling of agricultural chemicals can be used to evaluate effects of farming management systems on shallow ground-water quality. Two techniques for estimating the mass of nitrate in ground water from water-quality sampling data have been demonstrated. The techniques were based on the assumption that the mass of an agricultural chemical in the saturated zone beneath a farmed plot is related to the farming management system being used on the plot.

IVM and GMS volume modeling systems were used to develop three-dimensional volume models of the concentration distributions of agricultural chemicals in ground water, develop three-dimensional displays of the volume models, and perform volumetric calculations on the three-dimensional concentration distributions to estimate the mass of agricultural chemicals in the saturated zone beneath six test plots at the Rosholt Research Farm. Both techniques take advantage of recent developments in computer hardware and software that utilizes available computing power required to model and visualize three-dimensional data sets.

The Rosholt Research Farm in Westport, Minnesota was established to evaluate the impact on ground-water quality of agricultural management systems used for corn and soybean farming. The farm is located on an unconfined glacial outwash sand-plain aquifer. The near surface materials at the site are characterized by hydrologic properties that tend to allow rapid movement of contaminants into the aquifer. Six test plots, each about 1 acre in area, were established on the farm to evaluate three common corn and soybean agricultural management systems. The three farming management systems were implemented on the test plots as follows: (1) continuous cropping of corn using 160 pounds of nitrogen fertilizer and 454 grams of atrazine per acre, on plots 1 and 3; (2) continuous cropping of corn using 214 pounds of nitrogen fertilizer and 454 grams of atrazine per acre, on plots 2 and 5; and (3) a corn-soybeans crop rotation sequence (corn on even years) with 160 pounds of nitrogen fertilizer and 454 grams of atrazine per acre applied on corn, and 15
pounds nitrogen fertilizer per acre (no atrazine) applied on soybeans, on plots 4 and 6. Forty-two observation wells surrounding the test plots were periodically sampled for nutrients (nitrate), and triazine herbicides (atrazine).

Two techniques were used to generate models of nitrate concentration distributions and estimates of the nitrate mass that were realistic and indicative of conditions observed in the sub-surface at the Rosholt Research Farm. In general, the mass estimates generated by IVM were 20 to 30 percent lower than the mass estimates generated by GMS. Estimates of nitrate mass indicate that 20 to 28 percent less nitrate occurs beneath test plots were a corn-soybean rotation is used, than beneath test plots where corn is grown continuously. Estimates of atrazine mass also indicate that less atrazine occurs beneath test plots were a corn-soybean rotation is used, than beneath test plots where corn is grown continuously.

IVM and GMS volume modeling systems both produced gridded estimates of nitrate concentration distributions and volume estimates from those models that could be used to estimate the mass of nitrate in the saturated zone at the Rosholt Research Farm. IVM was easier to use than GMS. However, applications involving very complex geology would be better handled by the GMS system. In terms of visualization, IVM software was far superior. IVM’s smooth renderings of three-dimensional grid models were excellent for gaining insight into model results, and for communicating ideas and results generated by this study to other researchers and non-researchers.
RECOMMENDATIONS

Based on the experiences gained in this study some recommendations may be made concerning future investigations of the impact of farming management systems on groundwater quality, and the general application of volume modeling systems for hydrologic investigations.

Several aspects of the Rosholt Farm experimental design probably contributed to cross-contamination between test plots, making it more difficult to assess the effects of the farming management systems on groundwater quality. Future experiments would be more robust if:

1) test plots are separated by a distance large enough to isolate them hydrologically from each other,
2) adjacent test plots are oriented perpendicular to the direction of groundwater flow,
3) the site is isolated from other farming activities to the maximum extent possible, and
4) the farming management systems being evaluated are sufficiently different from each other so that a difference in water quality can be expected.

Volume modeling systems can be used to model conditions, such as chemical concentration distributions in an aquifer. The accuracy of such models, though somewhat dependent upon the underlying gridding algorithms and other mathematics used by the volume modeling systems, is largely controlled by the number and placement of sampling locations. Ideal sampling locations would be evenly distributed in three dimensions throughout a volume that extends somewhat beyond the region of interest, interpolation by the software would be limited to volumes between data points.
Use of volume modeling systems is not recommended when sampling locations are:

1) not distributed in three dimensions, including for example, samples taken from supply or irrigation wells with vertically extensive screened intervals;
2) clustered, with many wells in a few locations and large distances between the clusters; and
3) not sufficient in number or areal extent to provide control points that surround the area of interest entirely.
REFERENCES CITED


Geological Society of America Committee for the magnetic map of North America, 1987, Magnetic anomaly map of North America.


Turner, A. K., 1990, Three-Dimensional GIS: Possibilities attract geoscientists in many
industries, worldwide, Geobyte, Vol 5, n. 1, p 31-32.


APPENDIX A

Well locations, and land-surface and screen mid-point altitudes for the 46 observation wells at the Rosholt Research Farm

<table>
<thead>
<tr>
<th>Well Identification Number</th>
<th>Well Location X-coordinate (meters)</th>
<th>Y-coordinate (meters)</th>
<th>Land-surface altitude (feet)</th>
<th>Screen mid-point altitude (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W0L0950</td>
<td>-364,035.8</td>
<td>1,198,739.0</td>
<td>1,337.81</td>
<td>1,304.31</td>
</tr>
<tr>
<td>W0L1212</td>
<td>-364,041.6</td>
<td>1,198,667.0</td>
<td>1,335.32</td>
<td>1,305.82</td>
</tr>
<tr>
<td>W0M0950</td>
<td>-364,036.1</td>
<td>1,198,736.0</td>
<td>1,337.54</td>
<td>1,315.04</td>
</tr>
<tr>
<td>W0M1130</td>
<td>-363,888.4</td>
<td>1,198,683.0</td>
<td>1,334.94</td>
<td>1,312.94</td>
</tr>
<tr>
<td>W0M1212</td>
<td>-364,038.3</td>
<td>1,198,664.0</td>
<td>1,335.39</td>
<td>1,313.89</td>
</tr>
<tr>
<td>W0U0950</td>
<td>-364,035.8</td>
<td>1,198,743.0</td>
<td>1,337.48</td>
<td>1,322.48</td>
</tr>
<tr>
<td>W0U1130</td>
<td>-363,886.1</td>
<td>1,198,684.0</td>
<td>1,337.30</td>
<td>1,324.30</td>
</tr>
<tr>
<td>W0U1212</td>
<td>-364,041.8</td>
<td>1,198,665.0</td>
<td>1,335.30</td>
<td>1,322.30</td>
</tr>
<tr>
<td>W0U1360</td>
<td>-364,178.5</td>
<td>1,198,634.0</td>
<td>1,333.17</td>
<td>1,318.67</td>
</tr>
<tr>
<td>W0U1420</td>
<td>-363,984.0</td>
<td>1,198,597.0</td>
<td>1,330.39</td>
<td>1,317.89</td>
</tr>
<tr>
<td>W0U1510</td>
<td>-364,141.9</td>
<td>1,198,578.0</td>
<td>1,331.77</td>
<td>1,320.27</td>
</tr>
<tr>
<td>W1M0726</td>
<td>-363,979.8</td>
<td>1,198,808.0</td>
<td>1,336.00</td>
<td>1,315.00</td>
</tr>
<tr>
<td>W1U0726</td>
<td>-363,977.5</td>
<td>1,198,808.0</td>
<td>1,335.83</td>
<td>1,322.83</td>
</tr>
<tr>
<td>W1U0926</td>
<td>-364,006.5</td>
<td>1,198,749.0</td>
<td>1,336.60</td>
<td>1,322.60</td>
</tr>
<tr>
<td>W2L0726</td>
<td>-363,933.1</td>
<td>1,198,805.0</td>
<td>1,335.49</td>
<td>1,306.49</td>
</tr>
<tr>
<td>Well Identification Number</td>
<td>Well Location X-coordinate (meters)</td>
<td>Well Location Y-coordinate (meters)</td>
<td>Land-surface altitude (feet)</td>
<td>Screen mid-point altitude (feet)</td>
</tr>
<tr>
<td>---------------------------</td>
<td>-----------------------------------</td>
<td>-----------------------------------</td>
<td>-----------------------------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td>W2M0726</td>
<td>-363,936.5</td>
<td>1,198,805.</td>
<td>1,335.52</td>
<td>1,314.52</td>
</tr>
<tr>
<td>W2M0926</td>
<td>-363,952.0</td>
<td>1,198,746.</td>
<td>1,336.02</td>
<td>1,315.02</td>
</tr>
<tr>
<td>W2U0726</td>
<td>-363,931.5</td>
<td>1,198,805.</td>
<td>1,337.41</td>
<td>1,324.41</td>
</tr>
<tr>
<td>W2U0926</td>
<td>-363,954.4</td>
<td>1,198,746.</td>
<td>1,335.90</td>
<td>1,321.90</td>
</tr>
<tr>
<td>W3L0726</td>
<td>-363,887.3</td>
<td>1,198,803.</td>
<td>1,334.92</td>
<td>1,306.92</td>
</tr>
<tr>
<td>W3M0726</td>
<td>-363,890.0</td>
<td>1,198,803.</td>
<td>1,334.93</td>
<td>1,313.93</td>
</tr>
<tr>
<td>W3M0926</td>
<td>-363,905.0</td>
<td>1,198,744.</td>
<td>1,335.50</td>
<td>1,314.50</td>
</tr>
<tr>
<td>W3U0726</td>
<td>-363,885.5</td>
<td>1,198,803.</td>
<td>1,334.93</td>
<td>1,320.93</td>
</tr>
<tr>
<td>W3U0926</td>
<td>-363,907.3</td>
<td>1,198,744.</td>
<td>1,335.62</td>
<td>1,322.62</td>
</tr>
<tr>
<td>W4L0726</td>
<td>-363,844.0</td>
<td>1,198,800.</td>
<td>1,334.97</td>
<td>1,308.97</td>
</tr>
<tr>
<td>W4M0726</td>
<td>-363,841.1</td>
<td>1,198,800.</td>
<td>1,334.75</td>
<td>1,313.75</td>
</tr>
<tr>
<td>W4M0926</td>
<td>-363,859.8</td>
<td>1,198,740.</td>
<td>1,335.33</td>
<td>1,314.33</td>
</tr>
<tr>
<td>W4U0486</td>
<td>-363,840.3</td>
<td>1,198,880.</td>
<td>1,335.17</td>
<td>1,321.67</td>
</tr>
<tr>
<td>W4U0726</td>
<td>-363,839.5</td>
<td>1,198,800.</td>
<td>1,334.69</td>
<td>1,323.69</td>
</tr>
<tr>
<td>W4U0926</td>
<td>-363,862.1</td>
<td>1,198,740.</td>
<td>1,335.13</td>
<td>1,322.13</td>
</tr>
<tr>
<td>W5M0726</td>
<td>-363,787.8</td>
<td>1,198,797.</td>
<td>1,335.30</td>
<td>1,314.30</td>
</tr>
<tr>
<td>W5U0726</td>
<td>-363,785.4</td>
<td>1,198,797.</td>
<td>1,334.11</td>
<td>1,321.11</td>
</tr>
<tr>
<td>W5U0926</td>
<td>-363,812.0</td>
<td>1,198,738.</td>
<td>1,335.15</td>
<td>1,322.15</td>
</tr>
<tr>
<td>W6M0726</td>
<td>-363,732.1</td>
<td>1,198,795.</td>
<td>1,334.30</td>
<td>1,313.30</td>
</tr>
<tr>
<td>W6U0486</td>
<td>-363,730.5</td>
<td>1,198,874.</td>
<td>1,337.04</td>
<td>1,322.54</td>
</tr>
<tr>
<td>Well Identification Number</td>
<td>Well Location X-coordinate (meters)</td>
<td>Well Location Y-coordinate (meters)</td>
<td>Land-surface altitude (feet)</td>
<td>Screen mid-point altitude (feet)</td>
</tr>
<tr>
<td>---------------------------</td>
<td>------------------------------------</td>
<td>------------------------------------</td>
<td>-----------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>W6U0726</td>
<td>-363,730.1</td>
<td>1,198,794.</td>
<td>1,334.24</td>
<td>1,321.24</td>
</tr>
<tr>
<td>W6U0926</td>
<td>-363,759.6</td>
<td>1,198,733.</td>
<td>1,334.99</td>
<td>1,321.99</td>
</tr>
<tr>
<td>W9M0002</td>
<td>-363,936.6</td>
<td>1,199,035.</td>
<td>1,336.63</td>
<td>1,315.63</td>
</tr>
<tr>
<td>W9M0120</td>
<td>-364,012.6</td>
<td>1,199,004.</td>
<td>1,336.67</td>
<td>1,315.67</td>
</tr>
<tr>
<td>W9M0200</td>
<td>-363,959.1</td>
<td>1,198,978.</td>
<td>1,336.24</td>
<td>1,314.74</td>
</tr>
<tr>
<td>W9M0230</td>
<td>-364,015.3</td>
<td>1,198,972.</td>
<td>1,336.39</td>
<td>1,315.39</td>
</tr>
<tr>
<td>W9U0004</td>
<td>-363,704.9</td>
<td>1,199,020.</td>
<td>1,335.21</td>
<td>1,321.21</td>
</tr>
<tr>
<td>W9U0010</td>
<td>-364,009.5</td>
<td>1,199,040.</td>
<td>1,336.52</td>
<td>1,322.52</td>
</tr>
<tr>
<td>W9U0600</td>
<td>-364,026.8</td>
<td>1,198,853.</td>
<td>1,337.04</td>
<td>1,322.54</td>
</tr>
<tr>
<td>W9U0975</td>
<td>-363,603.6</td>
<td>1,198,720.</td>
<td>1,334.53</td>
<td>1,320.03</td>
</tr>
<tr>
<td>W9U1025</td>
<td>-363,723.6</td>
<td>1,198,704.</td>
<td>1,333.88</td>
<td>1,322.88</td>
</tr>
</tbody>
</table>
APPENDIX B

Water-level measurements in observation wells at the Rosholt Research Farm

<table>
<thead>
<tr>
<th>Well Identification</th>
<th>Water-level (feet above mean sea-level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WOL0950</td>
<td>1,322.59</td>
</tr>
<tr>
<td>WOL1212</td>
<td>1,322.78</td>
</tr>
<tr>
<td>WOM0950</td>
<td>1,322.62</td>
</tr>
<tr>
<td>WOM1130</td>
<td>1,322.64</td>
</tr>
<tr>
<td>WOM1212</td>
<td>1,322.76</td>
</tr>
<tr>
<td>WOU0950</td>
<td>1,322.58</td>
</tr>
<tr>
<td>WOU1130</td>
<td>1,322.67</td>
</tr>
<tr>
<td>WOU1212</td>
<td>1,322.81</td>
</tr>
<tr>
<td>WOU1360</td>
<td>1,322.00</td>
</tr>
<tr>
<td>WOU1420</td>
<td>1,321.90</td>
</tr>
<tr>
<td>WOU1510</td>
<td>1,323.05</td>
</tr>
<tr>
<td>W1M0726</td>
<td>1,322.40</td>
</tr>
<tr>
<td>W1U0726</td>
<td>1,322.40</td>
</tr>
<tr>
<td>W1U0926</td>
<td>1,322.54</td>
</tr>
<tr>
<td>W2L0726</td>
<td>1,322.31</td>
</tr>
<tr>
<td>Well Identification Number</td>
<td>Water-level (feet above mean sea-level)</td>
</tr>
<tr>
<td>----------------------------</td>
<td>----------------------------------------</td>
</tr>
<tr>
<td>W2M0726</td>
<td>1,321.94</td>
</tr>
<tr>
<td>W2M0926</td>
<td>-99.00</td>
</tr>
<tr>
<td>W2U0726</td>
<td>1,322.37</td>
</tr>
<tr>
<td>W2U0926</td>
<td>1,322.55</td>
</tr>
<tr>
<td>W3L0726</td>
<td>1,322.38</td>
</tr>
<tr>
<td>W3M0726</td>
<td>1,322.39</td>
</tr>
<tr>
<td>W3M0926</td>
<td>1,322.54</td>
</tr>
<tr>
<td>W3U0726</td>
<td>-99.00</td>
</tr>
<tr>
<td>W3U0926</td>
<td>1,322.55</td>
</tr>
<tr>
<td>W4L0726</td>
<td>1,322.38</td>
</tr>
<tr>
<td>W4M0726</td>
<td>1,322.38</td>
</tr>
<tr>
<td>W4M0926</td>
<td>1,322.40</td>
</tr>
<tr>
<td>W4U0486</td>
<td>-99.00</td>
</tr>
<tr>
<td>W4U0726</td>
<td>1,322.37</td>
</tr>
<tr>
<td>W4U0926</td>
<td>1,322.48</td>
</tr>
<tr>
<td>W5M0726</td>
<td>1,322.35</td>
</tr>
<tr>
<td>W5U0726</td>
<td>1,322.37</td>
</tr>
<tr>
<td>W5U0926</td>
<td>1,322.47</td>
</tr>
<tr>
<td>W6M0726</td>
<td>1,322.34</td>
</tr>
<tr>
<td>W6U0486</td>
<td>1,321.21</td>
</tr>
</tbody>
</table>
Well Identification | Water-level (feet above mean sea-level)
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>W6U0726</td>
<td>1,322.34</td>
<td>1,322.80</td>
<td>1,324.48</td>
<td>1,324.29</td>
<td>1,324.16</td>
<td>1,323.54</td>
<td>1,323.06</td>
<td>1,323.64</td>
<td>1,323.69</td>
<td>1,323.59</td>
<td>1,323.29</td>
<td>1,323.26</td>
</tr>
<tr>
<td>W6U0926</td>
<td>1,322.44</td>
<td>1,322.88</td>
<td>1,324.53</td>
<td>1,324.40</td>
<td>1,324.18</td>
<td>1,323.64</td>
<td>1,323.11</td>
<td>1,323.69</td>
<td>1,323.74</td>
<td>1,323.64</td>
<td>1,323.37</td>
<td>1,323.36</td>
</tr>
<tr>
<td>W9U0004</td>
<td>1,321.92</td>
<td>1,322.26</td>
<td>1,324.07</td>
<td>1,323.89</td>
<td>1,323.76</td>
<td>1,323.13</td>
<td>1,322.53</td>
<td>1,323.11</td>
<td>1,323.16</td>
<td>1,323.06</td>
<td>1,323.02</td>
<td>1,323.07</td>
</tr>
<tr>
<td>W9U0010</td>
<td>1,321.78</td>
<td>1,322.44</td>
<td>1,324.12</td>
<td>1,323.98</td>
<td>1,323.89</td>
<td>1,323.10</td>
<td>1,322.13</td>
<td>1,322.71</td>
<td>1,322.76</td>
<td>1,322.66</td>
<td>1,323.15</td>
<td>1,323.13</td>
</tr>
<tr>
<td>W9U0600</td>
<td>1,322.29</td>
<td>1,321.78</td>
<td>1,324.44</td>
<td>1,324.32</td>
<td>1,324.22</td>
<td>1,323.54</td>
<td>1,322.88</td>
<td>1,323.46</td>
<td>1,323.51</td>
<td>1,323.41</td>
<td>1,323.45</td>
<td>1,323.41</td>
</tr>
<tr>
<td>W9U0975</td>
<td>1,322.35</td>
<td>1,322.65</td>
<td>1,324.45</td>
<td>1,324.30</td>
<td>1,324.05</td>
<td>-99.00</td>
<td>1,323.01</td>
<td>1,323.59</td>
<td>1,323.64</td>
<td>1,323.54</td>
<td>1,323.23</td>
<td>1,323.25</td>
</tr>
<tr>
<td>W9U1025</td>
<td>1,322.43</td>
<td>1,322.81</td>
<td>1,324.54</td>
<td>1,324.40</td>
<td>1,324.18</td>
<td>1,323.63</td>
<td>1,323.09</td>
<td>1,323.67</td>
<td>1,323.72</td>
<td>1,323.62</td>
<td>1,323.37</td>
<td>1,323.34</td>
</tr>
</tbody>
</table>

1 the value -99.00 indicates that a water-level measurement was not available for the given well on the given date
APPENDIX C

Nitrate concentration measurements in observation wells at the Rosholt Research Farm

<table>
<thead>
<tr>
<th>Well Identification</th>
<th>Nitrate concentration (milligrams per liter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>---------------------</td>
<td>----------</td>
</tr>
<tr>
<td>W0L0950</td>
<td>0.3</td>
</tr>
<tr>
<td>W0L1212</td>
<td>0.3</td>
</tr>
<tr>
<td>W0M0950</td>
<td>9.9</td>
</tr>
<tr>
<td>W0M1130</td>
<td>0.0</td>
</tr>
<tr>
<td>W0M1212</td>
<td>2.8</td>
</tr>
<tr>
<td>W0U0950</td>
<td>10.1</td>
</tr>
<tr>
<td>W0U1130</td>
<td>10.0</td>
</tr>
<tr>
<td>W0U1212</td>
<td>9.2</td>
</tr>
<tr>
<td>W0U1360</td>
<td>11.8</td>
</tr>
<tr>
<td>W0U1420</td>
<td>5.6</td>
</tr>
<tr>
<td>W0U1510</td>
<td>9.3</td>
</tr>
<tr>
<td>W1M0726</td>
<td>11.0</td>
</tr>
<tr>
<td>W1U0726</td>
<td>16.0</td>
</tr>
<tr>
<td>W1U0926</td>
<td>7.2</td>
</tr>
<tr>
<td>W2L0726</td>
<td>0.0</td>
</tr>
</tbody>
</table>
### Identification Number

<table>
<thead>
<tr>
<th>Identification Number</th>
<th>Nitrate concentration (milligrams per liter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W2M0726</td>
<td>5.4</td>
</tr>
<tr>
<td>W2M0926</td>
<td>5.1</td>
</tr>
<tr>
<td>W2U0726</td>
<td>12.2</td>
</tr>
<tr>
<td>W2U0926</td>
<td>10.2</td>
</tr>
<tr>
<td>W3L0726</td>
<td>0.0</td>
</tr>
<tr>
<td>W3M0726</td>
<td>0.9</td>
</tr>
<tr>
<td>W3M0926</td>
<td>3.7</td>
</tr>
<tr>
<td>W3U0726</td>
<td>8.8</td>
</tr>
<tr>
<td>W3U0926</td>
<td>8.5</td>
</tr>
<tr>
<td>W4L0726</td>
<td>0.0</td>
</tr>
<tr>
<td>W4M0726</td>
<td>0.0</td>
</tr>
<tr>
<td>W4M0926</td>
<td>3.1</td>
</tr>
<tr>
<td>W4U0486</td>
<td>9.0</td>
</tr>
<tr>
<td>W4U0726</td>
<td>7.8</td>
</tr>
<tr>
<td>W4U0926</td>
<td>10.1</td>
</tr>
<tr>
<td>W5M0726</td>
<td>0.0</td>
</tr>
<tr>
<td>W5U0726</td>
<td>11.0</td>
</tr>
<tr>
<td>W5U0926</td>
<td>9.8</td>
</tr>
<tr>
<td>W6M0726</td>
<td>0.6</td>
</tr>
<tr>
<td>W6U0486</td>
<td>4.1</td>
</tr>
<tr>
<td>Well Identification Number</td>
<td>Nitrate concentration (milligrams per liter)</td>
</tr>
<tr>
<td>---------------------------</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>W6U0726</td>
<td>6.9</td>
</tr>
<tr>
<td>W6U0926</td>
<td>5.8</td>
</tr>
<tr>
<td>W9U0004</td>
<td>6.0</td>
</tr>
<tr>
<td>W9U0010</td>
<td>7.8</td>
</tr>
<tr>
<td>W9U0600</td>
<td>11.5</td>
</tr>
<tr>
<td>W9U0975</td>
<td>1.8</td>
</tr>
<tr>
<td>W9U1025</td>
<td>2.8</td>
</tr>
</tbody>
</table>

1. the value 0.0 indicates that the nitrate concentration was below the reporting limit of 0.1 mg/L
2. the value -99.00 indicates that a nitrate concentration value was not available for the given well on the given date
## APPENDIX D

Atrazine concentration measurements in observation wells at the Rosholt Research Farm

<table>
<thead>
<tr>
<th>Well identification number</th>
<th>Atrazine concentration (micrograms per liter)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4/18/89</td>
</tr>
<tr>
<td>W0U1510</td>
<td>0.00</td>
</tr>
<tr>
<td>W0U1360</td>
<td>0.02</td>
</tr>
<tr>
<td>W0U1420</td>
<td>0.00</td>
</tr>
<tr>
<td>W9U0975</td>
<td>-99.00</td>
</tr>
<tr>
<td>W9U1025</td>
<td>-99.00</td>
</tr>
<tr>
<td>W9U0004</td>
<td>-99.00</td>
</tr>
<tr>
<td>W9U0010</td>
<td>-99.00</td>
</tr>
<tr>
<td>W9U0600</td>
<td>-99.00</td>
</tr>
<tr>
<td>W4U0486</td>
<td>0.21</td>
</tr>
<tr>
<td>W6U0486</td>
<td>0.03</td>
</tr>
<tr>
<td>W6U0926</td>
<td>0.00</td>
</tr>
<tr>
<td>W5U0926</td>
<td>0.02</td>
</tr>
<tr>
<td>W1U0926</td>
<td>0.03</td>
</tr>
<tr>
<td>W0M1212</td>
<td>0.00</td>
</tr>
<tr>
<td>W0L1212</td>
<td>0.00</td>
</tr>
</tbody>
</table>

1. The number 0.00 indicates a concentration of 0.00 micrograms per liter.
2. The number -99.00 indicates no detection of atrazine.
<table>
<thead>
<tr>
<th>Well identification number</th>
<th>Atrazine concentration (micrograms per liter)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4/18/89</td>
</tr>
<tr>
<td>W0U1212</td>
<td>0.00</td>
</tr>
<tr>
<td>W0M0950</td>
<td>0.02</td>
</tr>
<tr>
<td>W0L0950</td>
<td>0.02</td>
</tr>
<tr>
<td>W0U0950</td>
<td>-99.00</td>
</tr>
<tr>
<td>W1U0726</td>
<td>-99.00</td>
</tr>
<tr>
<td>W1M0726</td>
<td>0.00</td>
</tr>
<tr>
<td>W6U0726</td>
<td>0.02</td>
</tr>
<tr>
<td>W6M0726</td>
<td>0.00</td>
</tr>
<tr>
<td>W0M1130</td>
<td>0.00</td>
</tr>
<tr>
<td>W0U1130</td>
<td>0.00</td>
</tr>
<tr>
<td>W2U0926</td>
<td>0.02</td>
</tr>
<tr>
<td>W2M0926</td>
<td>0.00</td>
</tr>
<tr>
<td>W2M0726</td>
<td>0.00</td>
</tr>
<tr>
<td>W2U0726</td>
<td>0.13</td>
</tr>
<tr>
<td>W2L0726</td>
<td>0.00</td>
</tr>
<tr>
<td>W3M0726</td>
<td>0.00</td>
</tr>
<tr>
<td>W3U0726</td>
<td>0.04</td>
</tr>
<tr>
<td>W3L0726</td>
<td>0.00</td>
</tr>
<tr>
<td>W4L0726</td>
<td>0.00</td>
</tr>
<tr>
<td>W4U0726</td>
<td>0.05</td>
</tr>
<tr>
<td>Well identification number</td>
<td>Atrazine concentration (micrograms per liter)</td>
</tr>
<tr>
<td>----------------------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>4/18/89</td>
</tr>
<tr>
<td>W4M0726</td>
<td>0.00</td>
</tr>
<tr>
<td>W5M0726</td>
<td>0.00</td>
</tr>
<tr>
<td>W5U0726</td>
<td>0.05</td>
</tr>
<tr>
<td>W4U0926</td>
<td>0.00</td>
</tr>
<tr>
<td>W4M0926</td>
<td>0.00</td>
</tr>
<tr>
<td>W3M0926</td>
<td>0.06</td>
</tr>
<tr>
<td>W3U0926</td>
<td>0.02</td>
</tr>
</tbody>
</table>

1The value 0.00 indicates that the atrazine concentration was below the reporting limit of 0.01 ug/L.
2The value -99.00 indicates that an atrazine concentration value was not available for the given well on the given date.
APPENDIX E

ARC/INFO coverage documentation for point coverages of nitrate concentration values, atrazine concentration values and water-level measurements

WELLS.NIT

DOCUMENTATION FILE
COMPILED BY WBATTAGLIN ON 91-03-20

COVER NAME: WELLS.NIT

COVER CONTENT: This coverage contains nitrate concentration data for 28 dates between October, 1986 and June, 1990, at as many as 43 wells at the Rosholt Research Farm, in Westport, Minnesota. All concentrations are reported in mg/L (ppm). Wells which were not sampled on a particular date are coded as -99. The item name for sampling data from May 12, 1987 would be NIT.051287. Also included in this coverage are items containing: the x and y coordinates of the well point, the altitude of the land surface at the well head, the altitude of the well screen mid-point, and the well identification number.

SOURCE MAP TITLE: Rosholt farm base map and survey data
SOURCE MAP SCALE: 1:2,400
SOURCE MAP MEDIA (PAPER OR MYLAR): mylar
SOURCE MAP ACCURACY:?
SOURCE MAP PROJECTION: local rectangular
PROJECTION PARAMETERS:
SOURCE CONTACT PERSON: William Battaglin
SOURCE CONTACT PHONE: (303)236-5939
SOURCE ORGANIZATION: USGS-WRD
SOURCE ADDRESS: box 25046, M.S. 406, D.F.C.
    : Lakewood, Co., 80225
PROCESS PERSON: William Battaglin
INPUT METHOD (SCANNED, DIGITIZED, DLG): generated
DATE FINISHED: 6/4/90
COVER ACCURACY: good
COVER PROJECTION: Alber's meters
PROJECTION PARAMETERS: 1st parallel 39 30 00
    : 2nd parallel 45 30 00
    : central meridian -90 30 00
NOTES: This coverage contains the relatable well identification number WID. WID is stored as a character string. If WID contains an ‘U’ the wells is screened in the upper portion of the aquifer. If WID contains an ‘M’ the wells is screened in the middle portion of the aquifer. If WID contains an ‘L’ the well is screened in the lower portion of the aquifer.

The output from the DESCRIBE command is as follows:

Description of SINGLE precision coverage WELLS.NIT

ARCS

<table>
<thead>
<tr>
<th>Arcs</th>
<th>Polygons</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Segments = 0
There is NO Polygon Topology.

0 bytes of Arc Attribute Data
0 bytes of Polygon Attribute Data

POLYGONS

POINTS

<table>
<thead>
<tr>
<th>Label Points</th>
<th>Tics</th>
</tr>
</thead>
<tbody>
<tr>
<td>47</td>
<td>4</td>
</tr>
</tbody>
</table>

124 bytes of Attribute Data/Point Annotations = 0

SECONdARY FEATURES

<table>
<thead>
<tr>
<th>Links</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

TOLERANCES

<table>
<thead>
<tr>
<th>Fuzzy</th>
<th>Dangle</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.046 N</td>
<td>0.000 N</td>
</tr>
</tbody>
</table>

The coverage has not been Edited since the last BUILD or CLEAN.

STATUS

<table>
<thead>
<tr>
<th>Coverage Boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>xmin = -364178.500</td>
</tr>
<tr>
<td>xmax = -363603.625</td>
</tr>
<tr>
<td>ymin = 1198577.500</td>
</tr>
<tr>
<td>ymax = 1199039.500</td>
</tr>
</tbody>
</table>

The contents of the PRJ file are as follows:

PROJECTION ALBERS

UNITS METERS

SPHEROID CLARKE1866

XSHIFT 0

YSHIFT 0

PARAMETERS
### DATAFILE NAME: WELLS.NIT.TIC  
**3/20/1991**

<table>
<thead>
<tr>
<th>COL</th>
<th>ITEM NAME</th>
<th>WDTH</th>
<th>OUTP</th>
<th>TYP</th>
<th>N.DEC</th>
<th>ALTERNATE NAME</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IDTIC</td>
<td>4</td>
<td>5</td>
<td>B</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>XTIC</td>
<td>4</td>
<td>12</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>YTIC</td>
<td>4</td>
<td>12</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

**NUMBER OF RECORDS IN TIC FILE IS 4**

---

### WELLS.ATR

**DOCUMENTATION FILE**

**COMPILED BY WBATTAGLIN ON 91-03-20**

**COVER NAME: WELLS.ATR**

**COVER CONTENT:** This coverage contains atrazine concentration data for 21 dates between October, 1986 and September, 1989, at as many as 42 wells at the Rosholt Research Farm, in Westport, Minnesota. All concentrations are reported in ug/L (ppb). Wells which were not sampled on a particular date are coded as -99. The item name for sampling data from May 12, 1987 would be ATR.051287. Also included in this coverage...
are items containing: the x and y coordinates of the well point, the altitude of the land surface at the well head, the altitude of the well screen mid-point, and the well identification number.

SOURCE MAP TITLE: Rosholt farm base map and survey data
SOURCE MAP SCALE: 1:2,400
SOURCE MAP MEDIA (PAPER OR MYLAR): mylar
SOURCE MAP ACCURACY:?
SOURCE MAP PROJECTION: local rectangular
PROJECTION PARAMETERS:
SOURCE CONTACT PERSON: William Battaglin
SOURCE CONTACT PHONE: (303)236-5939
SOURCE ORGANIZATION: USGS-WRD
SOURCE ADDRESS: box 25046, M.S. 406, D.F.C.
: Lakewood, Co., 80225
PROCESS PERSON: William Battaglin
INPUT METHOD (SCANNED, DIGITIZED, DLG): generated
DATE FINISHED: 6/4/90
COVER ACCURACY: good
COVER PROJECTION: Alber's meters
PROJECTION PARAMETERS: 1st parallel 39 30 00
: 2nd parallel 45 30 00
: central meridian -90 30 00
: easting 0.0
: northing 0.0
NOTES: This coverage contains the relatable well identification number WID. WID is stored as a character string. If WID contains an ‘U’ the wells is screened in the upper portion of the aquifer. If WID contains an ‘M’ the wells is screened in the middle portion of the aquifer. If WID contains an ‘L’ the well is screened in the lower portion of the aquifer.

The output from the DESCRIBE command is as follows:

Description of SINGLE precision coverage WELLS.ATR

ARCS POLYGONS

Arcs = 0 Polygons = 0
Segments = 0 There is NO Polygon Topology.
0 bytes of Arc Attribute Data 0 bytes of Polygon Attribute Data

POINTS SECONDARY FEATURES

Label Points = 47 Tics = 4
124 bytes of Attribute Data/Point Annotations = 0
Links = 0

TOLERANCES STATUS

Fuzzy = 0.046 N The coverage has not been Edited
Dangle = 0.000 N since the last BUILD or CLEAN.

COVERAGE BOUNDARY

Xmin = -364178.500 Ymin = 1198577.500
Xmax = -363603.625 Ymax = 1199039.500

The contents of the PRJ file are as follows:

PROJECTION ALBERS
UNITS METERS
SPHEROID CLARKE1866
XSHIFT 0
YSHIFT 0
PARAMETERS
39 30 00
45 30 00
-90 30 00
35 00 00
0
0

INFO templates for coverage files are as follows:

DATAFILE NAME: WELLS.ATR.BND 3/20/1991
4 ITEMS: STARTING IN POSITION 1
COL ITEM NAME WDTH OPUT TYP N.DEC ALTERNATE NAME
1 XMIN 4 12 F 3
5 YMIN 4 12 F 3
9 XMAX 4 12 F 3
13 YMAX 4 12 F 3
$RECNO XMIN YMIN XMAX YMAX
1 -364,178.5001198578.000 -363,603.6001199040.000
### DATAFILE NAME: WELLS.ATR.PAT 3/20/1991

30 ITEMS: STARTING IN POSITION 1

<table>
<thead>
<tr>
<th>COL</th>
<th>ITEM NAME</th>
<th>WDTH</th>
<th>OPUT</th>
<th>TYP</th>
<th>N.DEC</th>
<th>ALTERNATE NAME</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AREA</td>
<td>4</td>
<td>12</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>PERIMETER</td>
<td>4</td>
<td>12</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>WELLS.ATR#</td>
<td>4</td>
<td>5</td>
<td>B</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>WELLS.ATR-ID</td>
<td>4</td>
<td>5</td>
<td>B</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>WID</td>
<td>8</td>
<td>8</td>
<td>C</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>X-COORD</td>
<td>4</td>
<td>12</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Y-COORD</td>
<td>4</td>
<td>12</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>LS_ALT</td>
<td>4</td>
<td>12</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>SC_ALT</td>
<td>4</td>
<td>12</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>ATR.102386</td>
<td>4</td>
<td>10</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>ATR.022687</td>
<td>4</td>
<td>10</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>49</td>
<td>ATR.051287</td>
<td>4</td>
<td>10</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>53</td>
<td>ATR.061187</td>
<td>4</td>
<td>10</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>57</td>
<td>ATR.062687</td>
<td>4</td>
<td>10</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>61</td>
<td>ATR.071087</td>
<td>4</td>
<td>10</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>65</td>
<td>ATR.072487</td>
<td>4</td>
<td>10</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>69</td>
<td>ATR.080787</td>
<td>4</td>
<td>10</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>73</td>
<td>ATR.082587</td>
<td>4</td>
<td>10</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>77</td>
<td>ATR.091687</td>
<td>4</td>
<td>10</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>81</td>
<td>ATR.040488</td>
<td>4</td>
<td>10</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>85</td>
<td>ATR.040788</td>
<td>4</td>
<td>10</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>89</td>
<td>ATR.042788</td>
<td>4</td>
<td>10</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>93</td>
<td>ATR.061688</td>
<td>4</td>
<td>10</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>97</td>
<td>ATR.070888</td>
<td>4</td>
<td>10</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>101</td>
<td>ATR.041889</td>
<td>4</td>
<td>10</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>105</td>
<td>ATR.050389</td>
<td>4</td>
<td>10</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>109</td>
<td>ATR.052589</td>
<td>4</td>
<td>10</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>113</td>
<td>ATR.070789</td>
<td>4</td>
<td>10</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>117</td>
<td>ATR.090789</td>
<td>4</td>
<td>10</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>121</td>
<td>ATR.091389</td>
<td>4</td>
<td>10</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

### DATAFILE NAME: WELLS.ATR.TIC 3/20/1991

3 ITEMS: STARTING IN POSITION 1

<table>
<thead>
<tr>
<th>COL</th>
<th>ITEM NAME</th>
<th>WDTH</th>
<th>OPUT</th>
<th>TYP</th>
<th>N.DEC</th>
<th>ALTERNATE NAME</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IDTIC</td>
<td>4</td>
<td>5</td>
<td>B</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>XTIC</td>
<td>4</td>
<td>12</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>YTIC</td>
<td>4</td>
<td>12</td>
<td>F</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

NUMBER OF RECORDS IN TIC FILE IS 4
WELLS.WL

DOCUMENTATION FILE
COMPILED BY WBATTAGLIN ON 91-03-20

COVER NAME: WELLS.WL

COVER CONTENT: This coverage contains water-level measurements for 47 dates between October, 1986 and July, 1990 at as many as 42 wells at the Rossholt Research Farm, in Westport, Minnesota. All water-levels are reported in feet above mean sea level. Wells which were not measured on a particular date are coded as -99. The item name for water-level data from May 12, 1987 would be WL.051287. Also included in this coverage are items containing: the x and y coordinates of the well point, the altitude of the land surface at the well head, the altitude of the well screen mid-point, and the well identification number.

SOURCE MAP TITLE: Rossholt farm base map and survey data
SOURCE MAP SCALE: 1:2,400
SOURCE MAP MEDIA (PAPER OR MYLAR): mylar
SOURCE MAP ACCURACY:?
SOURCE MAP PROJECTION: local rectangular
PROJECTION PARAMETERS:
SOURCE CONTACT PERSON: William Battaglin
SOURCE CONTACT PHONE: (303)236-5939
SOURCE ORGANIZATION: USGS-WRD
SOURCE ADDRESS: box 25046, M.S. 406, D.F.C.: Lakewood, Co., 80225
PROCESS PERSON: William Battaglin
INPUT METHOD (SCANNED, DIGITIZED, DLG): generated
DATE FINISHED: 6/4/90
COVER ACCURACY: good
COVER PROJECTION: Alber’s meters
PROJECTION PARAMETERS: 1st parallel 39 30 00
 : 2nd parallel 45 30 00
 : central meridian -90 30 00
 : easting 0.0
 : northing 0.0
NOTES: This coverage contains the relatable well identification number WID. WID is stored as a character string. If WID contains an ‘U’ the wells is screened in the upper portion of the aquifer. If WID contains an ‘M’ the wells is screened in the middle portion of
the aquifer. If WID contains an ‘L’ the well is screened in the lower portion of the aquifer.

The output from the DESCRIBE command is as follows:

Description of SINGLE precision coverage WELLS.WL

ARCS POLYGONS

Arcs = 0 Polygons = 0
Segments = 0 There is NO Polygon Topology.
0 bytes of Arc Attribute Data 0 bytes of Polygon Attribute Data

POINTS SECONDARY FEATURES

Label Points = 52 Tics = 4
268 bytes of Attribute Data/Point Annotations = 0

TOLERANCES STATUS

Fuzzy = 0.046 N The coverage has not been Edited
Dangle = 0.000 N since the last BUILD or CLEAN.

COVERAGE BOUNDARY

Xmin = -364210.875 Ymin = 1198556.750
Xmax = -363550.313 Ymax = 1199068.750
Arc:

The contents of the PRJ file are as follows:

PROJECTION ALBERS
UNITS METERS
SPHEROID CLARKE1866
XSHIFT 0
YSHIFT 0
PARAMETERS
39 30 00
45 30 00
-90 30 00
35 00 00
INFO templates for coverage files are as follows:

DATAFILE NAME: WELLS.WL.BND 3/20/1991
4 ITEMS: STARTING IN POSITION 1
COL ITEM NAME WDTH OPUT TYP N.DEC ALTERNATE NAME
  1 XMIN 4 12 F 3
  5 YMIN 4 12 F 3
  9 XMAX 4 12 F 3
 13 YMAX 4 12 F 3
$RECNO XMIN YMIN XMAX YMAX
  1 -364,210.875 1198556.750 -363,550.313 1199068.750

DATAFILE NAME: WELLS.WL.PAT 3/20/1991
66 ITEMS: STARTING IN POSITION 1
COL ITEM NAME WDTH OPUT TYP N.DEC ALTERNATE NAME
  1 AREA 4 12 F 3
  5 PERIMETER 4 12 F 3
  9 WELLS.WL# 4 5 B -
 13 WELLS.WL-ID 4 5 B -
 17 WID 8 8 C -
 25 X-COORD 4 12 F 3
 29 Y-COORD 4 12 F 3
 33 LS_ALT 4 12 F 3
 37 LS_ALT.M 4 12 F 3
 41 SC_ALT 4 12 F 3
 45 TO 4 12 F 3
 49 FROM 4 12 F 3
 53 WL_ALT.M 4 12 F 3
 57 TILL_ALT.M 4 12 F 3
 61 WL.101086 4 12 F 3
 65 WL.102486 4 12 F 3
 69 WL.022687 4 12 F 3
 73 WL.041487 4 12 F 3
 77 WL.051287 4 12 F 3
 81 WL.080687 4 12 F 3
 85 WL.081387 4 12 F 3
 89 WL.082087 4 12 F 3
<table>
<thead>
<tr>
<th>Year</th>
<th>WL</th>
<th>Code</th>
<th>Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>93</td>
<td>WL.090187</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>97</td>
<td>WL.090987</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>101</td>
<td>WL.091487</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>105</td>
<td>WL.092487</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>109</td>
<td>WL.100887</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>113</td>
<td>WL.121887</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>117</td>
<td>WL.032288</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>121</td>
<td>WL.032988</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>125</td>
<td>WL.040188</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>129</td>
<td>WL.041488</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>133</td>
<td>WL.042188</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>137</td>
<td>WL.042788</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>141</td>
<td>WL.051088</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>145</td>
<td>WL.060888</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>149</td>
<td>WL.062888</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>153</td>
<td>WL.070688</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>157</td>
<td>WL.071488</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>161</td>
<td>WL.072888</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>165</td>
<td>WL.081688</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>169</td>
<td>WL.091488</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>173</td>
<td>WL.092288</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>177</td>
<td>WL.100488</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>181</td>
<td>WL.041889</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>185</td>
<td>WL.042189</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>189</td>
<td>WL.050389</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>193</td>
<td>WL.052589</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>197</td>
<td>WL.061689</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>201</td>
<td>WL.071289</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>205</td>
<td>WL.080889</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>209</td>
<td>WL.090789</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>213</td>
<td>WL.091389</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>217</td>
<td>WL.101289</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>221</td>
<td>WL.113089</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>225</td>
<td>WL.032090</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>229</td>
<td>WL.050390</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>233</td>
<td>WL.060490</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>237</td>
<td>WL.062690</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>241</td>
<td>WL.071690</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>245</td>
<td>WL.073190</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>249</td>
<td>MEDIAN_87</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
<tr>
<td>253</td>
<td>MEDIAN_88</td>
<td>4</td>
<td>12</td>
<td>F</td>
</tr>
</tbody>
</table>
257 MEDIAN_89 4 12 F 3
261 MEDIAN_90 4 12 F 3

DATAFILE NAME: WELLS.WL.TIC 3/20/1991
3 ITEMS: STARTING IN POSITION 1
COL ITEM NAME WDTH OPUT TYP N.DEC ALTERNATE NAME
  1 IDTIC 4 5 B -
  5 XTIC 4 12 F 3
  9 YTIC 4 12 F 3

NUMBER OF RECORDS IN TIC FILE IS 4
APPENDIX F

ARC/INFO AML's used to create scattered data files of nitrate concentration, atrazine concentration, and water-level data from ARC/INFO coverages

make_nit_scat.aml:

/* ********************************************************************
/* make_nit_scat.aml
/*
/* This aml creates a scattered data file of nitrate concentration and sampling point location data
/* that can then be entered into the IVM software system.
/* The programs writes an ascii output file that contains the following information:
/*
/* X-COORDINATE, Y-COORDINATE, Z-COORDINATE, POINT-ID, FACTOR VALUE
/*
/* The factor value (nitrate concentration) is the item that is being modeled
/* The program allows the user to specify a null or missing value identifier.
/* The missing value identifier must be numeric (i.e. -99.)
/* The scattered data file will be named %item%.scat. Note that IVM will not read a
/* file name containing the character '-' so this character should not be used for item names.
/*
/*
/* **** PROGRAM HARDWIRED FOR NITRATE COVERAGE ****
/* PROGRAM ARGUMENTS:
/*
/* DATE OF NITRATE DATA
/*
/* WILLIAM A. BATTAGLIN 7/90
/* 10/90
/* converted to Unix 9/91
/* *********************************************************************/
&ARGS date

/*
** CHECKING INPUT FORMAT **
/*
&IF [NULL %date%] &THEN &RETURN &WARNING ~
Usage &R MAKE_NIT_SCAT <date>
/*
&IF [EXISTS nit.%date%.scat -FILE] &THEN &RETURN &WARNING ~
The file nit.%date%.scat already exists, please delete or CN existing file
/*
&S INCOVER = WELLS.NIT
&IF [EXISTS %INCOVER% -POINT] &THEN
&TYPE The coverage to be used is %INCOVER%
&ELSE &RETURN &WARNING ~
%INCOVER% does not exist, or it not a POINT cover
/*
/* SETTING NAME OF INFO FILE
/*
&S INFILE = %INCOVER%.PAT
/*
&TYPE
/*
/* CHECKING FOR EXISTANCE OF FACTOR AND COORDINATE ITEMS
/*
&IF [ITEMINFO %INCOVER% -POINT NIT.%date% -EXISTS] &THEN
&TYPE The factor item is NIT.%date%
&ELSE &RETURN &WARNING ~
The item NIT.%date% is not in %INCOVER%.
/*
&TYPE
/*
&S X-C = X-COORD
&S Y-C = Y-COORD
&S Z-C = SC_ALT
&S ID = WID
/*
&TYPE
/*
/*
&TYPE
/*
/*
/*
&TYPE
/*
&S here [DIR [PATHNAME *]]
/*
/* checking for use of missing value code
/*
&S MISSING = -99
&TYPE Missing value code is %MISSING%
&TYPE
&work %here%/info
&DATA info
arc
CALC $COMMA-SWITCH = -1
SEL %INFILE%
RES FOR NIT.%date% NE %MISSING%
OUTPUT %here%/nit.%date%.scat I
PRINT *W12,%X-C%,*W12,%Y-C%,*W12,%Z-C%,*W12,%ID%,*W12,NIT.%date%
ASEL
Q STOP
&END
&work %here%
/*
&TYPE
&TYPE The scatter data file nit.%date%.scat is ready to port to IVM
&type
&RETURN
/*  **********************************************************************
*  **********************************************************************

make_wl_scat.aml:

/* **********************************************************************
* MAKE_WL_SCAT.AML
/*
/* This AML creates a scattered data file of water-level estimates for a specified
/* date. Control points equal to the median water-level for all wells,
/* measured for that date are added to the perimeter of the data site to
/* to insure complete coverage over property scattered data files.
/* A TIN of the scattered measurements and control points was generated and then
/* resampled at a grid of points to generate the gridded elevations in the coverage
ro.grid.pts
/*
/* This program writes and ascii file containing:
/*
/* X-COORDINATE, Y-COORDINATE, Z-COORDINATE, POINT-ID
/*
/* The scattered data file will be named wl.%date%.scat
/*
/* DATE - date of desired water-level scattered data file
/*
/* WILLIAM A. BATTAGLIN 9/90
/* ported to UNIX 9/91
/*
/* **********************************************************************
/* &ARGS DATE
/* ** CHECKING INPUT FORMAT **
/*&IF [NULL %DATE%] &THEN &RETURN &WARNING ~
Usage &R MAKE_WL_SCAT <date>
/*&IF [ITEMINFO wells.wl -POINT WL.%DATE% -EXISTS] &THEN &TYPE ~
WL.%DATE% exists in wells.wl
&ELSE &RETURN &WARNING ~
WL.%DATE% is not an item in wells.wl
/*&IF [ITEMINFO ro.grid.pts -POINT WL.%DATE% -EXISTS] &THEN &TYPE ~
WL.%DATE% exists in ro.grid.pts
&ELSE &RETURN &WARNING ~
WL.%DATE% is not an item in ro.grid.pts
/*
/*
&IF [EXISTS wl.%DATE%.scat -FILE] &THEN &SYS rm wl.%DATE%.scat
/*
/*
/* ENTERING INFO AND WRITING SCATTERED DATA FILE
/*
&S here [DIR [PATHNAME *]]
&work %here%/info
&DATA info
arc
CALC $COMMA-SWITCH = -1
SEL RO.GRID.PTS.PAT
OUTPUT %here%/WL.%DATE%.SCAT I
PRINT *W12,X-COORD,*W12,Y-COORD,*W12,WL.%DATE%
ASEL
Q STOP
&END
&work %here%
/*
&TYPE
&TYPE The scatter data file wl.%DATE%.scat is ready to port to IVM
&type
&RETURN
/*
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
*************************************************************************
WARE
/*/ SYSTEM. THE PROGRAM WILL WRITE AN ASCII OUTPUT FILE WITH A USER
/*/ SPECIFIED NAME THAT CONTAINS THE FOLLOWING INFORMATION:
/*/ 
/*/ X-COORDINATE, Y-COORDINATE, Z-COORDINATE, POINT-ID, FACTOR
VALUE
/*/ 
/*/ THE FACTOR VALUE IS THE ITEM FOR WHICH A THREE DIMENSIONAL
/*/ REPRESENTATION IS BEING CREATED. THE PROGRAMS ALLOWS THE USER TO
/*/ SPECIFY A MISSING OR NULL VALUE CODE. THIS PROGRAM ALLOWS THE USER
/*/ TO DECLARE A NULL OR MISSING VALUE IDENTIFIER. THE DATA IN THE ITEM
/*/ TO BE CONTOURED WILL BE SCANNED FOR THE INDICATED MISSING VALUE
/*/ CODE AND FEATURES CONTAINING THIS CODE WILL BE SKIPPED WHEN THE
/*/ SCATTERED DATA FILE IS WRITTEN. THE MISSING DATA CODE MUST BE
/*/ NUMERIC (i.e. -99).
/*/ THE SCATTERED DATA FILE WILL AUTOMATICALLY BE NAMED %ITEM%.-
SCAT
/*/ NOTE THAT IVM WILL NOT READ FILENAME CONTAINING '-' SO THIS
/*/ CHARACTER SHOULD NOT BE PRESENT IN THE ITEMNAMES FOR WHICH
/*/ SCATTERED DATA FILES ARE MADE.
/*/ 
/*/ **** HOTWIRED FOR atrazine COVERAGE
/*/ PROGRAM ARGUMENTS:
/*/ 
/*/ DATE OF NITRATE DATA
/*/ 
/*/ WILLIAM A. BATTAGLIN 7/90
/*/ 10/90
/*/ converted to Unix 9/91
/*/ converted to atrazine 11/91
/*/ **************************************************
/*/ 
/*/ &ARGS date
/*/ 
/*/ ** CHECKING INPUT FORMAT **
/*
 &IF [NULL %date%] &THEN &RETURN &WARNING ~
 Usage &R MAKE_ATR_SCAT <date>
 /*
 &IF [EXISTS atr.%date%.scat -FILE] &THEN &RETURN &WARNING ~
 The file atr.%date%.scat already exists, please delete or CN existing file
 /*
 &S INCOVER = WELLS.ATR
 &IF [EXISTS %INCOVER% -POINT] &THEN
 &TYPE The coverage to be used is %INCOVER%
 &ELSE &RETURN &WARNING ~
 %INCOVER% does not exist, or it not a POINT cover
 /*
 /* SETTING NAME OF INFO FILE
 /*
 &S INFILE = %INCOVER%.PAT
 /*
 &TYPE
 /*
 /* CHECKING FOR EXISTANCE OF FACTOR AND COORDINATE ITEMS
 /*
 &IF [ITEMINFO %INCOVER% -POINT ATR.%date% -EXISTS] &THEN
 &TYPE The factor item is ATR.%date%
 &ELSE &RETURN &WARNING ~
 The item ATR.%date% is not in %INCOVER%
 /*
 &TYPE
 /*
 &S X-C = X-COORD
 &S Y-C = Y-COORD
 &S Z-C = SC_ALT
 &S ID = WID
 /*
 &TYPE
 &TYPE
 /*
 &S here [DIR [PATHNAME *]]
 /*
 /* checking for use of missing value code
 /*
&S MISSING = -99
&TYPE Missing value code is %MISSING%
&TYPE
&work %here%/info
&DATA info
arc
CALC $COMMA-SWITCH = -1
SEL %INFILE%
RES FOR ATR.%date% NE %MISSING%
OUTPUT %here%/atr.%date%.scat I
PRINT *W12,%X-C%,*W12,%Y-C%,*W12,%Z-C%,*W12,%ID%,*W12, ATR.%date%
ASEL
Q STOP
&END
&work %here%
/*
&TYPE
&TYPE The scatter data file atr.%date%.scat is ready to port to IVM
&type
&RETURN
APPENDIX G

C-shell scripts used to make volume models and calculate agricultural chemical mass

3dmodel.sc:

#!/bin/csh
#
# ******************************************************
# program - 3dmodel
# This C-shell script runs IVM software, generating a 3-dimensional
# model of the scattered data entered.
# ******************************************************
# programs arguments
# ndate - date of nitrate sampling
# wdate - date of water level measurement used for upper bounding
#        surface
# ******************************************************
#
# command line argument check
#
if ( $#argv != 2 ) then
echo "Two arguments are expected for this command the syntax should be"
echo
echo "3dmodel.sc [date of N sampling] [date of wl meas.]"
echo
echo "dates should be in the following format, May 29, 1962 = 052962"
goto program-end
endif
#
# assigning arguments to variables
#
set ndate = $1
echo The date of nitrate sampling is: $1
set wdate = $2
echo The date of water-level measurement is: $2
# checking for existence of scattered data files
if ( -r nit.${ndate}.scat ) then
   echo The data file nit.${ndate}.scat exists
else
   echo The grid file nit.${ndate}.scat was not found
   goto program-end
endif

# running the ism3 program to calculate water-level grid
ism3 <<endinp
bill

8
2
3
wl.${wdate}.scat
1
water-level data from ${wdate}
1

1
no
X
1,13
yes
Y
14,26
yes
Z
27,39
yes

5
39 30 00
45 30 00
-90 30 00
35 00 00
0.0
0.0
yes
no
7
3
1
1
wl.${wdate}.scat
1
2
100, 100
2
yes

wl.${wdate}.grid
gridded water-level data ${wdate}
1

4
6
endinp
#
# running ivmcalc and making 3-d grid of nitrate data
#
ivmcalc <<endinp
bill
yes
8
3
1
nit.$\{n\text{date}\}.scat
yes
nitrate raw data from $\{n\text{date}\}$
1

1
no
X
1,13
yes
Y
14,26
yes
Z
27,39
yes
wid
40,47
no
p1
48,65
yes

4
1
39 30 00
45 30 00
-90 30 00
35 00 00
0,0
0,0
2
yes
yes
yes
yes
wid
1
no
3
-364200,-363600,1198575,1199050,1296,1327
3ddisplay.sc:

#!/bin/csh
#
# **************************************************************************
# ***
# #
# echo Program has completed execution
# #
# program-end:
# #
# **************************************************************************
# ***
#
#**************************************************************************
# ***
# This C-shell script runs IVM software, generating a 3-dimensional
# display file of an existing 3-d gridded model
# ******************************************************************************
# programs arguments
# ndate - date of nitrate sampling
# wdate - date of water level measurement used for upper bounding
#   surface
# ******************************************************************************
#
# command line argument check
#
if ( $#argv != 2 ) then
    echo "Two arguments are expected for this command the syntax should be"
    echo "3ddisplay.sc [date of N sampling] [date of wl meas.]"
    echo "dates should be in the following format, May 29, 1962 = 052962"
goto program-end:
endif
#
# assigning arguments to variables
#
set ndate = $1
echo The date of nitrate sampling is: $1
set wdate = $2
echo The date of water-level measurement is: $2
#
# checking for existence of gridded data files
#
if ( -r nit.${ndate}.grid ) then
    echo The gridded data file nit.${ndate}.grid exists
else
    echo The gridded data file nit.${ndate}.grid was not found
    goto program-end:
endif
#
if ( -r wl.${wdate}.grid ) then
    echo The gridded data file wl.${wdate}.grid exists
else
    echo The grid file wl.${wdate}.grid was not found
    goto program-end:"
endif
#
#
# running ivmcalc and making 3-d display file of nitrate data
#
ivmcalc <<endinp
bill

5 ! create display file
nit.${ndate}.grid
no

newbound.xy
wl.${wdate}.grid
0.2
till.grid
0.2
no
3
1.0
3.0
5.0
7.0
9.0
11.0
13.0
15.0
17.0
19.0
21.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0

Nitrate concentrations on ${ndate}
mg/L
nit.$\{\text{ndate}\}.faces
display file of nitrate data on $\{\text{ndate}\}$
1
50
7
endinp
#
#
#
#
echo Program has completed execution
#
program-end:
#
vol1mg.sc:

#! /bin/csh
#******************************************************************************
# program - vol1.sc
# This C-shell script runs IVM software, calculating the volumes
# of water in one mg/L incremental shells at the Rosholt Research
# farm. Porosity of the aquifer is incorporated as a yield factor
# in the FIELDS.POLY polygon file (0.27). The conversion to square
# meters (from M*M*Feet) is accomplished by the conversion factor in
# the report generation routine.
#******************************************************************************
# programs arguments
# ndate - date of nitrate sampling
# wdate - date of water level measurement used for upper bounding
# surface
# nmax - maximum nitrate concentration for given date rounded up to
# the next largest even integer
#******************************************************************************
# command line argument check
#
if ( $#argv != 3 ) then
  echo "Three arguments are expected for this command the syntax should be"
  echo
  echo "voll.sc [date of N sampling] [date ofwl meas.] [max. N value]"
  echo
  echo "dates should be in the following format, May 29, 1962 = 052962"
  echo "maximum N value in mg/L should be rounded up to"
  echo "the next largest even integer"
  goto program-end
endif
#
# assigning arguments to variables
#
set ndate = $1
echo The date of nitrate sampling is: $1
set wdate = $2
echo The date of water-level measurement is: $2
@ nmax = $3
echo Maximum nitrate concentration rounded to the next largest even integer is: $3
#
vol1mg.sc: continued
# checking for existence of grid files
#
if ( -r nit.${ndate}.grid ) then
  echo The grid file nit.${ndate}.grid exists
else
  echo The grid file nit.${ndate}.grid was not found
  goto program-end
endif
#
if ( -r wl.${wdate}.grid ) then
  echo The grid file wl.${wdate}.grid exists
else
  echo The grid file wl.${wdate}.grid was not found
  goto program-end
endif
#
# initializing loop counting variables
#
@ count1 = 0
@ count2 = 1
#
# running the ivmcalc program to calculate volumetric data on the
# specified grid
#
return:
echo $count1, $count2
ivmcalc <<endinp
bill

6 ! volumetrics
1 ! volume calculations
nit.${ndate}.grid
fields.poly ! lateral bounding polygons
1 ! top defined by grid
wl.${wdate}.grid ! top grid
1 ! bottom defined by grid
till.grid ! bottom grid
3 ! yield factor from polygon file
! no z limit
vollmg.sc: continued
$count1, \$count2
vf$\{count2}.n$\{ndate}\ volume file for nitrate model on $ndate $count1 - $count2 mg/L
1 ! protection
50 ! days
2 ! volume report
vf$\{count2}.n$\{ndate} ! volume file
vr$\{count2}.n$\{ndate} ! volume report
volumetrics report nitrate model on $ndate $count1 - $count2 mg/L
1 ! protection
50 ! days
volumetrics report nitrate model on $ndate $count1 - $count2 mg/L
0.3048 ! feet to meters conversion
1 ! default report
field

field area
no
volume of water (m3)
3 ! return to main menu
7 ! exit
endinp
#
# testing for completion of programs
#
if ( $#count2 >= $nmax ) then
#
    echo Program has completed execution
goto program-end
else
    @ count1 = $count1 + 1
    @ count2 = $count2 + 1
goto return
endif
#
#
#
program-end:
# ******************************************************************************
#
# ******************************************************************************

---

sitevol.sc

#!/bin/csh
#
# ******************************************************************************
#
# program - sitevol.sc
# This script runs IVM software, calculating the volumes
# of water in one mg/L incremental shells at the Rosholt Research
# farm. Porosity of the aquifer is incorporated as a yield factor
# in the SITE.POLY polygon file (0.27). The conversion to square
# meters (from M*M*Feet) is accomplished by the conversion factor in
# the report generation routine.
# programs arguments
# ndate - date of nitrate sampling
# wdate - date of water level measurement used for upper bounding surface
# nmax - maximum nitrate concentration for given date rounded up to the next largest even integer

# command line argument check
#
if ( $#argv != 3 ) then
  echo "Three arguments are expected for this command the syntax should be"
  echo "voll.sc [date of N sampling] [date of wl meas.] [max. N value]"
  echo "dates should be in the following format, May 29, 1962 = 052962"
  echo "maximum N value in mg/L should be rounded up to"
  echo "the next largest even integer"
  goto program-end
endif

# assigning arguments to variables
#
set ndate =$1
echo The date of nitrate sampling is : $1
set wdate =$2
echo The date of water-level measurement is : $2
@ nmax =$3
echo Maximum nitrate conc. rounded to the next largest even integer is: $3

# checking for existence of grid files
#
if ( -r nit.${ndate}.grid ) then
  echo The grid file nit.${ndate}.grid exists
else
  echo The grid file nit.${ndate}.grid was not found
  goto program-end
endif

if ( -r wl.${wdate}.grid ) then
echo The grid file wl.${ wdate}.grid exists
else
  echo The grid file wl.${ wdate}.grid was not found
  goto program-end
endif
#
#initializing loop counting variables
#
@ count1 = 0
@ count2 = 1
#
# running the ivmcalc program to calculate volumetric data on the
# specified grid
#
return:
echo $count1, $count2
ivmcalc <<endinp
bill

6 ! volumetrics
1 ! volume calculations
nit.${ ndate}.grid
site.poly ! lateral bounding polygons
1 ! top defined by grid
wl.${ wdate}.grid ! top grid
1 ! bottom defined by grid
till.grid ! bottom grid
2 ! constant yield factor
0.27 ! yield factor
! no z limit
$count1, $count2
vf${count2}.n${ ndate}
volume file for nitrate model on ${ ndate} $count1 - $count2 mg/L
1 ! protection
50 ! days
2 ! volume report
vf${count2}.n${ ndate} ! volume file
vr${count2}.n${ ndate} ! volume report
volumetrics report nitrate model on ${ ndate} $count1 - $count2 mg/L
1 ! protection
50 ! days
volumetrics report nitrate model on $ndate $count1 - $count2 mg/L
0.3048 ! feet to meters conversion
1 ! default report
field

field area
no
volume of water (m3)
3 ! return to main menu
7 ! exit
endinp
#
# testing for completion of programs
#
if ( $count2 >= $nmax ) then
#
  echo Program has completed execution
  goto program-end
else
  @ count1 = $count1 + 1
  @ count2 = $count2 + 1
  goto return
endif
#
#
#
 program-end:


vol3layer.sc:

#!/bin/csh
#
# ***********************************************************************************************************************
# program - vol3layer.sc
# This C-shell script runs IVM software, calculating the volumes
# of water in one mg/L incremental shells at the Rosholt Research
Porosity of the aquifer is incorporated as a yield factor in the FIELDS.POLY polygon file (0.27). The conversion to square meters (from M*M*Feet) is accomplished by the conversion factor in the report generation routine. This program was modified to calculate three volume reports for each model. This first represent the mass in the volume of water from the median water level to 5' below the median water level, the second 5' to 10' below median, and the third 10' to 15' feet below the median. 

```
# programs arguments
# ndate - date of nitrate sampling
# wdate - date of water level measurement used for upper bounding surface
# nmax - maximum nitrate concentration for given date rounded up to the next largest even integer
# mwl5 - median water level minus 5'
# mwl10 - median water level minus 10'
# mwl15 - median water level minus 15'
```

```bash
if ( $#argv != 6 ) then
    echo "Six arguments are expected for this command the syntax should be"
    echo "vol3layer.sc [date of N sampling] [date of wl meas.] [max. N value]"
    echo "[median water level - 5] [mwl - 10] [ mwl - 15]"
    echo "dates should be in the following format, May 29, 1962 = 052962"
    echo "maximum N value in mg/L should be rounded up to"
    echo "the next largest even integer"
    goto program-end
endif

set ndate = $1
echo The date of nitrate sampling is : $1
set wdate = $2
echo The date of water-level measurement is : $2
@ nmax = $3
echo Maximum nitrate conc. rounded to the next largest even integer is: $3
set mwl15 = $4
echo median water level -5 is: $4
set mwl10 = $5
echo median water level - 10 is: $5
set mwl15 = $6
echo median water level - 15 is: $6
#
# checking for existence of grid files
#
if ( -r nit.${ndate}.grid ) then
  echo The grid file nit.${ndate}.grid exists
else
  echo The grid file nit.${ndate}.grid was not found
goto program-end
endif
#
if ( -r wl.${wdate}.grid ) then
  echo The grid file wl.${wdate}.grid exists
else
  echo The grid file wl.${wdate}.grid was not found
goto program-end
endif
#
#initializing loop counting variables
#
@ count1 = 0
@ count2 = 1
#
# running the ivmcalc program three times to calculate volumetric data for
# the specified grid
#
return:
echo $count1, $count2
#
# 1
ivmcalc <<endinp
bill
6 ! volumetrics
1 ! volume calculations
nit.${ndate}.grid
fields.poly ! lateral bounding polygons
1 ! top defined by grid
wl.${wdate}.grid ! top grid
2 ! bottom defined by constant
$4 ! value of constant
d3 ! yield factor from polygon file
! no z limit
$count1, $count2
vfu${count2}.n$.${ndate} ! volume file for upper nitrate model on $ndate $count1 - $count2 mg/L
1 ! protection
50 ! days
2 ! volume report
vfu${count2}.n$.${ndate} ! volume file
vru${count2}.n$.${ndate} ! volume report
volumetrics report upper nitrate model on $ndate $count1 - $count2 mg/L
1 ! protection
50 ! days
volumetrics report upper nitrate model on $ndate $count1 - $count2 mg/L
0.3048 ! feet to meters conversion
1 ! default report
field
field area
no
volume of water (m3)
3 ! return to main menu
7 ! exit
endinp
#
# 2
ivmcalc <<endinp
bill

6 ! volumetrics
1 ! volume calculations
nit.${ndate}.grid
fields.poly ! lateral bounding polygons
2 ! top defined by constant
$4 ! constant
2 ! bottom defined by grid
$5 ! second constant
3 ! yield factor from polygon file
! no z limit
$count1, $count2
$vfm${count2}.n${ndate}
volume file for middle nitrate model on $ndate $count1 - $count2 mg/L
1 ! protection
50 ! days
2 ! volume report
$dvfm${count2}.n${ndate} ! volume file
$vrm${count2}.n${ndate} ! volume report
volumetrics report middle nitrate model on $ndate $count1 - $count2 mg/L
1 ! protection
50 ! days
volumetrics report middle nitrate model on $ndate $count1 - $count2 mg/L
0.3048 ! feet to meters conversion
1 ! default report
field

field area
no
volume of water (m3)
3 ! return to main menu
7 ! exit
din
#
#
ivmcal <<endin
bill

6 ! volumetrics
1 ! volume calculations
$nit.${ndate}.grid
fields.poly ! lateral bounding polygons
2 ! top defined by constant
$5 ! constant
2 ! bottom defined by constant
$6 ! constant
3 ! yield factor from polygon file
! no z limit
$count1, $count2
vfl${count2}.n${ndate}
volume file for lower nitrate model on $ndate $count1 - $count2 mg/L
1 ! protection
50 ! days
2 ! volume report
vfl${count2}.n${ndate} ! volume file
vrl${count2}.n${ndate} ! volume report
volumetrics report lower nitrate model on $ndate $count1 - $count2 mg/L
1 ! protection
50 ! days
volumetrics report lower nitrate model on $ndate $count1 - $count2 mg/L
0.3048 ! feet to meters conversion
1 ! default report
field

field area
no
volume of water (m3)
3 ! return to main menu
7 ! exit
endinp
#
# testing for completion of programs
#
if ( $count2 >= $nmax ) then
#
echo Program has completed execution
goto program-end
else
@ count1 = $count1 + 1
@ count2 = $count2 + 1
goto return
endif
program-end:
#*******************************************************************************
mass_calc.sc:

#!/bin/csh
#*******************************************************************************
# program - mass_calc
# This C-shell script calculates the mass of nitrate under each of
# 6 test plots at the Rosholt Research farm. The program processes
# the volumetric report files generated by IVM and sums mass of nitrate
# under each field.
#*******************************************************************************
# programs arguments
# ndate - date of nitrate sampling
#*******************************************************************************
#
# command line argument check
#
if ( $#argv != 1  ) then
    echo "One argument is expected for this command the syntax should be"
echo
echo "mass_calc.sc [date of N sampling]"
echo
echo "dates should be in the following format, May 29, 1962 = 052962"
goto program-end
endif
#
set ndate = $1
#
# checking for volumetric data files
#
if ( -r vrl.n$n{ndate} ) then
    echo The volumetric files for $ndate exists
else
    echo The volumetric reports for $ndate were not found
    goto program-end
endif
# #
# running awk and grep commands to processes data files
#
mass_calc.sc: continued
#
# remove fields wanted from files
#
grep FIELD vr*.n${ndate} | tr -d ' ' > vol.${ndatej.dat
#
# echo starting awk
#
# use awk to compute lbs
#
awk '{c= substr($1,3,2)-.5}{print $3,c,$7,c*$7*0.002205}'  vol.$l.dat>lbs.$Ldat
#
# echo starting sort
#
# sort in order by fields and concentration range
#
sort +0n +ln lbs.$1.dat>lbs.$1.sort
#
# echo starting total
#
# use awk to compute totals for each field
#
awk '{$1==1{s1+=$4} $1==2{s2+=$4} $1==3{s3+=$4} $1==4{s4+=$4} $1==5{s5+=$4} $1==6{s6+=$4} {print s1,s2,s3,s4,s5,s6}}'  lbs.$1.sort>lbs.$1.sum
#
# echo results and list last line of lbs.${ndate}.sum file
#
# echo Sums of the Fields
echo ' 1  2  3  4  5  6  
#
echo tail -1 lbs.${ndate}.sum
#
#
# program-end:
#
*************************************************************************
mass_site.sc:

#!/bin/csh
#
# This C-shell script calculates the mass of nitrate under the whole
# site at the Rosholt Research farm. The program processes
# the volumetric report files generated by IVM and sums mass of nitrate
# programs arguments
# ndate - date of nitrate sampling
#
# command line argument check
#
if ( $#argv != 1 ) then
    echo "One argument is expected for this command the syntax should be"
    echo
    echo "mass_site.sc [date of N sampling]"
    echo
    echo "dates should be in the following format, May 29, 1962 = 052962"
    goto program-end
endif

set ndate = $1

# checking for volumetric data files
#
if ( -r vrl.n$ndate ) then
    echo The volumetric files for $ndate exists
else
    echo The volumetric reports for $ndate were not found
    goto program-end
endif

# running awk and grep commands to processes data files
#
# remove fields wanted from files
#
grep SITE vr*.n${ndate} | tr -d ',' > vol.${ndate}.dat
#

echo starting awk
mass_site.sc: continued
#
use awk to compute lbs
#
awk '{c = substr($l,3,2)-.5}{print $2,c,9,5*9*0.002205}' vol.$l.dat > lbs.$l.dat
#
#
use awk to compute totals for each field
#
#
program-end:


mass_3layer.sc:

#!/bin/csh
#******************************************************************************************************************************************************
# program - mass_3lay
#
# This C-shell script calculates the mass of nitrate under each of
# 6 test plots at the Rosholt Research farm. The program processes
# the volumetric report files generated by IVM and sums mass of nitrate
# under each field. Three layers of data are processed upper, middle and
# lower.
#******************************************************************************************************************************************************

# programs arguments
# ndate - date of nitrate sampling
#******************************************************************************************************************************************************

# command line argument check
#
if ($#argv != 1) then
  echo "One argument is expected for this command the syntax should be"
  echo
  echo "mass_calc.sc [date of N sampling]"


echo
echo "dates should be in the following format, May 29, 1962 = 052962"
goto program-end
endif
#
set ndate = $1
#
# checking for volumetric data files
#
if (-r vru1.n$ndate ) then
  echo The volumetric files for $ndate exists
else
  echo The volumetric reports for $ndate were not found
goto program-end
endif
#
#
# running awk and grep commands to processes data files
#
# remove fields wanted from files
#
grep FIELD vru*.n$ndate | tr -d ',' > volu.$ndate.dat
grep FIELD vrm*.n$ndate | tr -d ',' > volm.$ndate.dat
grep FIELD vrl*.n$ndate | tr -d ',' > voll.$ndate.dat
grep SITE vru*.n$ndate | tr -d ',' > volsu.$ndate.dat
grep SITE vrm*.n$ndate | tr -d ',' > volsm.$ndate.dat
grep SITE vrl*.n$ndate | tr -d ',' > volsl.$ndate.dat
#

echo starting awk
#
# use awk to compute lbs
#
awk '{c= substr($1,4,2)-.5} {print $3,c,$7,c*$7*0.002205}' volu.$ndate.dat>lbsu.$ndate.dat
awk '{c= substr($1,4,2)-.5} {print $3,c,$7,c*$7*0.002205}' volm.$ndate.dat>lbsm.$ndate.dat
awk '{c= substr($1,4,2)-.5} {print $3,c,$7,c*$7*0.002205}' voll.$ndate.dat>lbsl.$ndate.dat
awk '{c= substr($1,4,2)-.5} {print $3,c,$7,c*$7*0.002205}' volsu.$ndate.dat>lbssu.$ndate.dat
awk '{c= substr($1,4,2)-.5} {print $3,c,$7,c*$7*0.002205}' volsm.$ndate.dat>lbssm.$ndate.dat
awk '{c= substr($1,4,2)-.5} {print $3,c,$7,c*$7*0.002205}' volsl.$ndate.dat>lbssl.$ndate.dat
#

echo starting sort
#
# sort in order by fields and concentration range
#

sort +0n +1n lbsu.$1.dat>lbsu.$1.sort  
sort +0n +1n lbsm.$1.dat>lbsm.$1.sort  
sort +0n +1n lbsl.$1.dat>lbsl.$1.sort  
sort +0n +1n lbssu.$1.dat>lbssu.$1.sort  
sort +0n +1n lbssm.$1.dat>lbssm.$1.sort  
sort +0n +1n lbssl.$1.dat>lbssl.$1.sort  
#
# echo starting total
# use awk to compute totals for each field  
# awk '{s1+=1; s1+=1; s3+=1; s4+=1; s5+=1; s6+=1}{print s1,s2,s3,s4,s5,s6}' lbsu.$1.sort>lbsu.$1.sum  
# awk '{s1+=1; s1+=1; s3+=1; s4+=1; s5+=1; s6+=1}{print s1,s2,s3,s4,s5,s6}' lbsm.$1.sort>lbsm.$1.sum  
# awk '{s1+=1; s1+=1; s3+=1; s4+=1; s5+=1; s6+=1}{print s1,s2,s3,s4,s5,s6}' lbsl.$1.sort>lbsl.$1.sum  
# using awk to compute total for site for each layer  
# awk '{s1+=s1}{print s1}' lbssu.$1.sort>lbssu.$1.sum  
awk '{s1+=s1}{print s1}' lbssm.$1.sort>lbssm.$1.sum  
awk '{s1+=s1}{print s1}' lbssl.$1.sort>lbssl.$1.sum  
# echo results and list last line of lbs.$ndate.sum file  
# echo Sums of the Fields  
echo ' 1  2  3  4  5  6 '  
echo  
tail -1 lbsu.$ndate.sum  
tail -1 lbsm.$ndate.sum  
tail -1 lbsl.$ndate.sum  
# echo Sums for site upper/middle/lower  
echo  
tail -1 lbssu.$1.sum  
tail -1 lbssm.$1.sum
tail -1 lbssl.$1.sum
#
program-end:
APPENDIX H

Fortran program used to read GMS volume report files and calculate nitrate mass estimates

MASS_LYNX.F

program mass_lynx
   c
   c reads table of volume estimates from lynx and calculates
   c mass of nitrate (pounds) for each test plot and for the entire
   c site
   c--------------------------------------------------------------
   real volg(84), voll(84), lbstot(7)
   character*5 field(84)
   integer r,i,j,f
   c----------------------------------------------------------------
   c
   Q **************************************
   Q * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
   c reading in data
   close(9)
   close(10)
   open(9,file='lynx.vol',status='old')
   open(10,file='lynx.lbs',status='new')
   c
do 5000 r=1,84
   read(9,2)field(r),volg(r),voll(r)
5000 continue
c
do 3000 f=1,7
c   lbstot(f) = 0
   lbstot(f) = ( voll(f) * 0.5 * 0.00059535 )
3000 continue
c
  do 3100 f=1,7
    i=f+7
    j=f-7
    lbstot(f)=(lbstot(f)+(volg(f) - volg(i)) * 2 * 0.00059535))
 3100  continue

  c
  do 3200 f=8,14
    i=f+7
    j=f-7
    lbstot(j)=(lbstot(j) + ((volg(f) - volg(i)) * 4 * 0.00059535))
 3200  continue

  c
  do 3250 f=15,21
    i=f+7
    j=f-14
    lbstot(j)=(lbstot(j) + ((volg(f) - volg(i)) * 7.5 * 0.00059535))
 3250  continue

  c
  do 3300 f=22,28
    i=f+7
    j=f-21
    lbstot(j)=(lbstot(j)+(volg(f)-volg(i)) * 12.5 * 0.00059535))
 3300  continue

  c
  do 3400 f=29,35
    i=f+7
    j=f-28
    lbstot(j)=(lbstot(j)+(volg(f) - volg(i)) * 17.5 * 0.00059535))
 3400  continue

  c
  do 3500 f=36,42
    i=f+7
    j=f-35
    lbstot(j)=(lbstot(j)+(volg(f) - volg(i)) * 22.5 * 0.00059535))
 3500  continue

  c
  do 3600 f=43,49
    i=f+7
    j=f-42
    lbstot(j)=(lbstot(j)+(volg(f) - volg(i)) * 27.5 * 0.00059535))
3600 continue
c    do 3700 f=50,56
       i=f+7
       j=f-49
       lbstot(j)=(lbstot(j)+((volg(f)-volg(i)) * 32.5 * 0.00059535))
3700 continue
c    do 3800 f=57,63
       i=f+7
       j=f-56
       lbstot(j)=(lbstot(j)+((volg(f)-volg(i)) * 37.5 * 0.00059535))
3800 continue
c    do 3900 f=64,70
       i=f+7
       j=f-63
       lbstot(j)=(lbstot(j)+((volg(f)-volg(i)) * 42.5 * 0.00059535))
3900 continue
c    do 4100 f=71,77
       i=f+7
       j=f-70
       lbstot(j)=(lbstot(j)+((volg(f)-volg(i)) * 47.5 * 0.00059535))
4100 continue
c    do 4200 f=78,84
       i=f+7
       j=f-77
       lbstot(j)=(lbstot(j)+(volg(f) * 52.5 * 0.00059535))
4200 continue
c    do 4300 f=1,7
       write (10,3)field(f),lbstot(f)
4300 continue
c    close(9)
    close(10)
c
c  ************************************
c *****************************************************
2   format(a5, f10.0, f10.0)
3   format(a5, 2x, f12.2)
    stop
    end
**APPENDIX I**

Sample input file for scattered data file used by IVM and ascii well-log file used by GMS

---

**IVM scattered data file: nitrate concentrations on 9/7/89**

<table>
<thead>
<tr>
<th>x-coordinate (meters)</th>
<th>y-coordinate (meters)</th>
<th>Screen midpoint</th>
<th>Well ID number</th>
<th>Nitrate concentration (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-364141.900</td>
<td>1198578.00</td>
<td>1320.27</td>
<td>W0U1510</td>
<td>11.000</td>
</tr>
<tr>
<td>-364178.500</td>
<td>1198634.00</td>
<td>1318.67</td>
<td>W0U1360</td>
<td>11.000</td>
</tr>
<tr>
<td>-363984.000</td>
<td>1198597.00</td>
<td>1317.89</td>
<td>W0U1420</td>
<td>5.400</td>
</tr>
<tr>
<td>-363603.600</td>
<td>1198720.00</td>
<td>1320.03</td>
<td>W9U0975</td>
<td>0.800</td>
</tr>
<tr>
<td>-363723.600</td>
<td>1198704.00</td>
<td>1322.88</td>
<td>W9U1025</td>
<td>6.400</td>
</tr>
<tr>
<td>-363704.900</td>
<td>1199020.00</td>
<td>1321.21</td>
<td>W9U0004</td>
<td>6.900</td>
</tr>
<tr>
<td>-364009.500</td>
<td>1199040.00</td>
<td>1322.52</td>
<td>W9U0010</td>
<td>8.100</td>
</tr>
<tr>
<td>-364026.800</td>
<td>1198853.00</td>
<td>1322.54</td>
<td>W9U0600</td>
<td>2.700</td>
</tr>
<tr>
<td>-363840.300</td>
<td>1198880.00</td>
<td>1321.67</td>
<td>W4U0486</td>
<td>18.500</td>
</tr>
<tr>
<td>-363730.500</td>
<td>1198874.00</td>
<td>1322.54</td>
<td>W6U0486</td>
<td>14.000</td>
</tr>
<tr>
<td>-363759.600</td>
<td>1198733.00</td>
<td>1321.99</td>
<td>W6U0926</td>
<td>7.700</td>
</tr>
<tr>
<td>-363812.000</td>
<td>1198738.00</td>
<td>1322.15</td>
<td>W5U0926</td>
<td>22.000</td>
</tr>
<tr>
<td>-364006.500</td>
<td>1198749.00</td>
<td>1322.60</td>
<td>W1U0926</td>
<td>11.800</td>
</tr>
<tr>
<td>-364038.300</td>
<td>1198664.00</td>
<td>1313.89</td>
<td>W0M1212</td>
<td>5.000</td>
</tr>
<tr>
<td>-364041.600</td>
<td>1198667.00</td>
<td>1305.82</td>
<td>W0L1212</td>
<td>0.200</td>
</tr>
<tr>
<td>-364041.800</td>
<td>1198665.00</td>
<td>1322.30</td>
<td>W0U1212</td>
<td>5.300</td>
</tr>
<tr>
<td>-364036.100</td>
<td>1198736.00</td>
<td>1315.04</td>
<td>W0M0950</td>
<td>7.200</td>
</tr>
<tr>
<td>-364035.800</td>
<td>1198739.00</td>
<td>1304.31</td>
<td>W0L0950</td>
<td>0.100</td>
</tr>
<tr>
<td>-364035.800</td>
<td>1198743.00</td>
<td>1322.48</td>
<td>W0U0950</td>
<td>7.900</td>
</tr>
<tr>
<td>-363977.500</td>
<td>1198808.00</td>
<td>1322.83</td>
<td>W1U0726</td>
<td>23.700</td>
</tr>
<tr>
<td>-363979.800</td>
<td>1198808.00</td>
<td>1315.00</td>
<td>W1M0726</td>
<td>11.000</td>
</tr>
<tr>
<td>-363730.100</td>
<td>1198794.00</td>
<td>1321.24</td>
<td>W6U0726</td>
<td>20.800</td>
</tr>
<tr>
<td>-363732.100</td>
<td>1198795.00</td>
<td>1313.30</td>
<td>W6M0726</td>
<td>0.400</td>
</tr>
</tbody>
</table>
GMS ascii drill-log file: nitrate concentrations on 9/7/89

1 COLLAR HOLE NORTH EAST ELEV LENGTH SF1 SF2 REGION CG
1 SURVEY HOLE DEPTH AZIM DIP
1 CONCENTRATION HOLE FROM TO NITRATE
2 COLLAR W0U1510 1198578.0 -364,141.9 405.924 3.810 2.246 8.406 ROS AB
2 COLLAR W0U1360 1198634.0 -364,178.5 406.350 4.724 2.694 8.833 ROS AB
2 COLLAR W0U1420 1198597.0 -363,984.0 405.503 4.115 1.902 7.986 ROS AB
2 COLLAR W9U0975 1198720.0 -363,603.6 406.765 4.724 3.335 9.248 ROS AB
2 COLLAR W9U1025 1198704.0 -363,723.6 406.567 3.658 3.112 9.050 ROS AB
2 COLLAR W9U0004 1199020.0 -363,704.9 406.972 4.572 3.688 8.534 ROS AB
2 COLLAR W9U0010 1199040.0 -364,009.5 407.371 4.572 4.209 9.854 ROS AB
2 COLLAR W9U0600 1198853.0 -364,026.8 407.530 4.724 4.139 10.013 ROS AB
2 COLLAR W4U0486 1198880.0 -363,840.3 406.960 4.420 3.597 9.443 ROS AB

-363888.400 1198683.00 1312.94 W0M1130 0.100
-363886.100 1198684.00 1324.30 W0U1130 9.500
-363954.400 1198746.00 1321.90 W2U0926 7.300
-363952.000 1198746.00 1315.02 W2M0926 5.700
-363936.500 1198805.00 1314.52 W2M0726 9.400
-363931.500 1198805.00 1324.41 W2U0726 42.000
-363933.100 1198805.00 1306.49 W2L0726 0.300
-363890.000 1198803.00 1313.93 W3M0726 0.900
-363885.500 1198803.00 1320.93 W3U0726 20.300
-363887.300 1198803.00 1306.92 W3L0726 0.600
-363844.000 1198800.00 1308.97 W4L0726 0.000
-363839.500 1198800.00 1323.69 W4U0726 20.000
-363841.100 1198800.00 1313.75 W4M0726 0.300
-363788.400 1198748.00 1313.30 W5M0726 1.000
-363787.800 1198797.00 1311.11 W5U0726 53.600
-363862.100 1198740.00 1322.13 W4U0926 7.700
-363859.800 1198740.00 1314.33 W4M0926 2.200
-363905.000 1198744.00 1314.50 W3M0926 3.200
-363907.300 1198744.00 1322.62 W3U0926 14.000
<p>| 2 COLLAR W6U0486 | 1198874.0-363,730.5 | 407.530 | 4.724 | 4.142 | 10.013 | ROS | AB |
| 2 COLLAR W6U0926 | 1198733.0-363,759.6 | 406.905 | 4.267 | 3.444 | 9.388 | ROS | AB |
| 2 COLLAR W5U0926 | 1198738.0-363,812.0 | 406.954 | 4.267 | 3.469 | 9.437 | ROS | AB |
| 2 COLLAR W1U0926 | 1198749.0-364,006.5 | 407.396 | 4.572 | 3.902 | 9.879 | ROS | AB |
| 2 COLLAR W0M1212 | 1198664.0-364,038.3 | 407.027 | 6.858 | 3.460 | 9.510 | ROS | AB |
| 2 COLLAR W0L1212 | 1198667.0-364,041.6 | 406.905 | 9.296 | 3.441 | 9.754 | ROS | AB |
| 2 COLLAR W0U1212 | 1198665.0-364,041.8 | 407.000 | 4.267 | 3.429 | 9.754 | ROS | AB |
| 2 COLLAR W0M0950 | 1198736.0-364,036.1 | 407.682 | 7.163 | 4.173 | 10.165 | ROS | AB |
| 2 COLLAR W0L0950 | 1198739.0-364,035.8 | 408.765 | 10.516 | 4.264 | 10.668 | ROS | AB |
| 2 COLLAR W0U0950 | 1198743.0-364,035.8 | 407.664 | 4.877 | 4.142 | 10.147 | ROS | AB |
| 2 COLLAR W1U0726 | 1198808.0-363,977.5 | 407.161 | 4.267 | 3.716 | 9.644 | ROS | AB |
| 2 COLLAR W1M0726 | 1198808.0-363,979.8 | 407.213 | 6.706 | 3.795 | 9.696 | ROS | AB |
| 2 COLLAR W6U0726 | 1198794.0-363,730.1 | 406.676 | 4.267 | 3.231 | 9.159 | ROS | AB |
| 2 COLLAR W6M0726 | 1198795.0-363,732.1 | 406.695 | 6.706 | 3.289 | 8.534 | ROS | AB |
| 2 COLLAR W0M1130 | 1198683.0-363,888.4 | 406.890 | 7.010 | 3.368 | 7.620 | ROS | AB |
| 2 COLLAR W0U1130 | 1198684.0-363,886.1 | 407.609 | 4.267 | 4.084 | 10.092 | ROS | AB |
| 2 COLLAR W2U0926 | 1198746.0-363,954.4 | 407.182 | 4.572 | 3.682 | 9.665 | ROS | AB |
| 2 COLLAR W2M0926 | 1198805.0-363,952.0 | 407.219 | 6.706 | 3.694 | 9.702 | ROS | AB |
| 2 COLLAR W2M0726 | 1198805.0-363,936.5 | 407.067 | 6.706 | 3.630 | 9.549 | ROS | AB |
| 2 COLLAR W2U0726 | 1198805.0-363,931.5 | 407.643 | 4.267 | 4.209 | 10.126 | ROS | AB |
| 2 COLLAR W2L0726 | 1198805.0-363,933.1 | 407.057 | 9.144 | 3.645 | 10.668 | ROS | AB |
| 2 COLLAR W3M0726 | 1198803.0-363,890.0 | 406.887 | 6.706 | 3.444 | 9.370 | ROS | AB |
| 2 COLLAR W3U0726 | 1198803.0-363,885.5 | 406.887 | 4.572 | 3.441 | 9.370 | ROS | AB |
| 2 COLLAR W3L0726 | 1198803.0-363,887.3 | 406.884 | 8.839 | 3.444 | 9.144 | ROS | AB |
| 2 COLLAR W4L0726 | 1198800.0-363,844.0 | 406.899 | 8.230 | 3.469 | 8.839 | ROS | AB |
| 2 COLLAR W4U0726 | 1198800.0-363,839.5 | 406.814 | 3.658 | 3.383 | 9.296 | ROS | AB |
| 2 COLLAR W4M0726 | 1198800.0-363,841.1 | 406.832 | 6.706 | 3.399 | 9.315 | ROS | AB |
| 2 COLLAR W5M0726 | 1198797.0-363,787.8 | 407.000 | 6.706 | 3.554 | 9.482 | ROS | AB |
| 2 COLLAR W5U0726 | 1198797.0-363,785.4 | 406.637 | 4.267 | 3.200 | 9.120 | ROS | AB |
| 2 COLLAR W4U0926 | 1198740.0-363,862.1 | 406.948 | 4.267 | 3.466 | 9.431 | ROS | AB |
| 2 COLLAR W4M0926 | 1198740.0-363,859.8 | 407.009 | 6.706 | 3.511 | 9.492 | ROS | AB |
| 2 COLLAR W3M0926 | 1198744.0-363,905.0 | 407.060 | 6.706 | 3.554 | 9.543 | ROS | AB |
| 2 COLLAR W3U0926 | 1198744.0-363,907.3 | 407.097 | 4.267 | 3.603 | 9.580 | ROS | AB |
| 2 CONCENTRATION W0U1510 | 3.810 | 4.420 | 10.1 |
| 2 CONCENTRATION W0U1360 | 4.724 | 5.334 | 11.9 |
| 2 CONCENTRATION W0U1420 | 4.115 | 4.724 | 8.0 |
| 2 CONCENTRATION W9U0975 | 4.724 | 5.334 | 2.2 |
| 2 CONCENTRATION W9U1025 | 3.658 | 4.267 | 5.0 |
| 2 CONCENTRATION W9U0004 | 4.572 | 5.182 | 6.4 |
| 2 CONCENTRATION W9U0010 | 4.572 | 5.182 | 7.8 |
| 2 CONCENTRATION W9U0600 | 4.724 | 5.334 | 1.9 |</p>
<table>
<thead>
<tr>
<th>Sample Code</th>
<th>Concentration</th>
<th>Value1</th>
<th>Value2</th>
<th>Value3</th>
</tr>
</thead>
<tbody>
<tr>
<td>W4U0486</td>
<td>2 CONCENTRATION</td>
<td>4.420</td>
<td>5.029</td>
<td>38.8</td>
</tr>
<tr>
<td>W6U0926</td>
<td>2 CONCENTRATION</td>
<td>4.267</td>
<td>4.877</td>
<td>6.7</td>
</tr>
<tr>
<td>W5U0926</td>
<td>2 CONCENTRATION</td>
<td>4.267</td>
<td>4.877</td>
<td>35.7</td>
</tr>
<tr>
<td>W1U0926</td>
<td>2 CONCENTRATION</td>
<td>4.572</td>
<td>5.182</td>
<td>7.6</td>
</tr>
<tr>
<td>W0M1212</td>
<td>2 CONCENTRATION</td>
<td>6.858</td>
<td>7.468</td>
<td>4.0</td>
</tr>
<tr>
<td>W0L1212</td>
<td>2 CONCENTRATION</td>
<td>9.296</td>
<td>9.906</td>
<td>0.3</td>
</tr>
<tr>
<td>W0U1212</td>
<td>2 CONCENTRATION</td>
<td>4.267</td>
<td>4.877</td>
<td>7.1</td>
</tr>
<tr>
<td>W0M0950</td>
<td>2 CONCENTRATION</td>
<td>7.163</td>
<td>7.772</td>
<td>5.2</td>
</tr>
<tr>
<td>W0L0950</td>
<td>2 CONCENTRATION</td>
<td>10.516</td>
<td>11.125</td>
<td>0.3</td>
</tr>
<tr>
<td>W0U0950</td>
<td>2 CONCENTRATION</td>
<td>4.877</td>
<td>5.486</td>
<td>9.1</td>
</tr>
<tr>
<td>W1U0726</td>
<td>2 CONCENTRATION</td>
<td>4.267</td>
<td>4.877</td>
<td>13.3</td>
</tr>
<tr>
<td>W1M0726</td>
<td>2 CONCENTRATION</td>
<td>6.706</td>
<td>7.315</td>
<td>12.1</td>
</tr>
<tr>
<td>W6U0726</td>
<td>2 CONCENTRATION</td>
<td>4.267</td>
<td>4.877</td>
<td>17.7</td>
</tr>
<tr>
<td>W6M0726</td>
<td>2 CONCENTRATION</td>
<td>6.706</td>
<td>7.315</td>
<td>0.2</td>
</tr>
<tr>
<td>W0M1130</td>
<td>2 CONCENTRATION</td>
<td>7.010</td>
<td>7.620</td>
<td>0.6</td>
</tr>
<tr>
<td>W0U1130</td>
<td>2 CONCENTRATION</td>
<td>4.267</td>
<td>4.877</td>
<td>12.5</td>
</tr>
<tr>
<td>W2U0926</td>
<td>2 CONCENTRATION</td>
<td>4.572</td>
<td>5.182</td>
<td>8.9</td>
</tr>
<tr>
<td>W2M0926</td>
<td>2 CONCENTRATION</td>
<td>6.706</td>
<td>7.315</td>
<td>8.5</td>
</tr>
<tr>
<td>W2U0726</td>
<td>2 CONCENTRATION</td>
<td>4.267</td>
<td>4.877</td>
<td>31.8</td>
</tr>
<tr>
<td>W2L0726</td>
<td>2 CONCENTRATION</td>
<td>9.144</td>
<td>9.754</td>
<td>0.6</td>
</tr>
<tr>
<td>W3M0726</td>
<td>2 CONCENTRATION</td>
<td>6.706</td>
<td>7.315</td>
<td>0.3</td>
</tr>
<tr>
<td>W3L0726</td>
<td>2 CONCENTRATION</td>
<td>8.839</td>
<td>9.449</td>
<td>0.1</td>
</tr>
<tr>
<td>W4L0726</td>
<td>2 CONCENTRATION</td>
<td>8.230</td>
<td>8.839</td>
<td>0.1</td>
</tr>
<tr>
<td>W4U0726</td>
<td>2 CONCENTRATION</td>
<td>3.658</td>
<td>4.267</td>
<td>11.0</td>
</tr>
<tr>
<td>W4M0726</td>
<td>2 CONCENTRATION</td>
<td>6.706</td>
<td>7.315</td>
<td>0.1</td>
</tr>
<tr>
<td>W5M0726</td>
<td>2 CONCENTRATION</td>
<td>6.706</td>
<td>7.315</td>
<td>0.2</td>
</tr>
<tr>
<td>W5U0726</td>
<td>2 CONCENTRATION</td>
<td>4.267</td>
<td>4.877</td>
<td>15.6</td>
</tr>
<tr>
<td>W4U0926</td>
<td>2 CONCENTRATION</td>
<td>4.267</td>
<td>4.877</td>
<td>9.5</td>
</tr>
<tr>
<td>W4M0926</td>
<td>2 CONCENTRATION</td>
<td>6.706</td>
<td>7.315</td>
<td>1.3</td>
</tr>
<tr>
<td>W3M0926</td>
<td>2 CONCENTRATION</td>
<td>6.706</td>
<td>7.315</td>
<td>2.4</td>
</tr>
<tr>
<td>W3U0926</td>
<td>2 CONCENTRATION</td>
<td>4.267</td>
<td>4.877</td>
<td>7.9</td>
</tr>
</tbody>
</table>
APPENDIX J

Below is a time-step by time-step interpretation of the nitrate models generated using IVM. In some cases spatial and temporal characteristics of the nitrate occurrence are related to physical processes or conditions. In most case these interpretations represent possible causes of observed model conditions. More detailed information on the timing of rainfall events, irrigation, and nitrate applications is needed to make better arguments for cause and effect relations between processes and observed conditions.

07/21/88 model:
1) Lowest nitrate concentrations of all modeled dates with +10 mg/L concentrations occurring only between test plots 1 and 2. Due in part to drought conditions and the absence of recharge to the aquifer system
2) Small area of lower concentration near test plot 4
3) Some indication of on site migration of nitrate from the southwest
4) General decline in nitrate concentrations with depth

08/17/88 model:
1) Areally extensive and deep region of water with +10 mg/L nitrate concentrations. Occurrence pattern is similar that seen at the end of the summer in 1989. Change from 07/21/88 model result of recharge event (median water-level rise of 0.5 feet)
2) Two small areas of +25 mg/L nitrate concentrations, one at the top of the aquifer near test plot 2, and one slightly below the top of the aquifer near test plot 5
3) Elongation of +25 mg/L area in the general direction of ground-water flow
4) Some indication of up-gradient contribution of nitrates to area underlying test plots
5) General decline in nitrate concentrations with depth

04/18/89 model:
1) Vastly reduced region of water with +10 mg/L nitrate concentration. Occurrence
pattern is not similar to that seen in the spring of 1990. Represents the sampling time with the second lowest nitrate concentrations of any of the 13 models. Sampling was pre-application and under drought conditions.

2) Distinct area of low nitrate concentrations near the north end of test plot 2. This may be the result of concentrated winter recharge. Especially interesting is the fact that the area of low concentration is shallow, and is underlain by an area of higher nitrate concentration.

3) Area of +15 mg/L nitrate concentration beginning near test plot 5 shows some elongation in the direction of ground-water flow.

4) Area of low nitrate concentrations near highway to south of test plots.

5) General decline in nitrate concentrations with depth.

**05/03/89 model:**

1) Low concentration area that was present near the north end of test plot 2 is now absent.

2) Areally extensive but shallow region of +10 mg/L nitrate concentration.

3) Some indication of movement of nitrates to area beneath the test plots from upgradient (west and south-west).

4) Persistence of area of low nitrate concentration near highway.

5) General decline in nitrate concentrations with depth.

**05/25/89 model:**

1) Area of +10 mg/L nitrate concentration slightly deeper and more areally extensive than previous model. Still drought condition with little or no recharge and dropping water-levels.

2) Small area of +15 mg/L nitrate concentration appears to be down-gradient from test plots 1 and 2. This area coincides with the area of low nitrate concentration seen in the 4/18/89 model.

3) Area of low nitrate concentration near the highway spreading deeper and down gradient in the aquifer.

4) General decline in nitrate concentration with depth.

**07/10/89 model:**

1) Conditions very similar to 05/25/89 model.

2) Area of +15 mg/L nitrate concentration appears to have moved to the north.
could be the result of natural ground-water flow, or could be the result of pumping of the irrigation well in the north-western corner of the research farm

3) Low concentration area along the highway is slightly larger than in 05/25/89 model

4) Two pockets of +15 mg/L nitrate concentration beneath fields 1 and 2, and beneath fields 5 and 6

5) Area of +15 mg/L nitrate concentration beneath fields 1 and 2 may have a source to the west of the research farm

6) General decline in nitrate concentration with depth

08/09/89 model:

1) Strong high concentration area (+35 mg/L) near north end of test plot 2. Still drought conditions with dropping water-levels, probably some irrigation

2) Areas of +25 mg/L nitrate concentration at depth beneath test plots 5 and 6, and near the top of the aquifer beneath test plots 1, 2, and 3

3) Spreading to the north-west of the area of low concentration near the highway

4) General decline in nitrate concentration with depth

09/07/89 model:

1) Spreading and deepening of areas of +35 and +25 mg/L nitrate concentration. Large recharge event causes median water-levels to rise 0.5 feet

2) Area of +35 mg/L nitrate concentration at depth beneath test plots 5 and 6

3) Deepening of area of +10 mg/L nitrate concentration beneath entire research farm

4) Shrinking of area of low concentration near highway

5) Some indication of up-gradient contribution of nitrate

6) General decline in nitrate concentration with depth

09/13/89 model:

1) Spreading and deepening of areas of +35 mg/L nitrate concentrations downgradient from fields 2 and 5. Water-levels remain at same level as 9/7/89 model implying limited recharge

2) Deepening of area of +10mg/L nitrate concentration beneath entire test site

3) Some indication of elongation of nitrate plume in the direction of ground-water flow
4) General decline in nitrate concentrations with depth

10/11/89 model:
1) Area of +35 mg/L nitrate concentration persisting near north end of test plots 1 and 2
2) Distinct down-gradient elongation of area of +25 mg/L nitrate concentration
3) Area of +35 mg/L nitrate concentration at depth beneath test plots 5 and 6
4) Largest extent of area of +10 mg/L beneath research farm
5) Little change in the area of low concentration near the highway
6) General decline in nitrate concentration with depth

11/30/89 model:
1) Areas of +35 mg/L nitrate concentration have disappeared. Water-levels dropping implying lack of recharge
2) Area of +10 mg/L nitrate concentration is still areally extensive and relatively deep.
3) Area of +25 mg/L nitrate concentration is still near the northern ends of field 1 and 2, but appears to extend off the research farm to the west
4) Little change in the area of low concentration near the highway
5) General decline in nitrate concentration with depth

03/22/90 model:
1) No areas of +25 mg/L nitrate concentration, but areally extensive and deep areas of +15 and +10 mg/L nitrate concentration. Water-levels higher than in spring 1989 implying that more normal winter recharge has occurred
2) Area of low concentration near the highway is smaller than in prior models
3) General decline in nitrate concentration with depth

05/03/90 model:
1) Smaller areas of +15 and +10 mg/L nitrate concentration than for 03/22/90 model
2) Slightly large area of low concentration near the highway than for 03/22/90 model
3) General decline in nitrate concentration with depth