Iowa Geological Survey
Open File Report 84-2
1984

I. GROUNDWATER QUALITY AND HYDROGEOLOGY OF DEVONIAN-CARBONATE AQUIFERS IN FLOYD AND MITCHELL COUNTIES, IOWA

Robert D. Libra
Hydrogeologist, Geological Studies Division

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II. DEVONIAN STRATIGRAPHY OF NORTH-CENTRAL IOWA

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A report on grant number G007237-01
of the United States Environmental Protection Agency
from the
Iowa Geological Survey
Donald L. Koch, State Geologist and Director
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II. DEVONIAN STRATIGRAPHY OF NORTH-CENTRAL IOWA: A Geologic Framework For the Devonian Aquifer and Karst Systems in Floyd-Mitchell Counties

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TABLE OF CONTENTS

LIST OF FIGURES

I. GROUNDWATER QUALITY AND HYDROGEOLOGY OF DEVONIAN-CARBONATE AQUIFERS IN FLOYD AND MITCHELL COUNTIES, IOWA

II. DEVONIAN STRATIGRAPHY OF NORTH-CENTRAL IOWA

LIST OF TABLES

I. GROUNDWATER QUALITY AND HYDROGEOLOGY OF DEVONIAN-CARBONATE AQUIFERS IN FLOYD AND MITCHELL COUNTIES, IOWA

LIST OF APPENDICES

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I. GROUNDWATER QUALITY AND HYDROGEOLOGY OF DEVONIAN-CARBONATE AQUIFERS IN FLOYD AND MITCHELL COUNTIES, IOWA

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ABSTRACT

The Floyd-Mitchell Study is the third phase of an assessment of the hydrogeology and groundwater quality of karst-carbonate aquifers in northeast Iowa. The project was jointly funded and conducted by the Iowa Geological Survey and the U.S. Environmental Protection Agency, with cooperation from the Iowa Department of Water, Air and Waste Management.

Devonian rocks form the carbonate aquifer in the study area. A revised analysis of Devonian stratigraphy indicates the aquifer may best be described as a three-part system. The components of this system are informally termed the lower, middle, and upper aquifers, and are separated by relatively low permeability shale units. The regional effectiveness of these shales as confining beds is unclear. However, limited extant data suggest that a partially confined, deep flow system is present in the lower aquifer, generating strong upward flow components locally.

Four geologic regions are delineated in the Floyd-Mitchell area - Deep Bedrock, Shallow Bedrock, Karst, and Incipient Karst. These areas present unique interrelationships between surficial geology, hydrology, and the resultant groundwater quality. The

distribution of karst topography is controlled by depth to bedrock and the distribution of Devonian strata. Prominent karst development occurs where "Upper Cedar Valley" limestones are close to the land surface. In other areas where bedrock lies at shallow depth, the Devonian units are dolomite, and karst features are less common or absent.

Fifty wells, distributed over the four geologic regions, were selected for an initial and site and water-quality inventory. Surficial well construction and placement were examined, and water samples were collected for nitrate and bacteria analyses. These wells were chosen from the I.G.S. well log file; therefore, the location of completed intervals with respect to stratigraphy were known. Based on the results of this inventory, twenty wells were selected for a monthly monitoring network. Three surface-water sites and two drainage tile outlets were also included in this network. Monthly sampling included nitrate and bacteria analyses. Samples for pesticide analysis were also collected, on a less frequent basis.

Monthly monitoring of groundwater quality from the various geologic regions in the Floyd-Mitchell area reinforces the conclusions of prior studies in northeast Iowa, and shows that the use of these regions provides a valid means of defining the relationships between surficial geology, hydrology, and resultant groundwater quality. Data from the "protected" Deep Bedrock Region provide a background against which the water quality from other "less protected" regions may be evaluated. Properly constructed wells in this region produce water with <5 mg/l nitrate. The highest and relatively constant levels of nitrate in groundwater occur in the Incipient Karst Region (68 mg/l, annual mean). This region is characterized by high rates of infiltrating recharge which leaches nitrates from shallow soil horizons. Karst-area groundwater shows the next highest levels of nitrate (41 mg/l), and the greatest variability of concentrations. This variability is caused by different recharge mechanisms which operate in open-karst areas. In Shallow Bedrock regions, groundwater contains intermediate concentrations of nitrate (22 mg/l), less than the Karst/ Incipient Karst regions, but significantly greater than the Deep Bedrock areas.

Pesticides were not detected in wells from the protected Deep Bedrock region. Pesticides were detected at least once in over two/thirds of the wells in the other geologic regions--Shallow Bedrock, Karst, and Incipient Karst. In almost all instances, pesticides were delivered to groundwater through infiltration processes. Total pesticide concentrations generally ranged up to 2.0 µg/l. Locally, however, groundwater containing 4.5 to 21 µg/l total pesticides was detected, evidently caused by infiltration leaching from fields which received excessive chemical applications. Pesticides detected in well water samples include Atrazine, Sencor, Lasso, Bladex, and Dual. All these pesticides were present in samples collected prior to the 1983 application of pesticides, indicating the potential for year-round pesticide persistence in groundwater and shallow soil horizons.

Both nitrate and pesticide concentrations show seasonal variations with higher concentrations occurring during wet (recharge) periods of the year. Analysis of nitrate-pesticide concentrations, from all parts of the hydrologic system in the area, indicates a relationship between these contaminants. Local variables and the environmental characteristics of the various chemicals complicate this relationship. Thus, nitrate concentrations in groundwater are not an accurate predictor of pesticide presence in groundwater.

Hydrologic responses and trends in contaminant levels are very similar, both in groundwater and surfacewater, in the Floyd-Mitchell and Big Springs area, demonstrating the regional applicability of the findings of this report and prior studies. These findings indicate that groundwater in the combined Shallow Bedrock-Karst areas are being degraded by the infiltration of surface-applied chemicals. These regions constitute over 6800 square miles (17,600 sq. km) of the land surface in northeastern Iowa; strategies developed to protect groundwater resources must consider this entire area, not just the "sinkhole" or karst areas.

INTRODUCTION

The Floyd-Mitchell County investigation is part of the series of studies of the hydrogeology and groundwater quality in the carbonate-karst aquifer terrane of northeast Iowa. These studies (Hallberg and Hoyer, 1982; Hallberg et al., 1983a, 1983b) have reviewed the various regional and local hydrogeologic factors affecting groundwater quality. Regionally, Hallberg and Hoyer (1982) identified three prominent karst terranes in northeast Iowa: 1. karst developed along the Silurian and Devonian escarpment, in southern Clayton, eastern Fayette, and Winneshiek Counties; 2. karst developed in the Galena Plateau region of Clayton and Allamakee Counties; and 3. karst developed in the Devonian carbonate rocks in a belt paralleling the Cedar River, best developed in the Floyd-Mitchell County area. The Big Spring Study (Hallberg et al., 1983b) has provided a detailed assessment of hydrogeology and groundwater quality in the Galena karst area. The Big Spring study provides insights pertinent to all karst areas, and is particularly applicable to the karst along the Silurian Escarpment as well. The Floyd-Mitchell County area is quite different from these other regions in terms of the physiography and geology of the karst terrane, and is also different in terms of landuse patterns. Thus, the Floyd-Mitchell County study was undertaken to: 1. gather detailed data on the hydrogeology and groundwater quality of this particular area; 2. assess the groundwater quality in different hydrogeologic settings; and 3. further study how surficial contaminants are delivered into the carbonate aquifers. These data are also necessary to provide a perspective for the evaluation of the impact of agricultural drainage wells on the groundwater quality in the carbonate aquifers in this area.

The monitoring and analysis of data from the Floyd-Mitchell region cannot be done in the same detail as in the Big Spring area because the groundwater-flow system cannot be analyzed in the same manner. However, by comparison with the Big Spring study findings, the conclusions of both studies can be amplified.

Location

The location of Floyd and Mitchell Counties is shown on figure 1. These counties are located in the northwestern corner of the twenty-two county region reported on by Hallberg and Hoyer (1982) in the first of this series of studies dealing with the carbonate-karst aquifers. In this report a six-county region was used to evaluate the hydrogeologic setting, including Chickasaw and Howard Counties to the east, and Cerro Gordo and Worth Counties to the west. Worth and Cerro Gordo Counties were not included in the study by Hallberg and Hoyer (1982). However, minor karst and shallow-carbonate bedrock areas occur in these two counties, and their inclusion here complements the earlier study and provides a complete overview of the karst areas in northeastern Iowa.

HYDROGEOLOGIC FRAMEWORK

A detailed discussion of the stratigraphy and related stratigraphic problems of the carbonate aquifers in the area is provided by Witzke and Bunker in this volume. This discussion will outline other general hydrogeologic characteristics of the Floyd-Mitchell area. On maps for the six-county region, the data for Floyd, Mitchell, Chickasaw, and Howard Counties were derived from Hallberg and Hoyer (1982). Data for Cerro Gordo and Worth Counties were compiled using the same procedures described in Hallberg and Hoyer (1982).

Distribution of Sinkholes

The mapped distribution of sinkholes for the six-county region is shown on figure 2. The sinkholes in Cerro Gordo and Worth Counties were mapped from soil surveys (DeWitt, 1981; Buckner and Highland, 1976) as described in Hallberg and Hoyer (1982). Over 1,200 sinkholes are mapped in Mitchell County and over 300 in Floyd County. The sinkholes shown in Floyd County are a conservative estimate, because a modern soil survey is not yet complete. The greatest concentrations of sinkholes in Floyd and Mitchell County are located in two areas: 1. in a belt adjacent to the Cedar River, particularly on the west side of the river in northern Floyd County; and 2. on the broad, flat, upland areas in Mitchell County, north of the town of Osage.

The formation and distribution of sinkholes are the resultant of many factors. Hallberg and Hoyer (1982) point out that in northeastern Iowa the most important factors affecting the formation and distribution of sinkholes

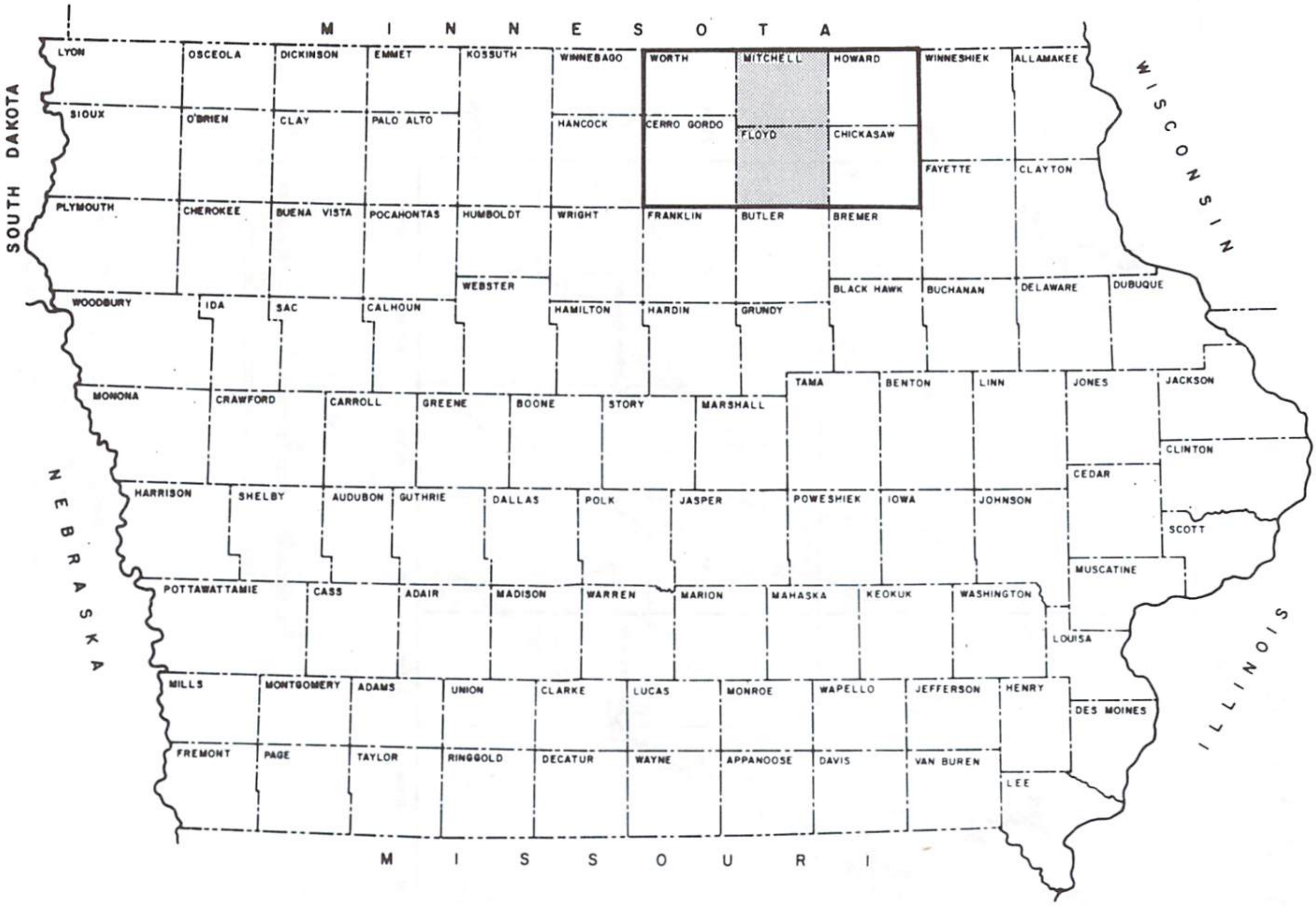


Figure 1. Location of Floyd and Mitchell Counties, and six-county area included in regional synthesis.

are lithology and structure of the karst-forming rocks, erosional relief, and thickness of Quaternary-age deposits which mantle the bedrock.

Depth to Bedrock

An important factor controlling the appearance of sinkholes at the land surface and which affects groundwater quality is the depth to bedrock, or conversely the thickness of Quaternary surficial materials over the rock. Few, if any, sinkholes appear in areas where the depth to the carbonate bedrock is greater than about 35 feet (10 m). Where sinkholes occur, surfacewater, tile-drainage water, and contaminants they carry, may run into the sinkholes and enter directly into the groundwater system. In addition to this direct recharge, such "shallow bedrock" areas are also marked by high rates of infiltration resulting from precipitation which percolates through the soil and into the aquifer below. This infiltration water may incorporate chemicals and carry them in solution to the aquifer below. On the regional scale, shallow-bedrock aquifer areas in northeastern Iowa (and all shallow aquifers), even

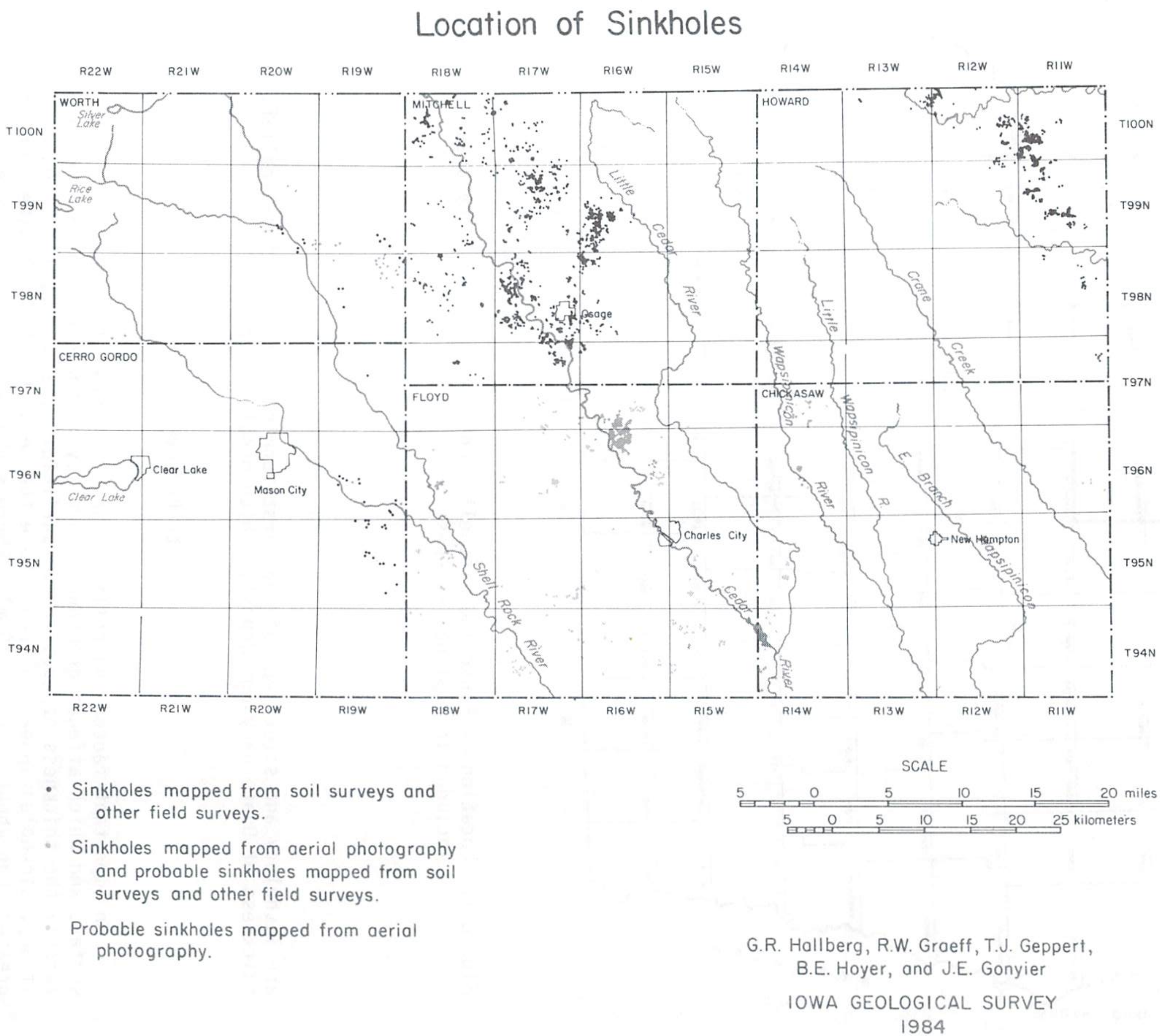


Figure 2. Location of sinkholes in six-county area.

those without sinkholes, show significantly elevated concentrations of nitrates to depths of 100 to 200 feet (Hallberg and Hoyer, 1982; Hallberg et al., 1983a). As shown in the Big Spring study by Hallberg and others (1983b), even in karst areas the majority of nitrates and soluble pesticides that are found in groundwater in the carbonate aquifers are delivered through simple infiltration.

The areas of bedrock outcrop (i.e., where bedrock is exposed or within five feet of the land surface) are shown on figure 3. The generalized depth to bedrock over the area is shown on figure 4. Figure 4 was compiled from well, quarry, and outcrop records at the Iowa Geological Survey (IGS) in conjunction with the outcrop map (figure 3; see Hallberg and Hoyer, 1982 for details). The depth to bedrock varies from 0 to over 300 feet (90 m) across the area. The areas where rock is at the greatest depths below the land surface are in eastern Mitchell County.

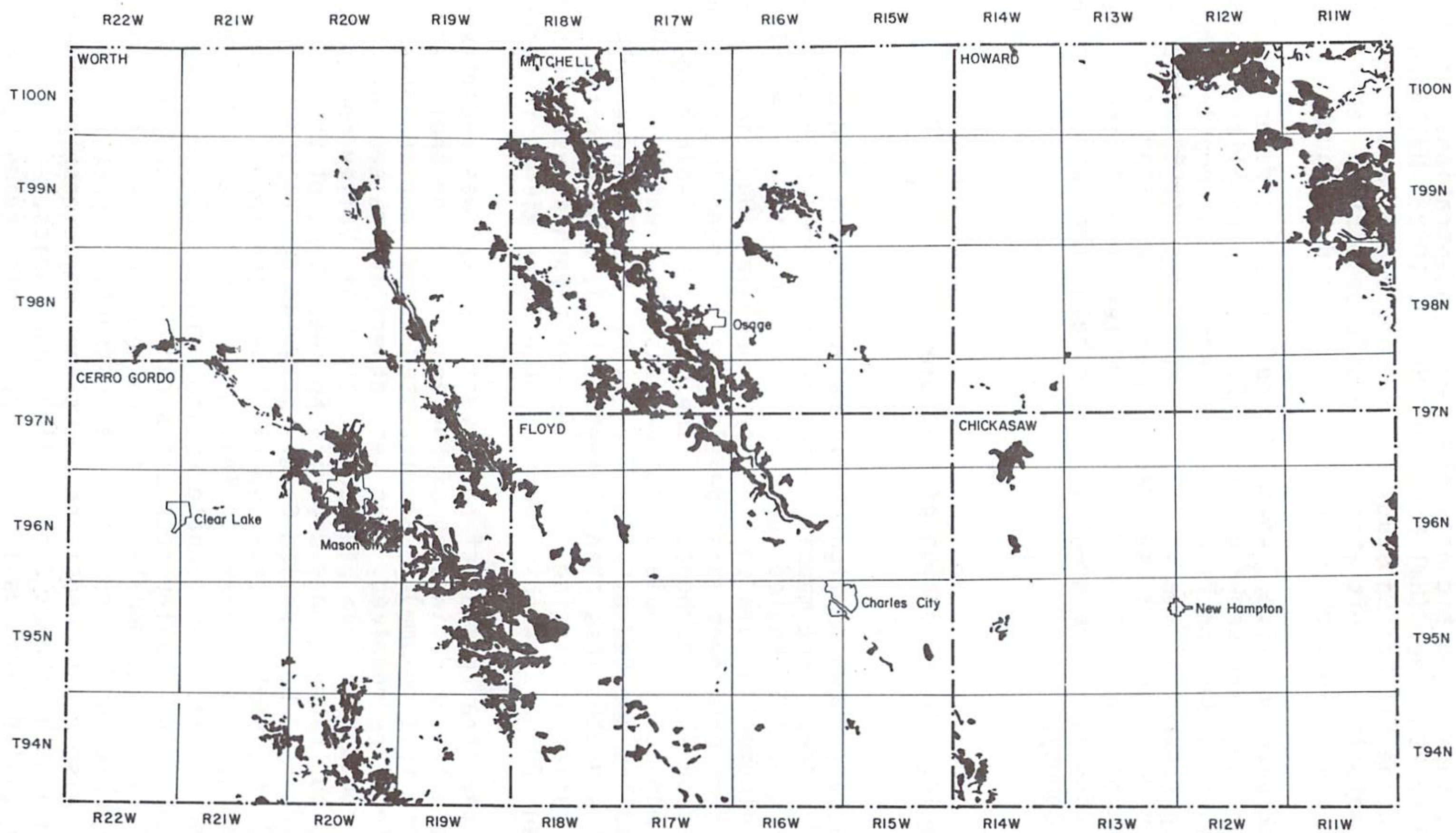
Geologic Distribution of Sinkholes

The mapped sinkholes are shown on figure 5 in relation to the bedrock geologic units in the study area. The mapping units are the same as those used in Hallberg and Hoyer (1982). Sinkholes occur in all three units of Devonian rocks. Minor karst development occurs in the Upper Devonian (Du) Lime Creek Formation carbonates. More prominent karst development is found in the area of the Shell Rock Formation (Dsr) carbonates. The major karst-sinkhole regions occur in the area mapped as Middle Devonian rocks (Dm), which are dominantly what have been called the Cedar Valley Formation. However, even where these rocks are at shallow depth (less than 25 feet; 7.5 m), the concentration of sinkholes is quite variable; ranging from 100 per township east of the Cedar River to less than 20 per township west of the Cedar River in Floyd County, for example.

A reexamination of the stratigraphy of the Devonian rocks was undertaken for this project to enable better definition of the aquifer(s) and their geometry (Witzke and Bunker, this volume). As discussed by Witzke and Bunker, some stratigraphic problems are resolved, and yet others are raised by this study. Portions of the rocks that have been called the Cedar Valley Formation are not Middle Devonian, but rather Upper Devonian in age. Some of these various carbonate rocks which have been called Cedar Valley do not relate to the Cedar Valley Formation to the south in Iowa, where it has been more thoroughly studied. These rock units, here referred to informally as "Upper Cedar Valley" form the important surficial-carbonate aquifer in the Floyd-Mitchell County study area. These Cedar Valley rock units can be described and correlated as a series of cyclic carbonate units (called A-E; see Witzke and Bunker). The stratigraphic and structural reconstructions prepared here (e.g., figures 6 and 7) also raise questions about the relationship between the Shell Rock Formation and the "Upper Cedar Valley" rock units.

The Devonian (often called Cedar Valley) aquifer in this region has often been treated as a single unit. It may be better described, however, as a three-part aquifer system (figure 6): a lower aquifer formed by the newly-defined Spillville Formation; a middle aquifer composed of the Wapsipinicon and Cedar Valley Formations, below the "Rapid shale"; and an upper aquifer composed of the remainder of the Cedar Valley Formation and the "Upper Cedar Valley" limestones. The base of the aquifer system is confined by the

Location of Bedrock Outcrop



Mapped areas indicate less than 5 feet of soil mantle over bedrock and actual bedrock exposure.

SCALE

5 0 5 10 15 20 miles

5 0 5 10 15 20 25 kilometers

compiled by

J.E. Gonyier, G.R. Hallberg, D.J. Quade, G.A. Ludvigson, R.W. Graeff

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Figure 3. Bedrock-outcrop areas in six-county area.

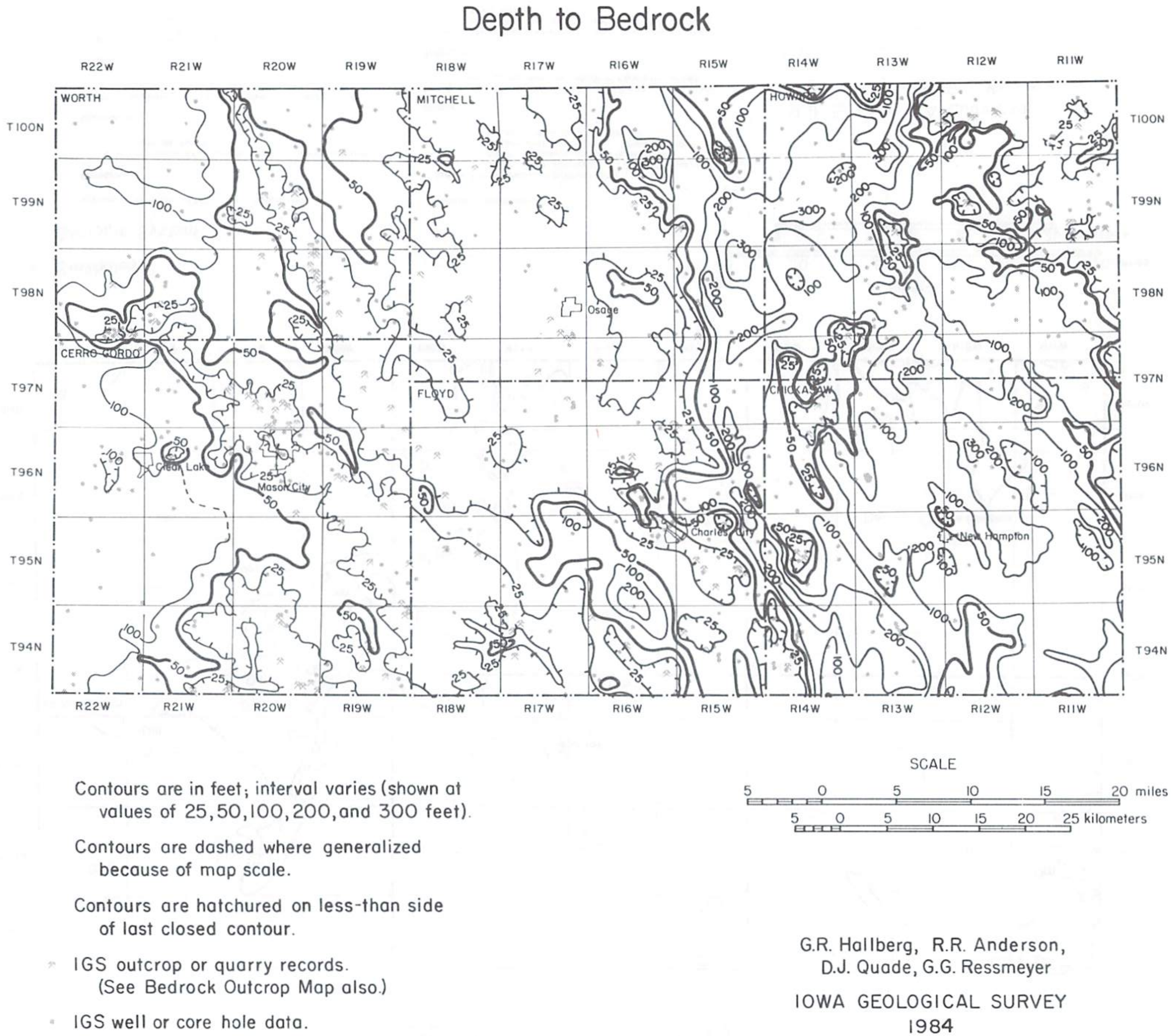
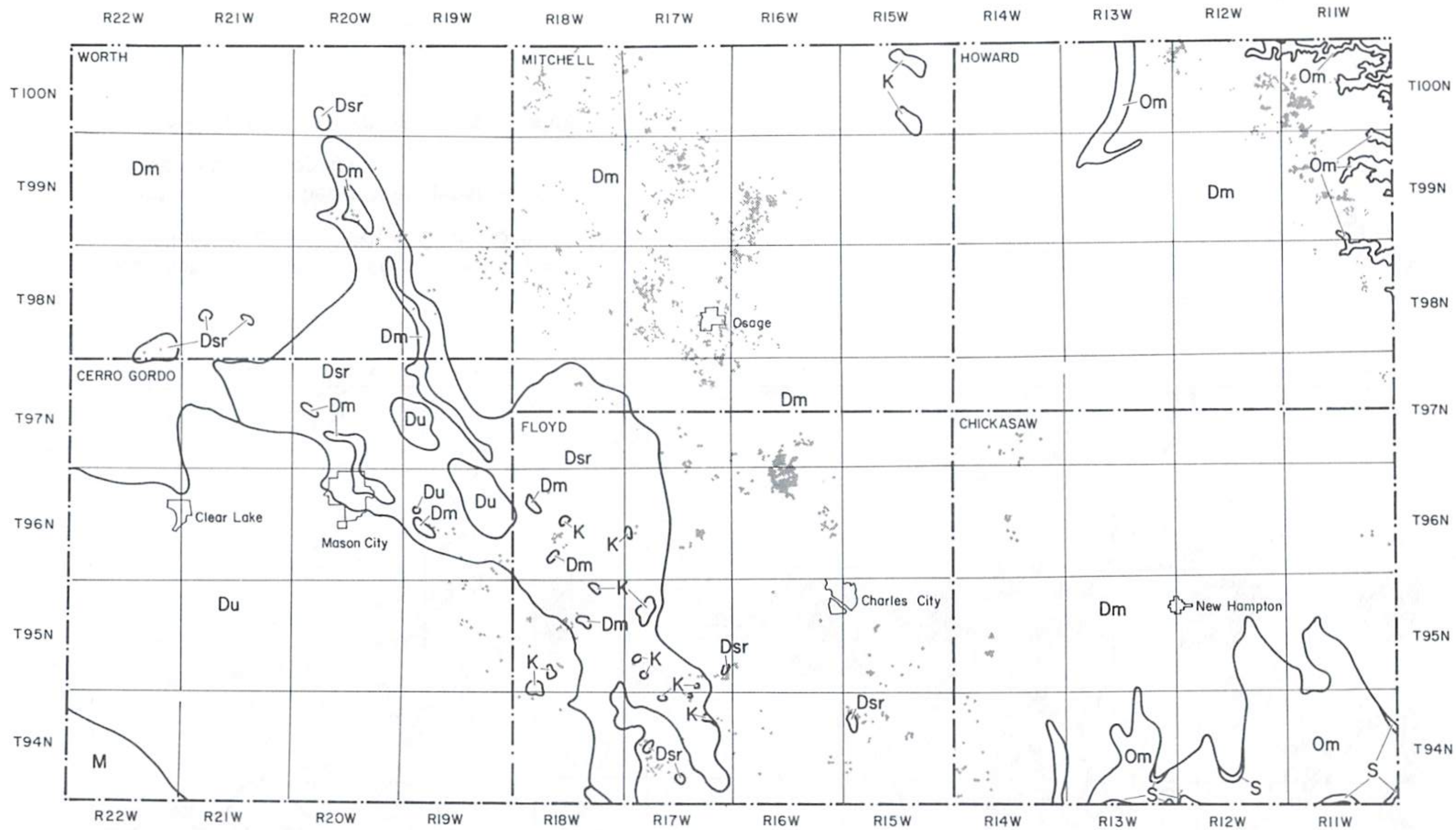


Figure 4. Depth to Bedrock in six-county area.

Bedrock Geologic Map



Sinkholes

Geologic System

Symbol: Formations or rock units — Description

Cretaceous

K — Cretaceous rocks Undifferentiated — sandstone, conglomerate, iron ore.

Mississippian

M — Mississippian Undifferentiated — limestone, dolomite, and shale; minor karst development.

Devonian

Du — Upper Devonian Undifferentiated
Yellow Spring Group — shale and minor shaly carbonates.
Lime Creek Formation — shale and carbonates; minor karst development.

Dsr — Shell Rock Formation — limestone, dolomite and minor shale; minor karst development.

[Devonian, continued]

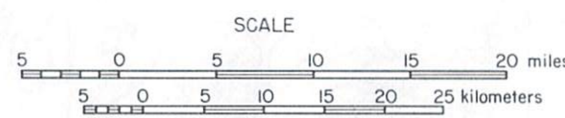
Dm — Middle Devonian Undifferentiated
Cedar Valley Formation — limestone, dolomite, minor shale; prominent karst development.
Wapsipinicon Formation — limestone, dolomite, and shale; minor karst development.

Silurian

S — Silurian Undifferentiated — dolomite, cherty dolomite, some limestone; prominent karst development.

Ordovician

Om — Maquoketa Formation — shale, limestone and dolomite; minor karst development in carbonate interval in lower portion of formation.



B.J. Bunker, G.A. Ludvigson,
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Figure 5. Generalized bedrock geologic map and sinkhole locations for six-county area.

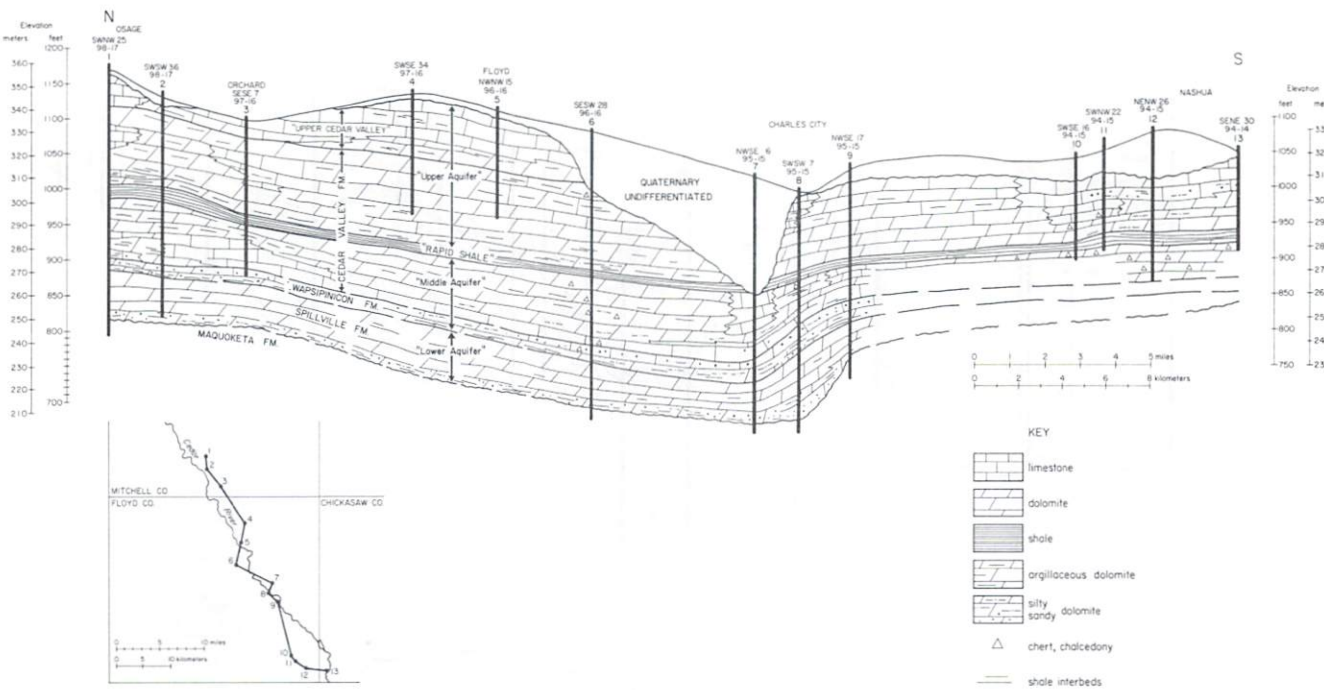

Figure 6. North-south geologic cross-section of Devonian rocks in Floyd and Mitchell Counties.

shales of the Maquoketa Formation. The lower, middle, and upper aquifers are separated, and at least partially confined, by shales in the lower Wapsipinicon Formation, and by the "Rapid shale," respectively. This new stratigraphic and structural framework (see figure 7) allows the explanation of a variety of hydraulic and water-quality observations.

These refined interpretations also allow a more thorough understanding of the disparate distribution of sinkholes and karst features in the region. Numerous sinkholes occur in Mitchell County and north-central Floyd County where "Upper Cedar Valley" limestones form the bedrock (e.g., near Floyd, point 5, on figure 6). In other areas, where more dolomitic rocks of the Cedar Valley Formation (cycles A-C) form the bedrock, or where, through facies changes, the "Upper Cedar Valley" (cycles D-E) is dolomitized, fewer sinkholes are apparent and karst development is less pronounced. The prominent sinkhole region in northeastern Howard County occurs where the carbonates of the Spillville and Wapsipinicon Formations rise toward the land surface (as on the eastern side of figure 7), near the erosional edge of the Devonian rocks.

These refined interpretations of the Devonian stratigraphy begin to resolve many hydrogeologic problems; these answers are still incomplete, however, and they also raise other questions. These questions can only be answered by further detailed investigations. Also, the geologic map, shown on figure 5, cannot be refined without further investigation.

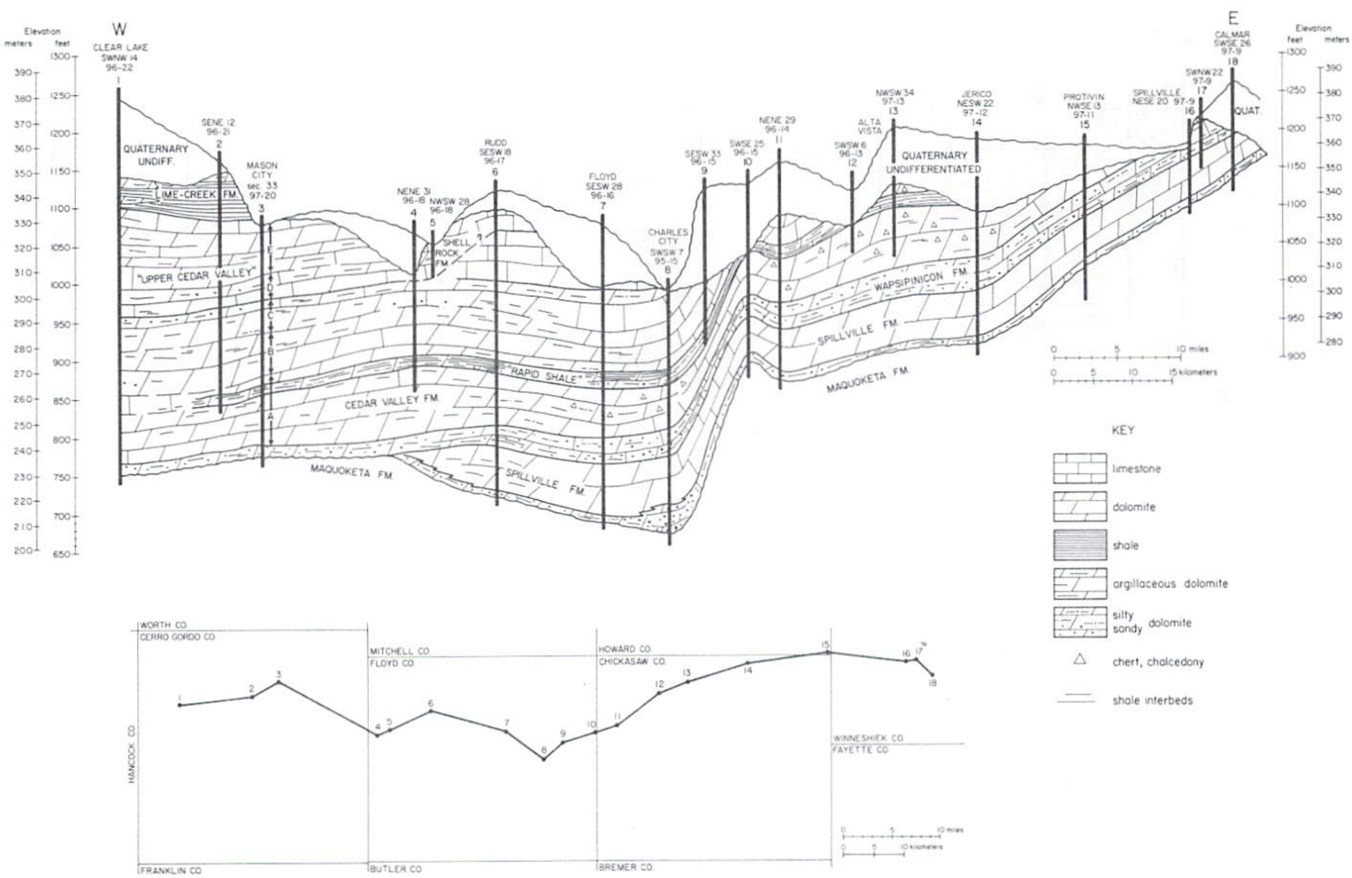

Figure 7. East-west geologic cross section of Devonian rocks from Winneshiek to Cerro Gordo Counties.

Potentiometric Surface of the Devonian Aquifer

The generalized potentiometric surface in the Devonian aquifer is shown on figure 8. This map was compiled from static water-level data at IGS. The potentiometric contours only represent the upper surface of the head (or pressure) distribution in the aquifer. At any given point, the exact flow path of the groundwater will be controlled by the vertical head distribution throughout the aquifer, for which little data is available. The map is therefor only a generalized view, which is most representative of the conditions in the shallow part of the aquifer system.

Flow through the system will follow a gradient from areas of high potential (or head, as shown in feet on the map) to low potential, at right angles to the contours. As shown on figure 8, the groundwater divides and surface-water divides are generally coincident. Groundwater flows from these divides and discharges along the major streams, such as the Cedar River. Deeper, more regional flow undoubtedly is more complex. Strong upward flow components occur in the Floyd-Mitchell County area in the lower aquifer (Spillville Formation). For example, the strong vertical flow reported at Charles City by Munter (1980) is now known to issue from the lower aquifer. The lower aquifer

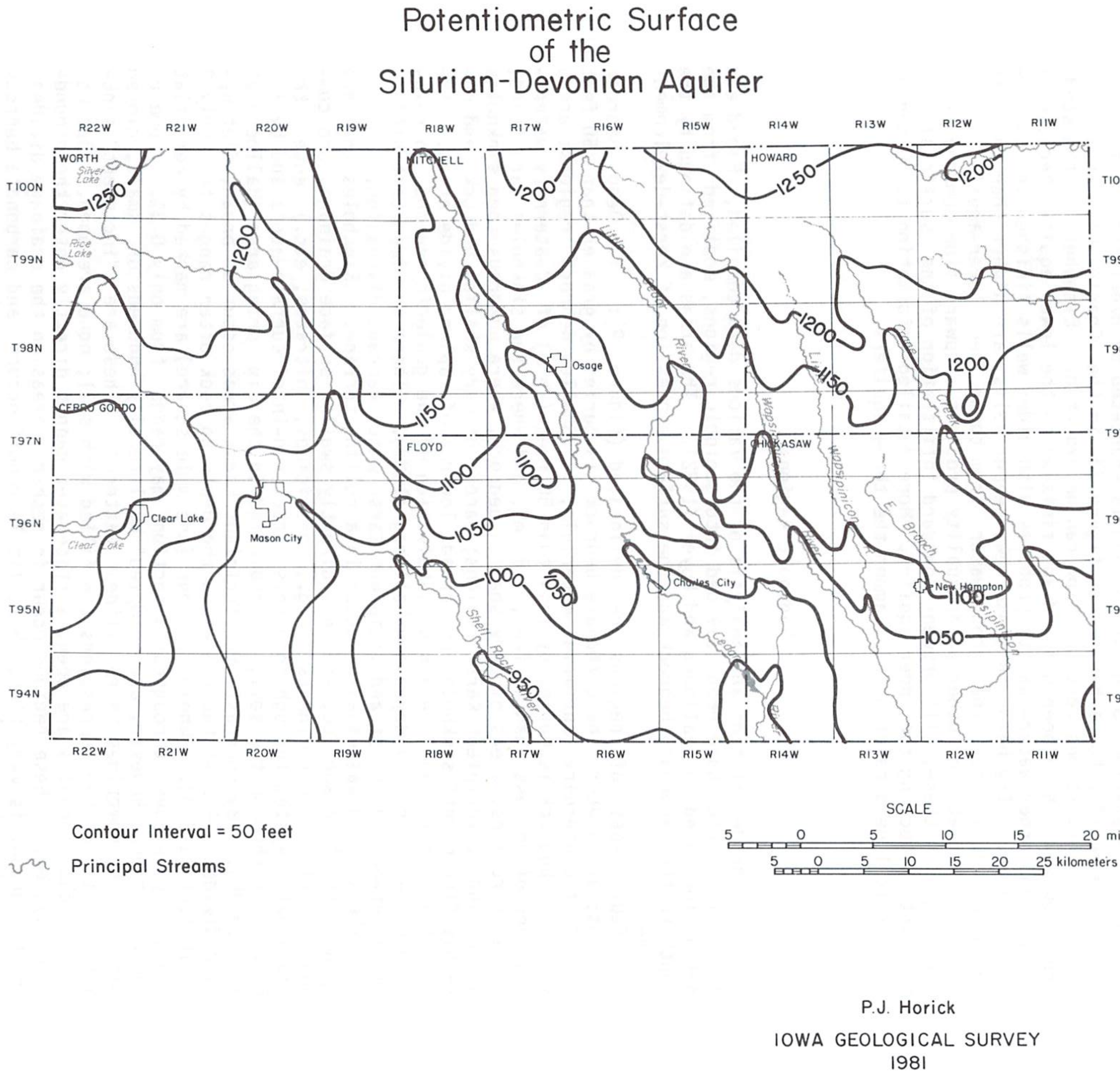

Figure 8. Generalized potentiometric surface in "the" Devonian aquifer in six-county area.

descends in elevation to the south and is truncated by overlying units, confining the aquifer to a basin (see figure 7) in the Charles City area. In such a setting, strong vertical flow can be expected. Elsewhere in the study area, new wells have been drilled and finished in the lower aquifer because of nitrate and other water-quality problems with older wells finished in the upper aquifers. The heads in these new, deeper wells, are higher than those in the upper aquifers. The groundwater from these new, lower-aquifer wells showed no nitrates or other water-quality problems. Upward flow components in areas such as these, will prevent downward infiltration of the surficial contaminants affecting the upper aquifer. More detailed information is needed on the vertical head relationships among the three aquifers.

Geologic Regions

For the description and analysis of the various data compiled, Floyd and Mitchell Counties have been divided into geologic regions, modified from the definitions used by Hallberg and Hoyer (1982). The areas are defined by the depth to the carbonate bedrock and the surface expression of karst-development in the area.

Four types of regions are delineated (figure 9): 1. Deep Bedrock regions; areas where the carbonate bedrock is buried by greater than 50 feet (15 m) of Quaternary surficial materials; 2) Shallow Bedrock regions; areas where the bedrock is buried by less than 50 feet (15 m) of Quaternary materials (and often less than 25 feet, 7.5 m), and where few sinkholes are found; 3. Karst regions; areas of very shallow bedrock, where numerous open sinkholes occur; and 4. Incipient Karst regions; areas of very shallow bedrock and numerous "incipient" sinkholes on broad, low-relief upland divide areas. The Incipient Karst areas are a new subdivision of the geologic regions in relation to past work by Hoyer and Hallberg (1982). There are important differences between the Karst and Incipient Karst which warrant discussion.

The Karst areas usually occur in a rolling terrane. Sinkholes that are open to the land surface, and thus directly swallow surface drainage, are common. Surface contaminants (e.g., pesticides, nitrates, etc.) enter the groundwater system through both this direct run-in of surfacewaters and by infiltration through the soil, as documented in the Big Spring area (Hallberg et al., 1983b). By contrast, the Incipient Karst areas occur on broad, flat upland divides. Across these divides the depth to rock often ranges from only 3 to 10 feet (1-3 m). Whole sections (one mile square) are marked by very flat topography; slopes throughout a section may range from only 0-3%. Some of these sections, however, are "dimpled" by literally hundreds of small, closed depressions, sometimes in rectilinear patterns. These are "incipient" sinkholes. All of the depressions are filled with soil; none are open. Because none of the sinkholes are open, surfacewater cannot directly enter the groundwater system. These regions occur in recharge areas on the drainage divides. The topography is very flat, thus, little runoff occurs and carbonate bedrock is very close to the land surface. These factors combine to promote high rates of infiltration recharge through the soil mantle. By isolating the analyses of groundwater quality from these areas (from the uppermost aquifer) various conclusions can be drawn about the delivery of contaminants to groundwater through infiltration.

Thus, the four geologic regions present differing hydrogeologic settings

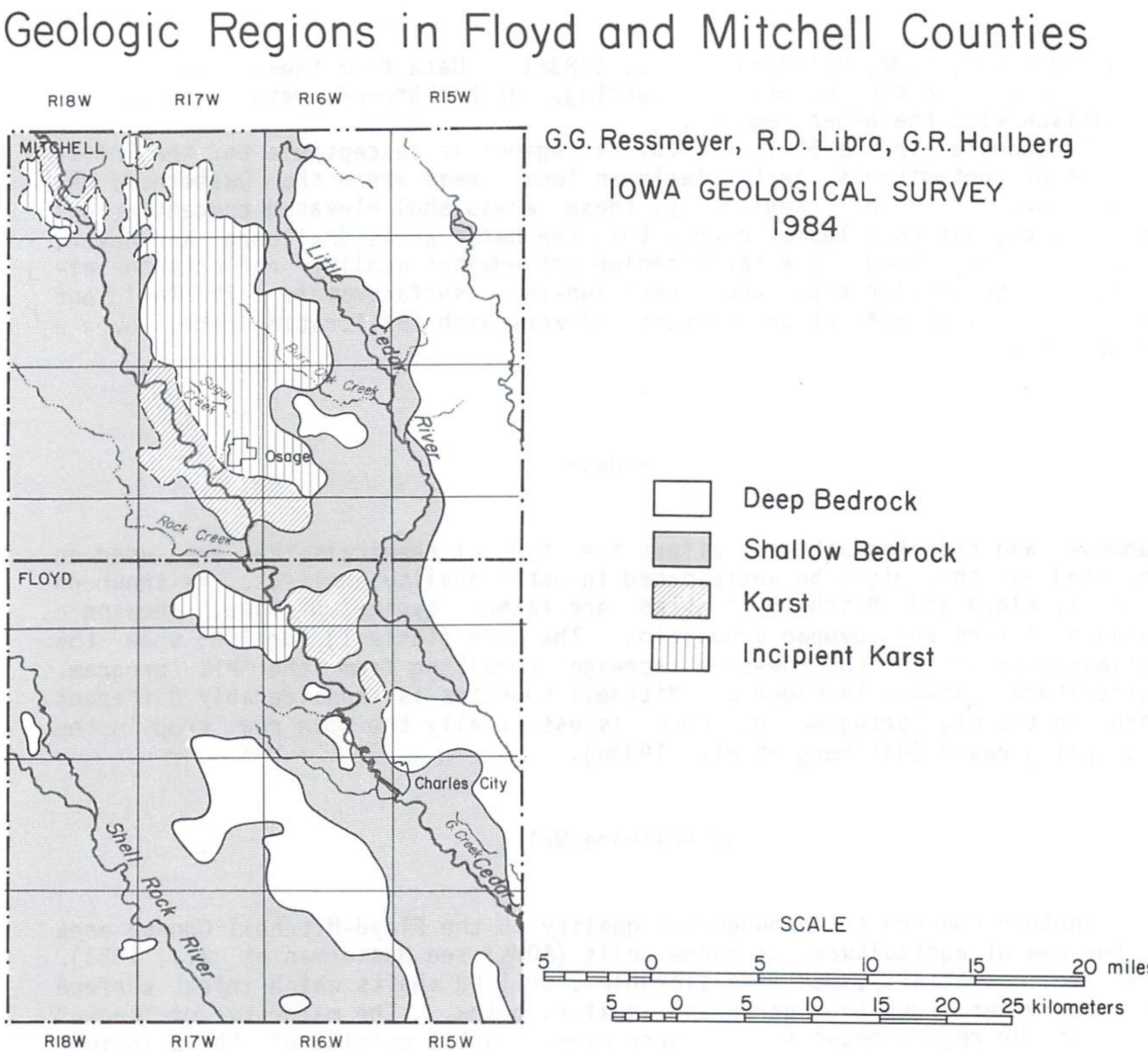

Figure 9. Surficial-geologic regions in Floyd and Mitchell counties.

which affect groundwater quality. The Deep Bedrock settings are relatively "protected" from infiltration of surface-applied chemicals by the thickness of low-permeability Quaternary deposits (over 50 feet) overlying the bedrock. It may take a long time for water to infiltrate through this thickness of material (thus, it may simply be a matter of time before such contaminants are noted in these areas). Also, because of the low permeability of these deposits, local, shallow flow systems will develop, transporting some of the chemicals laterally. On the regional level, groundwater in these settings contains essentially no nitrates (<5 mg/l) or other surface-derived contaminants (Hallberg and Hoyer, 1982; Hallberg et al., 1983a). Data from these areas provide a perspective on the naturally occurring, or background, water quality for comparison with the other regions.

Groundwater in the Shallow Bedrock regions is susceptible to the infiltration of contaminants, particularly in local areas where the Quaternary deposits are very thin. Regionally, these areas show elevated concentrations of nitrates, but to a lesser degree than the Karst areas (Hallberg and Hoyer, 1982). As discussed, the Karst region groundwater quality reflects the effects of both infiltration and direct run-in of surfacewater. The Incipient Karst region will reflect the effects of very high infiltration rates over a large area.

Landuse

Landuse and cropping patterns affect the type of chemicals that are used on the land and that might be anticipated in water-quality analyses. As shown on Table 1, Floyd and Mitchell Counties are rather typical of Iowa, showing a balance of corn and soybean production. The data (Table 1) for 1983 show the estimated reduction in row-crop acreage resulting from the PIK program. Agricultural landuse in Floyd and Mitchell Counties is considerably different than in the Big Spring basin. Corn is essentially the sole row crop in the Big Spring basin (Hallberg et al., 1983b).

Ag-Drainage Wells

Another concern for groundwater quality in the Floyd-Mitchell County area is the use of agricultural drainage wells (ADWs; see Musterman et al., 1981). ADWs are, essentially, man-made sinkholes, drilled shafts which inject surface drainage water into the carbonate aquifers below. The majority of "known" ADWs in the region occur in southern Floyd County, outside of the principal area of sampling in this report. A few ADWs are reported from the sampling area in northern Floyd County. Most of these are actually sinkholes that have been modified with casing and grates to "permanently" take surface drainage.

Although ADWs may locally affect groundwater quality, their regional impact is probably overshadowed by sinkholes and infiltration problems. In Floyd and Mitchell Counties, over 1,500 sinkholes are known, compared to estimates of 50-100 ADWs, for example. Any evaluation of the impact of ADWs must also be put in the context of the background groundwater quality in the aquifer. Such data are described in this report.

PROCEDURES AND BACKGROUND INFORMATION

A variety of quantitative data will be presented in this report. The following section outlines the principal analytical procedures used.

Table 1. Row-crop acreage in Floyd and Mitchell Counties (data from Iowa Crop and Livestock Reporting Service).

	Floyd County	Mitchell County
	in 1,000s of acres	
Total land area	321.9	298.9
Total farm acreage	307.7	291.9
(% of Total)	96	98
Corn acreage (% of farm acreage)		
1981	142 (46)	143 (49)
1982	138 (45)	137 (47)
1983 est.*	88 (29)	88 (30)
Soybean acreage (% of farm acreage)		
1981	108 (35)	90 (31)
1982	112 (36)	91 (31)
1983 est.*	104 (34)	85 (29)

*1983 acreages are estimates, accounting for PIK reduced row-crop acreage.

Well-Water Sampling Procedures

The quality of water within an aquifer is generally investigated through chemical analysis of well-water samples. However, several factors may cause a well sample to be unrepresentative of the water within the aquifer. The presence of metal well casing, the type of pumping mechanism, and an open connection to the surface provided by the well may contribute or adsorb dissolved species, allow for equilibration of dissolved gases with the atmosphere, and alter the eH-pH conditions of the water. The magnitude of chemical changes are generally greatest when water is in storage within the casing, and effectively isolated from the zone of active groundwater flow.

Several methods of overcoming the above problems and obtaining representative groundwater samples are commonly employed. The preferred method involves pumping the well until several casing volumes of water are removed, allowing for movement of representative groundwater into the well (Gibb et al., 1981; Scalf et al., 1981). Alternative methods suggest monitoring changes in a chemical or physical parameter during pumping until a stable condition exists. Specific conductance, temperature, and pH are easily measured parameters that stabilize during pumping (Summers and Branvold, 1967).

Groundwater samples collected for this study were taken from existing domestic water wells. Information about the depth and size of casing, and depth to water, needed to calculate the water-filled casing volume, are not available for all of the wells. Therefore, temperature was monitored while the wells were pumped. Temperature was chosen as the monitoring parameter because of the ease of measurement and because other recommended parameters, such as pH and specific conductance, are temperature dependent and will not stabilize until the temperature is constant. In most cases, a stable temperature was reached within ten minutes of pumping, after which time the samples were collected and conductivity and temperature were recorded.

The water chemistry can also be affected if the water is passed through a cistern, storage tank, or water-conditioning equipment. Unless specified, no water samples were taken which passed through such devices. All samples were collected directly at the well head, from the hydrant closest to the well head or, in a few cases, directly from unsoftened kitchen taps.

Field Analyses

Conductivity, or specific conductance, and temperature were measured in the field.

Conductivity

Conductivity of the water was measured in the field at each sample site. A quart jar was filled with sample water, water temperature was determined with a thermometer, then conductivity was measured using a Beckman RB3 Solu Bridge conductivity meter. Specific conductance was determined in micromhos/cm, instrumentally corrected to a standard of 25° C.

Chemical Analyses

All water chemical analyses were performed by the University Hygienic Laboratory (UHL) using standard analytical methods. Details of the analytical procedures may be obtained from UHL.

Nitrate

Nitrates are analyzed using EPA method 353.2 ("Methods for Chemical Analysis of Water and Wastes," EPA-600/4-79-020) with minor modifications. This is the standard cadmium reduction method for nitrate/nitrite analysis. Results are reported as milligrams per liter, nitrate (mg/l, NO_3).

Bacteria

Total coliform bacteria were determined using the most probable number (MPN) method, in accord with EPA standard methods ("Microbiological Methods for Monitoring the Environment," EPA-600/8-78-017, December, 1978). The data are reported as the statistical MPN of total coliform individuals per 100 ml of water. The MPN classes are 0, 2.2, 5.1, 9.2, 16, and 16+. Any value above 0 is considered unsatisfactory (2.2 -5.1) or unsafe (>5.1). These data generally exhibit an irregular frequency distribution with the mode at 0, and a secondary mode of 16+ (see Hallberg and Hoyer, 1982, p. 15-19).

Pesticide Analysis

Pesticide concentrations in the water samples were run by standard gas-chromatographic column methods, following EPA guidelines ("Methods for Organochlorine Pesticides and Chlorophenoxy Acid Herbicides in Drinking Water and Raw Source Water," EPA-Interim Methods, July, 1978; and "Manual of Analytical Methods," EPA). Samples were collected in quart-size, wide-mouth, glass mason jars with teflon liners. Samples were refrigerated prior to analysis. Results are reported as micrograms per liter (μg/l). Detection limits vary for individual pesticides and with other water constituents (miscellaneous organic compounds), which may interfere with the chromatographic peaks.

Water-Quality Inventory

As a first step towards evaluating groundwater quality in the Floyd-Mitchell County study area, approximately fifty wells were chosen for an initial inventory. These wells were selected according to several criteria. All wells were chosen from the IGS well-log file, and cuttings from the wells had been examined and described by IGS staff. Construction details, such as the depth of casing and completed intervals were also available for most wells. Details of site-specific geology and well construction allow for definition of the stratigraphic source of the water supplying a given well. Where possible, closely-spaced wells completed at different stratigraphic horizons were chosen as a first step towards defining the geologic controls on water quality in the study area. This was only possible in a few areas.

The areal distribution of the wells for the initial inventory was selected to provide sampling of groundwater in the different geologic regions (as previously described). Previous studies on water quality in the karst-carbonate aquifers of Iowa (Hallberg and Hoyer, 1982; Hallberg et al., 1983a,b) have shown that the criteria used to classify these regions, such as depth to bedrock and the presence or absence of karst features, exhibit a major control on the impact that surficial activities have on groundwater quality.

The water-quality inventory was conducted by IGS staff during the week of December 13, 1982. Fifty-five rural water supply wells were inventoried. Water samples were collected for nitrate and bacterial analyses from forty-eight wells. In addition to the wells initially chosen for the inventory, several others were added in the field to fill gaps in the distribution of sampling points. Qualitative information on the geology and construction of these additional wells were obtained from owners of the water supplies. One spring, two drainage-tile outlets, and three small surface streams were also sampled for nitrate and bacteria. Water temperatures and conductivities were measured in the field at all sampling sites. Distribution of sampling sites is shown on Figure 10.

In addition to collecting water samples, IGS staff also surveyed local conditions that may affect well-water quality. These included well placement in relation to local contaminant sources, surficial construction of the wells, presence of cisterns or holding tanks, and the general condition of the site water system. Rural residents were questioned about past water-quality problems. The effects of local environmental factors on water quality have been discussed in prior studies (Hallberg and Hoyer, 1982; Hallberg et al., 1983b). Information concerning local factors, though qualitative in nature, helps in locating sampling sites that will primarily reflect conditions in the aquifer itself, not local well-construction problems.

Results of the Water-Quality Inventory

Results of the water-quality inventory are given in Table 2. Sites 1-53 are well samples; OS is Osage Spring, a natural groundwater discharge point. Samples BO, SC, and GC are from Burr Oak, Sugar, and Goose Creeks, respectively. Sites labeled DT are drainage-tile outlets.

Summary statistics for the well samples are given in Table 3. Nitrate concentrations from all wells varied from less than 5 mg/l to 92 mg/l. Twenty-two samples were collected from wells in the protected, Deep Bedrock region; only one of these samples contained nitrates above the 5 mg/l (lower) detection limit. Median concentrations from the Shallow Bedrock and Karst/Incipient Karst regions were 11 mg/l and 30 mg/l, respectively. Six samples, representing 12% of the wells, contained nitrate concentrations in excess of the 45 mg/l drinking-water standard; these samples were collected from four Karst/Incipient Karst region wells and two Shallow Bedrock region wells.

Areal distribution of nitrate contaminations is shown on figure 11, superimposed upon the geologic regions map. Here again, the strong controls of depth to bedrock and presence or absence of karst features on nitrate levels is demonstrated. The correspondence of low, generally undetectable nitrates with the Deep Bedrock region is very clear. Also of note, are the relatively low nitrate levels occurring in some samples from the Shallow Bedrock and Karst/Incipient Karst regions. Figure 12 is a histogram of nitrate concentrations from the inventory broken down by geologic regions. While the Deep Bedrock samples cluster at less than detectable levels, samples from Shallow Bedrock and Karst/Incipient Karst areas vary widely.

With an understanding of the controls the geologic setting has on nitrate levels in groundwater, the effects of other factors may be examined. Figure 13 includes three plots relating nitrate concentrations from inventory wells to depth to bedrock, casing depth, and well depth. At depths to bedrock in excess of fifty feet, nitrate levels are below detection limits; at depths less than fifty feet, high nitrate levels may occur, but no consistent relationship is apparent (Figure 13-A). Wells with shallow casing are also more susceptible to nitrate contamination (Figure 13-B). Notice, however, that three wells with casings extending down 100 to 150 feet contain 20-40 mg/l nitrate. These three wells are located in the Shallow Bedrock region. The elevated nitrate concentrations in these wells indicate that surficial contaminants are present, at least locally, to significant depths within the

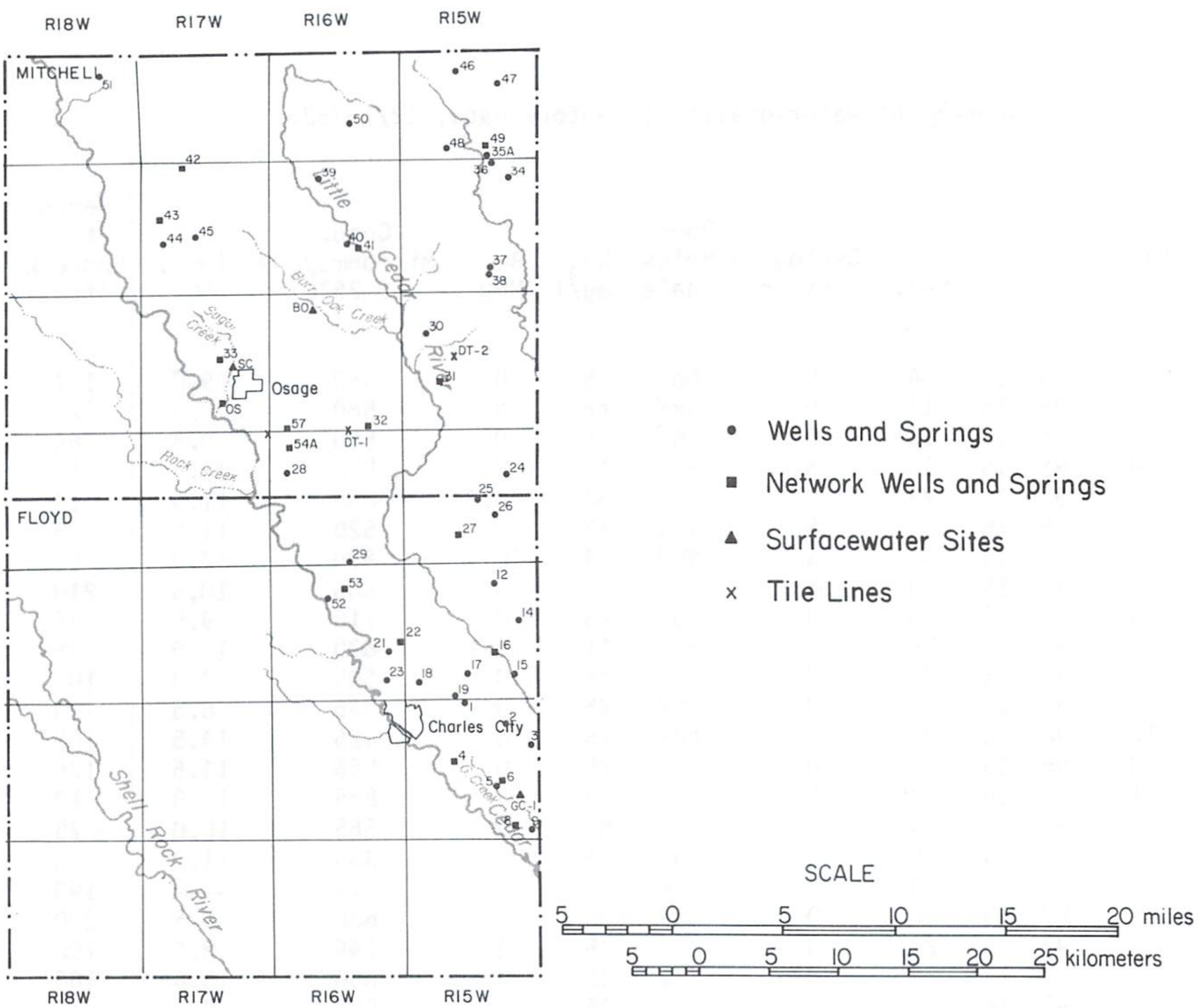

Figure 10. Location of water-quality inventory sampling sites.

aquifer. Total well depth (Figure 13-C) has, at best, only a general relationship with nitrate in the wells inventoried. These plots indicate that depth to bedrock is the most important control on the distribution of nitrates in the wells inventoried, and that deep wells with a shallow casing are susceptible to nitrate contamination. Prior studies have shown similar results (Hallberg and Hoyer, 1982; Hallberg et al., 1983a).

Table 3 (and figure 12) summarize bacteria data from the inventory; 25% of the wells inventoried had some level of bacterial contamination. These wells are located in all geologic regions, although almost half were from the Shallow Bedrock zone. Comparison of nitrate and bacteria levels (Table 2) does not show any clear relationship between these contaminants.

Table 2. Summary of water-quality inventory data, 12/15/82.

Site No.	T	R	Sec.	Geologic[1] Setting	Open Below Shale	NO_3 mg/l	Bac. MPN	Cond. microhms/cm[2] @ 25°C	Temp. °C	Depth to Bedrock (ft)
1	95	15	4	D	No	<5	0	580	9.0	137
2§	95	15	11	D	NR[2]	<5	0	580	9.5	220
3§	95	15	13	D	NR[2]	<5	0	500	9.5	185
* 4	95	15	16	S	No	11	2.2	825	14.5	15
* 6	95	15	23	S	No	32	9.2	600	11.5	10
* 8	95	15	35	S	Yes	23	0	520	11.5	35
9	95	15	36	S	NR[2]	44	16+	570	12.0	55
12§	95	15	3	D	NR[2]	<5	0	665	10.5	210
14	96	15	3	D	No	<5	0	710	9.5	85
15	96	15	26	S	NR[2]	11	5.1	630	12.0	35
*16§	96	15	27	D	NR[2]	<5	0	605	9.0	105
17	96	15	28	D	NR[2]	<5	0	545	8.5	110
18	96	15	31	D	NR[2]	<5	0	525	14.5	105
19	96	15	23	D	X[3]	<5	0	565	11.5	125
21	96	16	24	S	No	49	16	885	10.0	12
*22	96	16	24	K	No	50	16+	565	10.0	75
23	96	16	36	S	No	<5	0	330	11.0	30
24	97	15	14	D	Yes	<5	0	---	----	190
25	97	15	22	D	NR[2]	<5	0	630	9.5	290
26§	97	15	23	D	NR[2]	<5	0	745	8.5	150
*27	97	15	28	D	Yes	<5	0	560	10.0	100
28	97	16	7	S	Yes	34	0	550	9.5	<5
29	97	16	34	K	NR[2]	13	0	725	11.0	5
30§	98	15	7	S	No	<5	0	600	10.0	35
*31	98	15	20	D	Yes	<5	9.2	670	8.0	95
*32	98	16	35	S	NR[2]	8	5.1	675	9.0	25
*33	98	17	15	I	NR[2]	27	0	540	10.0	10
34	99	15	2	D	X[3]	<5	0	380	8.0	95
35	99	15	3	S	No	<5	0	520	9.0	40
36	99	15	3	S	No	<5	16	480	9.0	41
37	99	15	27	D	NR[2]	<5	5.1	580	9.0	280
38§	99	15	34	D	NR[2]	<5	0	555	8.0	?
39	99	16	4	D	NR[2]	<5	0	550	10.0	295
40	99	16	22	S	NR[2]	25	0	690	10.0	10
*41	99	16	22	S	No	51	0	605	11.0	15
*42	99	17	4	I	NR[2]	61	0	540	10.0	26
*43	99	17	17	I	NR[2]	92	0	570	11.0	15
44	99	17	20	I	NR[2]	70	0	545	11.0	15
45	99	17	21	I	NR[2]	8	0	520	9.0	35
46	100	15	9	S	No	<5	0	450	7.0	40
47	100	15	14	D	X[3]	<5	0	540	9.0	90
48	100	15	32	D	No	6	16	360	6.5	110
*49	100	15	34	S	No	10	0	345	8.0	10
50	100	16	27	D	No	<5	0	400	9.0	60

Table 2. Continued

Site No.	T	R	Sec.	Geologic[1] Setting	Open Below Shale	NO_3 mg/l	Bac. MPN	Cond. microhms/cm[2] @ 25°C	Temp. °C	Depth to Bedrock (ft)
51	100	18	14	D	NR[2]	<5	0	650	9.0	50
52	96	16	9	K	NR[2]	6	5.1	520	9.0	~10
*53	96	16	10	K	X[3]	30	0	755	8.2	12
*OS	98	17	28	?		<5	0	---	----	0
Surfacewater Site										
*BO	98	16	32	---	---	67	16+	---	----	
SC	98	17	14	---	---	65	16+	---	----	
*GC	95	15	26	---	---	38	16+	---	----	
Tile Lines										
*DT-1	97	16	3	---	---	127	16+	---	----	
*DT-2	98	15	16	---	---	105	16+	---	----	

[1] D--Deep, depth to bedrock >50'; S--Shallow, depth to bedrock <50'; K--Karst region; I--Incipient Karst region.
[2] No record available.
[3] Wells open above and below the "Rapid shale"

*Network sites.

§Samples contained H_2S.

Effects of Local Factors

Only three of the wells inventoried appeared to have well construction and/or placement problems that seemed likely to allow surface or shallow subsurface drainage into the well. Samples from these wells (#34, #37, and #46) indicated nitrate concentrations of less than 5 mg/l; only one of these wells (#37) showed any bacterial contamination. The construction/placement problems noted at other sites appeared to have little effect on well-water quality, at least under the climatic and hydrologic conditions prevailing at the time of sampling. Three residents (sites #9, #15, and #41) reported that their well water turned turbid or exhibited other problems following major rains or snowmelt. These wells showed elevated levels of nitrate or bacteria

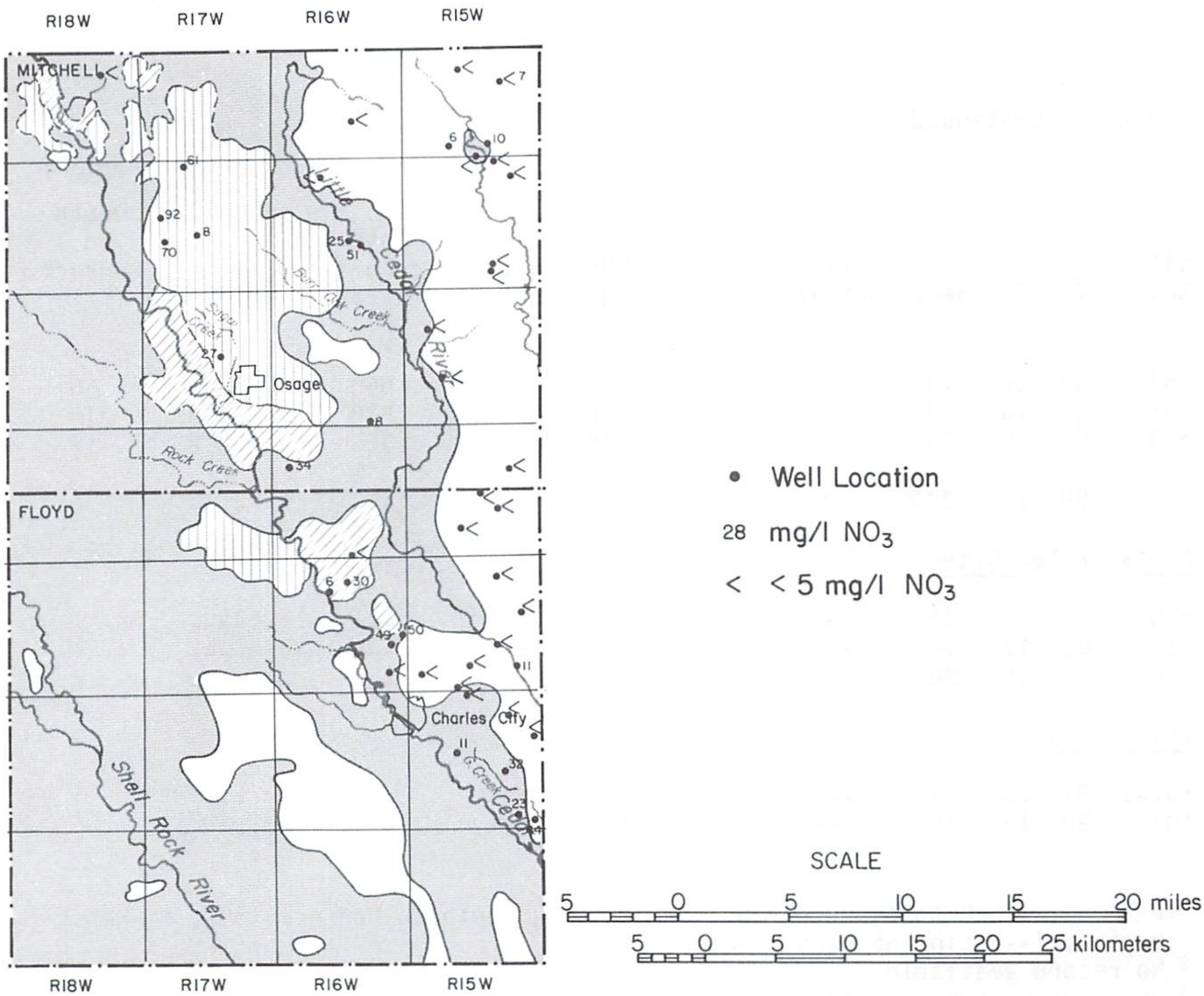

Figure 11. Nitrate concentration in groundwater from inventory samples, in relation to the geologic regions.

(Table 2) during the inventory sampling.

Six of the wells sampled during the inventory were known or believed to be completed below the "Rapid shale." Four of these wells are located in the Deep Bedrock region, and yielded water samples which contained less than 5 mg/l nitrate. Because of their location in the Deep Bedrock zone, the results from these wells cannot be used to evaluate any effect the "Rapid shale" may have on groundwater quality. The other two wells, sites 6 and 8 (Figure 11 and Table 2) yielded samples with 32 mg/l and 23 mg/l nitrate, respectively. This data suggests that surficial contaminants are present below the shale, and, therefore, that the shale is not an effective barrier to groundwater flow, at least in the area adjacent to and upgradient from these wells. However, a comparison of the location of these wells (figure 11) with the map showing the known distribution of the "Rapid shale" (see Witzke and

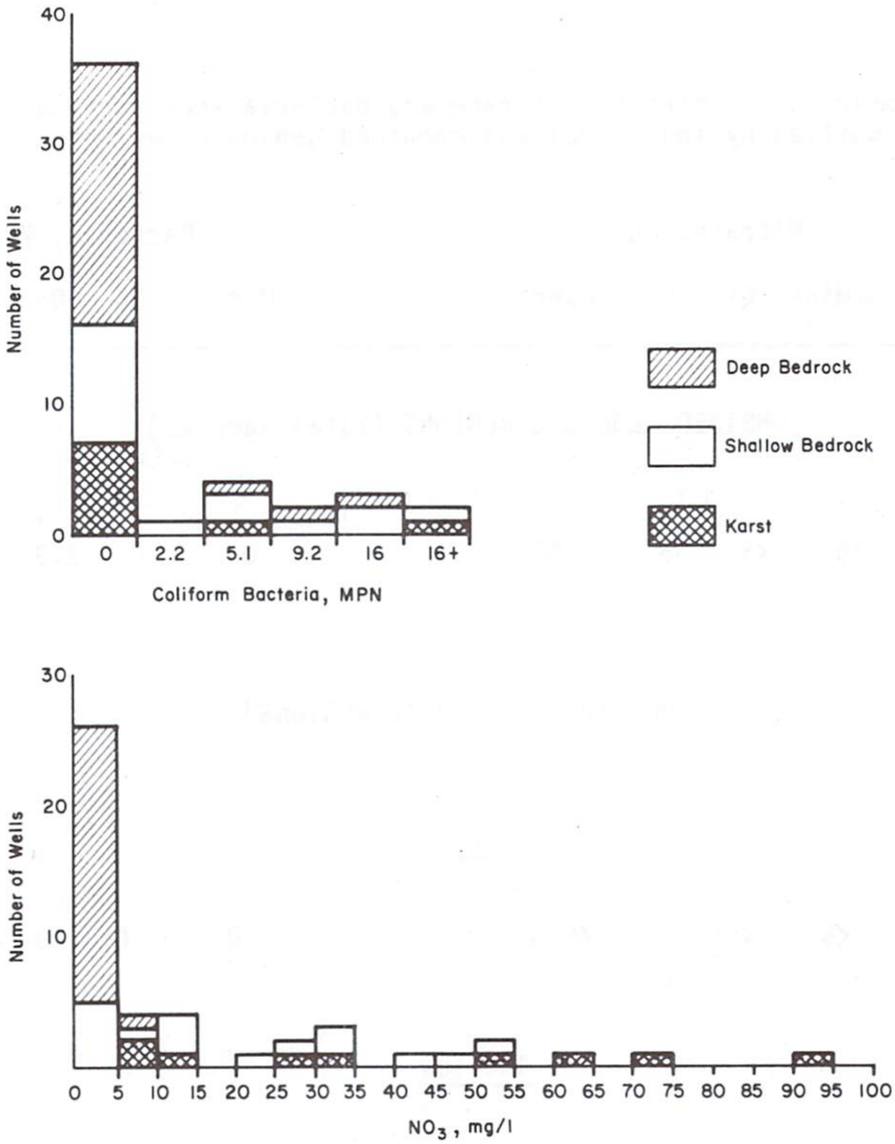

Figure 12. Histograms of nitrate concentrations and coliform-bacteria MPN from inventory groundwater samples.

Bunker, this volume) indicates the shale is absent immediately east of the wells. Existing potentiometric data (figure 8) indicates that wells 6 and 8 are downgradient from the area where the "Rapid shale" is absent. Therefore, surficial contaminants may be infiltrating to the groundwater system in areas where the "Rapid shale" is absent, and delivered to wells 6 and 8 by horizontally-flowing groundwater. One other important geological factor affects the interpretation of the nitrate levels in these wells. While the "Rapid shale" is absent immediately upgradient, depth to bedrock increases to greater than fifty feet over a short distance in the upgradient direction (figure 4). The complex, incompletely defined distribution of permeable and

Table 3. Summary statistics for nitrate and bacteria inventory data classified by individual and combined geologic regions, 12/15/82.

N (Number)	Nitrate, mg/l Median	Q_1	Q_3	Range	Bacteria, MPN Median	Q_1	Q_3	Range
COMBINED GEOLOGIC REGIONS (Total Samples)								
47	<5	<5	33	<5-92	0	0	2.2	0-16+
INDIVIDUAL GEOLOGIC REGIONS[1]								
Deep								
22	<5	<5	<5	<5-6	0	0	0	0-16
Shallow								
16	11	<5	34	<5-51	2.2	0	9.2	0-16+
Karst and Incipient Karst								
9	30	11	66	<5-92	0	0	0	0-16+

[1] Deep, depth to bedrock >50'; Shallow, depth to bedrock <50'; Karst and Incipient Karst, depth to bedrock generally <35'.

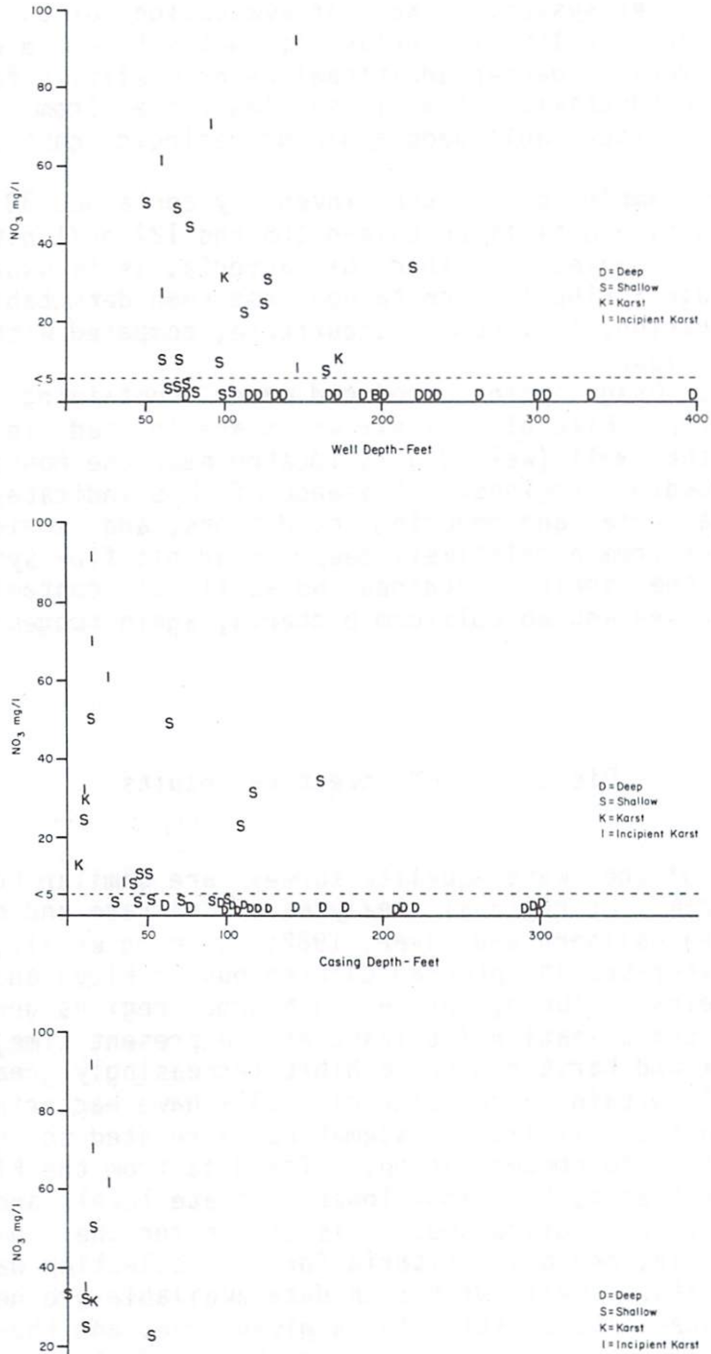

Figure 13. Relationship between nitrate concentration and A. total well depth; B. casing depth in the well; and C. depth to bedrock at well site.

non-permeable units, and the absence of data on vertical-head distributions within the groundwater system, makes an evaluation of the effects of the "Rapid shale" on water-quality inconclusive; wells 6 and 8 were included in the monitoring network to gather additional water-quality data.

The specific conductivity of well samples varied from 330 to 885 μmhos/cm^2. There is no discernable geographic or geologic control on this variation.

Surfacewaters sampled during the inventory contained 38 mg/l to 67 mg/l nitrate. The two tile outlets contained 105 and 127 mg/l nitrate. All surface and tile-water samples contained 16+ bacteria, as is usually the case for such samples. Osage Spring (OS) contained less than detectable nitrate and no bacterial contamination, an uncommon occurrence, compared with other carbonate aquifer springs in Iowa.

Six wells and Osage Spring produced water containing hydrogen sulfide (H_2S) gas (Table 2). Five of the six wells are located in the Deep Bedrock region, and the other well (well 30) is located near the boundary between the Deep and Shallow Bedrock regions. Presence of H_2S indicates the presence of sulfate-fixing bacteria and reducing conditions, and indicates that these wells produce water from a relatively deep, anaerobic flow system. Water from these wells and the spring contained no surficial contaminants; that is, no detectable nitrates and no coliform bacteria, again suggesting a relatively deep flow system.

Discussion of Inventory Results

The results of the water-quality survey are similar to other surveys, well-testing programs, or regional analyses of nitrate and bacteria data in northeast Iowa (see Hallberg and Hoyer, 1982; Hallberg et al., 1983a, b), including a rural water-testing program carried out in Floyd and Mitchell Counties, discussed below. "Deep," protected bedrock regions generally show little or no nitrate contamination (at least at the present time). Less protected Shallow Bedrock and Karst regions exhibit increasingly greater (median) nitrate levels. A certain percentage of wells have bacterial problems, but bacterial contamination is less systematically related to the hydrogeologic setting than is nitrate concentration. The data from the Floyd-Mitchell inventory fit these trends, but show lower nitrate levels and fewer bacteria problems. As previously discussed, wells chosen for the inventory came from the IGS well-log file, and one criteria for well selection was good geologic and construction data. Wells with such data available are generally younger than the bulk of the wells existing in a given area, and therefore, are less likely to have developed problems, such as shallow casing cracks, that would allow for input of surficial contaminants. Such newer wells are generally better constructed and placed with more regard for local contaminant sources than older wells. In this regard, no cisterns were in use with wells inventoried for this project. Cisterns are a major source of bacterial contamination in rural-domestic water supplies (see Hallberg et al., 1983b).

Prior Water-Quality Sampling in Floyd and Mitchell Counties

A large set of data on groundwater quality is provided in the results of a mass rural water-well testing program that was conducted in Floyd County in September and October of 1970 and in Mitchell County during October and November of 1969, and January of 1970 (see Hallberg and Hoyer, 1982, p. 41-43). The sampling programs were directed by the County Extension Directors (Iowa State University, Cooperative Extension Service). The samples were collected by various volunteer groups such as the FFA and 4-H. The water samples were tested for coliform bacteria and nitrates at the Mower County Sanitation Commission laboratory at Austin, Minnesota. Unfortunately, the raw data were not kept and the results were never published but they were summarized on mimeographed sheets and distributed to rural residents.

The summaries simply compared the analytical results to drinking-water standards of zero colonies of coliform bacteria/100 ml, and 45 mg/l nitrate. Some generalizations can be made from the summaries. The summaries can also be grossly related to geologic regions (Table 4).

In Floyd County this data could be divided into three geologic regions; Deep Bedrock, Shallow Bedrock, and Karst (Karst and Incipient Karst of this report). However, in Mitchell County the data could only be divided into Non-Karst (Deep and Shallow Bedrock) and Karst (Karst and Incipient Karst) regions. The data clearly show the trend that has been apparent in all the large regional water-quality data sets (see Hallberg and Hoyer, 1982). Groundwater quality gets progressively worse going from the Deep Bedrock to the Karst regions. This trend is most apparent for nitrate concentration. In Floyd County, for example, the percentage of wells exceeding 45 mg/l nitrate increases from 13% in the Deep Bedrock, to 27% in the Shallow Bedrock areas, and to 38% in the Karst areas. Only a subtle (but consistent) change is apparent in the bacteria data. On a county-wide basis, a comparison can be made with the 1977-1980 UHL data analyzed by Hallberg and Hoyer (1982). These data (Table 4) show very similar results, in relation to the drinking-water standards. Slight increases in the percentages of analyses exceeding standards (1977-80) are evident in the later UHL data. No significant trend can be postulated for these small changes, however, since the Extension study was conducted by canvass methods during fall and winter, whereas the UHL data came from people who wanted their water tested and includes samples from all seasons of the year.

As with the UHL data (see Hallberg and Hoyer, 1982), some of these water-quality problems are undoubtedly contributed by local well construction and water-system problems (such as the use of cisterns). This was assessed in a general way in the Extension study summaries. The wells which failed to meet drinking-water standards were, on the average, more shallow, had less depth of casing, and were older than wells that "passed" standards. Also, for both counties, water from 58% of the wells that had dug pits around the well head failed to meet drinking-water standards. These water samples were not restricted to wells taken from the carbonate aquifers either. A number of wells in non-karst areas that failed to meet standards were noted to be shallow sand-point wells.

These effects are evident when compared with the current IGS inventory samples. The IGS samples were taken only from known bedrock wells which tend to be much younger and better constructed than the average wells. For example, in the IGS inventory data, only 12% exceed 45 mg/l nitrate compared to 22-24% in the UHL-Extension data, and only 25% showed bacterial contamination,

Table 4. Background water-quality data for Floyd/Mitchell County from I.S.U. Cooperative Extension Service samples and UHL samples.

		% of wells in given area with:		
No Samples	% of Total	Bacteria Problems	Nitrate >45 mg/l	Both NO_3 Bacteria
FLOYD COUNTY				
1977-1980 UHL data from Hallberg and Hoyer (1982)				
307	100	37	23	
1970 Extension Sampling Total				
251	100	29	24	21
Deep Bedrock Areas				
55	22	27	13	10
Shallow Bedrock Areas				
158	63	28	27	24
Karst Areas				
38	15	31	38	36
MITCHELL COUNTY				
1977-1980 UHL data from Hallberg and Hoyer (1982)				
262	100	41	24	
1969-70 Extension Sampling				
434	100	35	22	45
Non-Karst Areas				
178	41	30	10	
Karst Areas				
256	59	39	28	

compared to 29 to 41% in the UHL-Extension data. Thus, as emphasized, the IGS data are more clearly removed from the local environmental problems, and more clearly reflect conditions in the aquifer.

MONITORING DATA

A variety of chemical parameters were monitored at various surfacewater and groundwater sites during the period between December 1982 - December 1983. Climatic data from Osage and Charles City and discharge records for the Cedar River at Charles City were also compiled. A description of the monitoring network and the results of monitoring are presented in this section. A comparison of the results of the Floyd-Mitchell Study with data from the Big Spring area of Clayton County is included, as the basis for an analysis of regional hydrology and water quality.

Climatic Data

Climatic data for the Floyd-Mitchell Study was compiled from the Charles City and Osage weather stations (provided by Mr. Paul Waite, State Climatologist, Iowa Department of Agriculture). Monthly and annual precipitation, and average monthly temperatures for both weather stations are listed in Table 5, along with long-term averages. Of the two weather stations, Osage is more centrally located within the study area and therefore was selected as best representing average climatic conditions throughout the area. (Daily precipitation and temperature extremes from the Osage weather station are illustrated in figure 14.)

For the water-year October 1982 through September 1983, precipitation at the Osage weather station was 46% greater than the the long-term average, and at Charles City 32% greater. Total precipitation varied only 2.5% between the two weather stations, indicating precipitation as a whole was relatively uniform over the study area.

The distribution of monthly precipitation during the study was somewhat abnormal. In September, 1983, 7.9 inches of rain fell, representing 20% of the total precipitation during the 1983 water-year. The fall months of 1982, October through December, were also exceptionally wet, with 28% of the year's precipitation occurring over these three months. Comparatively, the long term averages for October through December, and the month of September, are 16% and 12%, respectively. During an average year, the majority of the precipitation in Osage occurs during the summer months (June-August), as shown in Table 5, under long-term averages.

In general, daily maximum and minimum temperatures were near normal. The only exception was the winter months (December-February) which were relatively warm (6°-8°F above average). Temperature variations between Osage and Charles City were minimal, with Charles City readings usually 1-2°F warmer then Osage.

Hydrologic Monitoring

Discharge data for the Cedar River at Charles City were obtained from the U.S. Geological Survey, and the discharge hydrograph for the Cedar River is shown on figure 14. The drainage area of the Cedar River at Charles City is 1,054 square miles (2,730 sq. km) and the average discharge from the twelve year period ending 1976 was 687 cubic feet per second (cfs; 19.5 cms) (Lara, 1979). Comparison of the Charles City discharge data with downstream gaging stations that have a longer period of record suggests the long-term average discharge at Charles City is probably lower, and on the order of 500 cfs (14.2

Table 5. Monthly climatic data for Charles City and Osage, Iowa (Oct. 1982 - Nov. 1983)

	CHARLES CITY				OSAGE			
	Precipitation in (mm)		Temperature F°(°C)		Precipitation in (mm)		Temperature F°(°C)	
1982	Total	Longterm Average	Average	Longterm Average	Total	Longterm Average	Average	Longterm Average
OCT	3.73 (94.7)	2.23 (56.6)	52.0 (11)	53 (12)	3.97 (100.8)	2.10 (53.3)	51 (11)	51 (11)
NOV	2.96 (75.2)	1.28 (32.5)	34 (1)	35 (2)	3.40 (86.4)	1.19 (30.2)	33 (0.6)	35 (2)
DEC	M	M	M	M	3.7 (94.0)	1.04 (26.4)	27 M (-3)	21 (-6)
1983								
JAN	0.82 (20.8)	0.84 (21.3)	23 (-5)	14 (-10)	1.19 (30.2)	0.88 (22.4)	21 M (-6)	13 (-11)
FEB	1.40 (35.6)	0.92 (23.4)	27 (-3)	21 (-6)	1.87 (47.5)	0.92 (23.4)	27 (-3)	20 (-7)
MARCH	2.81 (71.4)	2.17 (55.1)	35 (2)	32 (0)	2.04 (51.8)	2.24 (56.9)	34 (1)	31 (-0.6)
APRIL	3.28 (83.3)	3.34 (84.4)	43 (6)	48 (9)	3.22 (81.8)	2.95 (75.0)	42 (6)	47 (8)
MAY	8.62 (219.0)	4.10 (104.1)	55 (13)	60 (16)	6.92 (175.8)	3.91 (99.3)	55 (13)	60 (16)
JUNE	6.01 (152.7)	4.67 (118.6)	69 (21)	0 (-22)	4.39 (11.5)	4.48 (113.8)	69 (21)	68 (20)
JULY	2.21 (56.1)	4.21 (106.9)	76 (24)	73 (23)	1.48 (37.6)	4.43 (112.5)	76 (24)	72 (22)
AUG	3.23 (82.0)	4.13 (104.9)	77 (25)	71 (22)	M	M	M	M
SEPT	6.03 (153.2)	3.28 (83.3)	63 (17)	62 (17)	7.90 (200.7)	3.3 (83.8)	63.0 (17)	61 (16)
12 MONTH SUMMARY								
	41.10 (1,044.0)	31.17 (791.5)			40.08 (1,015.1)	27.53 (696.7)		
1983								
OCT	3.03 (77.0)	2.23 (56.6)	51 (11)	53 (12)	3.42 (86.9)	2.10 (53.3)	50 (10)	51 (11)
NOV	4.5 (114.3)	1.28 (32.5)	37 (3)	35 (2)	4.12 (104.6)	1.19 (30.2)	36 (2)	35 (2)

M -- Insufficient or partial data. M is appended to average and/or total values computed with 1-9 daily values missing. M appears alone if 10 or more daily values are missing.

cms) (Tom Dahl, U.S.E.P.A., personal communication). The average discharge during water year 1983 was 1,556 cfs (44.1 cms), well above the average, reflecting the greater than normal precipitation during the year of study, as well as wet antecedant conditions; average discharge for water year 1982 was 1,187 cfs (33.6 cms), also well above average.

The discharge hydrograph for the Cedar River shows several distinctive seasonal trends. Fall/early winter and spring/early summer are marked by high discharges generated by rainfall during these periods of low evapotranspiration. Mid-February through mid-March was also a high discharge period, reflecting snowmelt. Prior to snowmelt, frozen conditions cause a recession of discharge levels. A similar baseflow recession occurs during summer, caused by high evapotranspiration and low precipitation. During these baseflow periods, virtually all of the water in the Cedar River is groundwater discharge. During a typical year, about 64% of the Cedar River discharge is supplied by groundwater; in water year 1983, an estimated 54% of the discharge was groundwater, as estimated from baseflow recession, hydrograph separation methods (Oscar Lara, U.S.G.S., personal communication). Figure 15 shows the discharge hydrographs of the Cedar River at Charles City, the Turkey River at Garber, and Big Spring, the latter sites being located in Clayton County (see Hallberg et al; 1983b). Drainage basins for the above systems are 1,054, 1,545, and 103 square miles (2,730, 4,000, and 267 sq. km), respectively. The Floyd-Mitchell area lies about 80 miles (130 km) west of the Clayton County gaging sites. Despite the differences in drainage basin sizes and separation of the basins by 80 miles (130 km), a comparison of discharge hydrographs indicates that the overall seasonal trends, as described above, are strikingly similar; only the magnitude of discharge and small details of timing differ appreciably.

Water-Quality Monitoring Network

Following the initial water-quality inventory (conducted 12/15/82), 21 sites were selected for continued monitoring throughout 1983. These sites include 16 wells, 2 surfacewater sites, 2 tile line outlets, and Osage Spring. As monitoring progressed, 3 wells and the Cedar River were added to the network. This provided a total of 25 monthly monitoring locations. The locations of the monitoring network sites are shown on figure 16. The well-network well sites were chosen to represent a variety of geologic and hydrologic conditions within the study area. Major considerations in the well-network site selections were geographic distribution throughout the geologic regions, and avoidance of any obvious well construction problems. Where possible, wells that were known to be completed above or below the "Rapid shale" were included to try to examine stratigraphic controls on groundwater quality. Osage Spring (OS) and flowing artesian well (#16) (figure 16) were included to monitor water quality from depth within the Devonian aquifer in the discharge zones along the Cedar and Little Cedar Rivers.

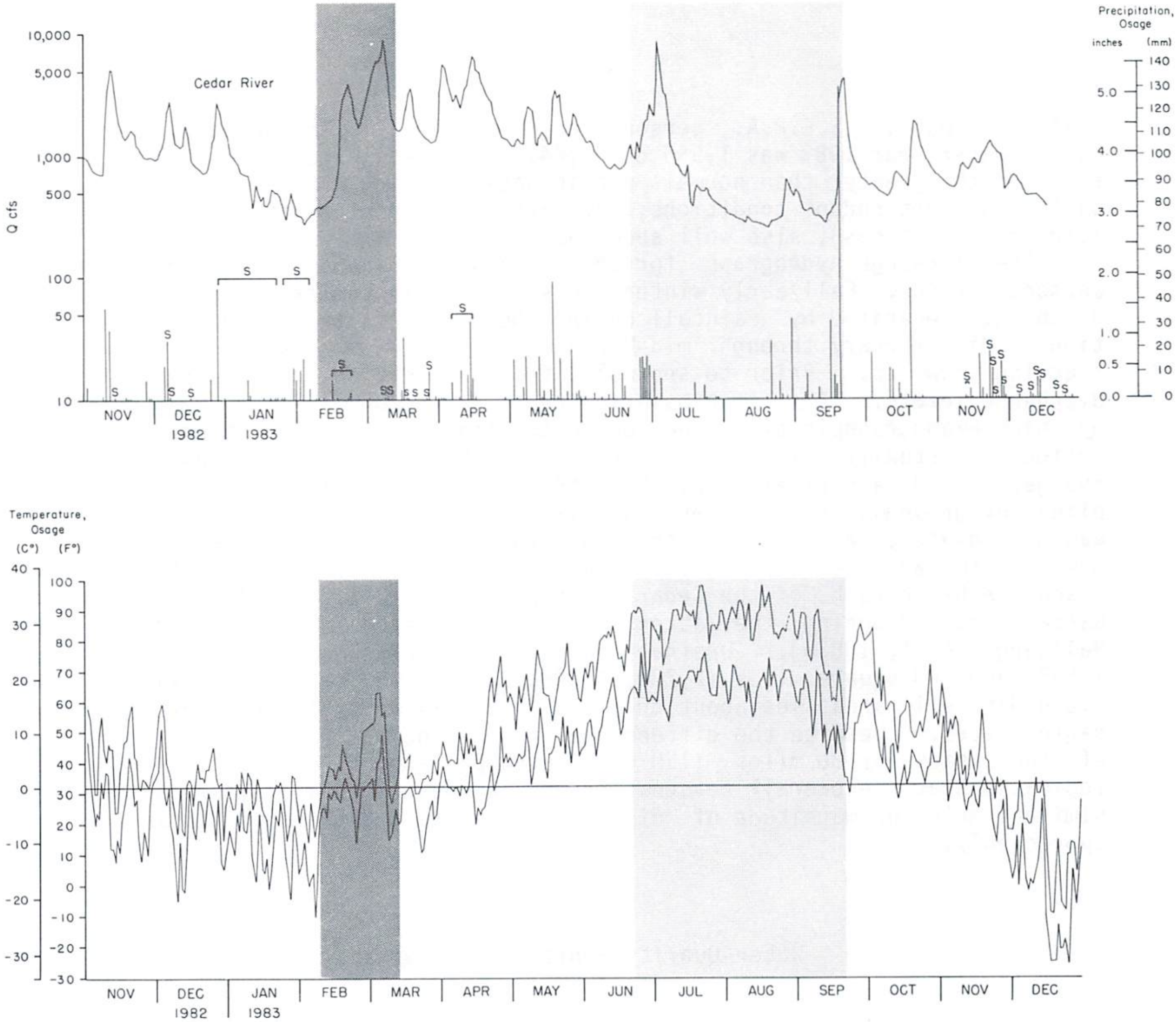

Figure 14. Discharge hydrograph for the Cedar River at Charles City; precipitation and daily minimum and maximum temperatures at Osage. Dark shading outlines snow-melt period; lighter shading outlines summer (growing-season) recession period. S over precipitation bar indicates that precipitation occurred as snow; plotted as water-equivalent.

Water-Quality Monitoring

A variety of water-quality parameters were monitored during the period of study in 1983. All the water-quality data from the monitoring-network sites are tabulated in Appendix 1, listed by site number, and then by date. Water-quality data from samples collected from other miscellaneous sites are tabulated in Appendix 2.

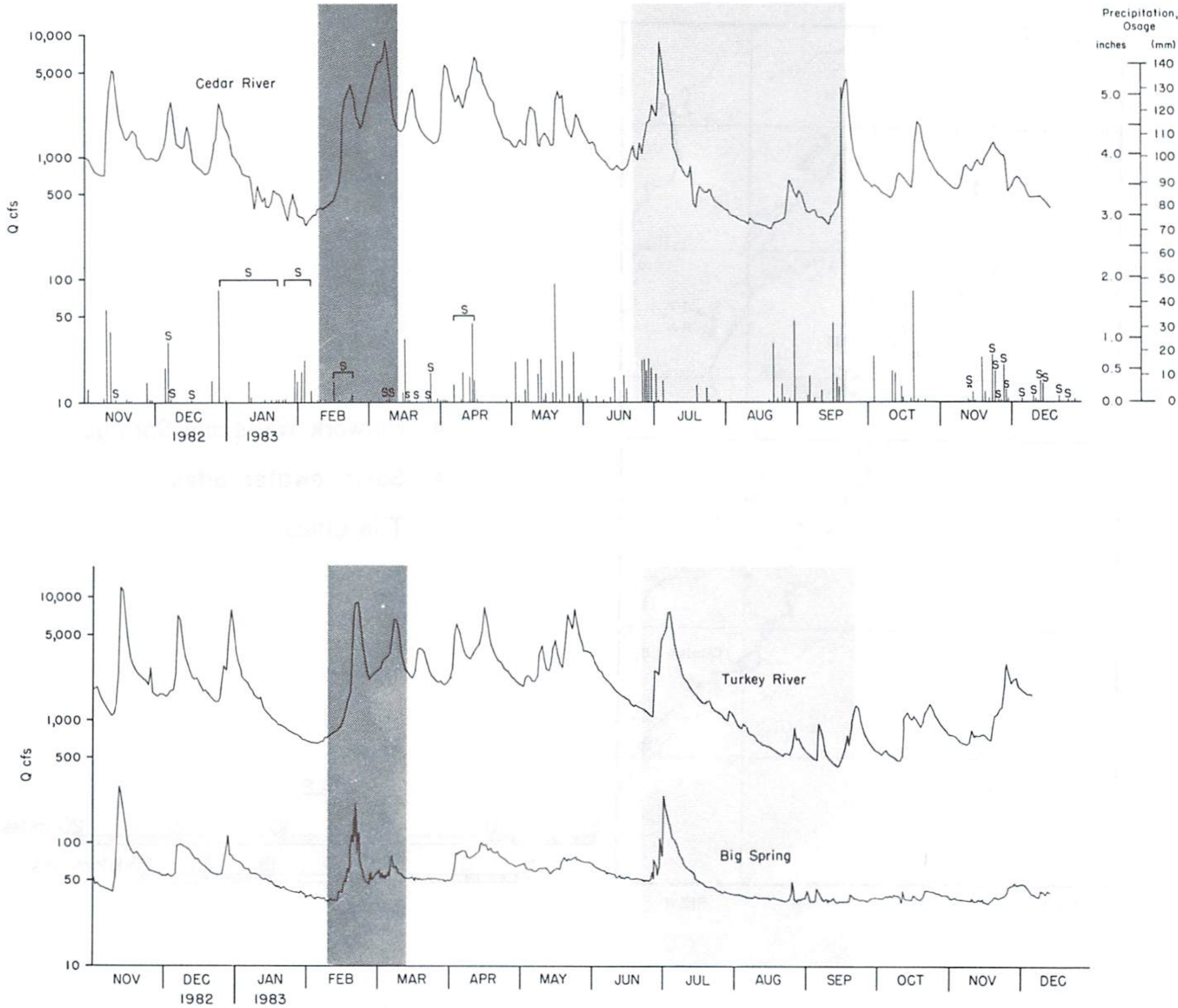

Figure 15. Discharge hydrographs for the Cedar River at Charles City, the the Turkey River at Garber, and Big Spring.

Samples for nitrate and bacteria analyses were collected approximately on a monthly basis at each monitoring site, along with field measurements of temperature and conductivity. The network was sampled four times for pesticides over the sampling period, once in spring, twice over the summer, and once again in fall. Pesticide samples were also collected during five additional months from selected wells, tile lines, and surfacewaters. Samples for analysis of mineral scans, dissolved metals, and radon were collected once. The following sections discuss the results of these water-quality analyses.

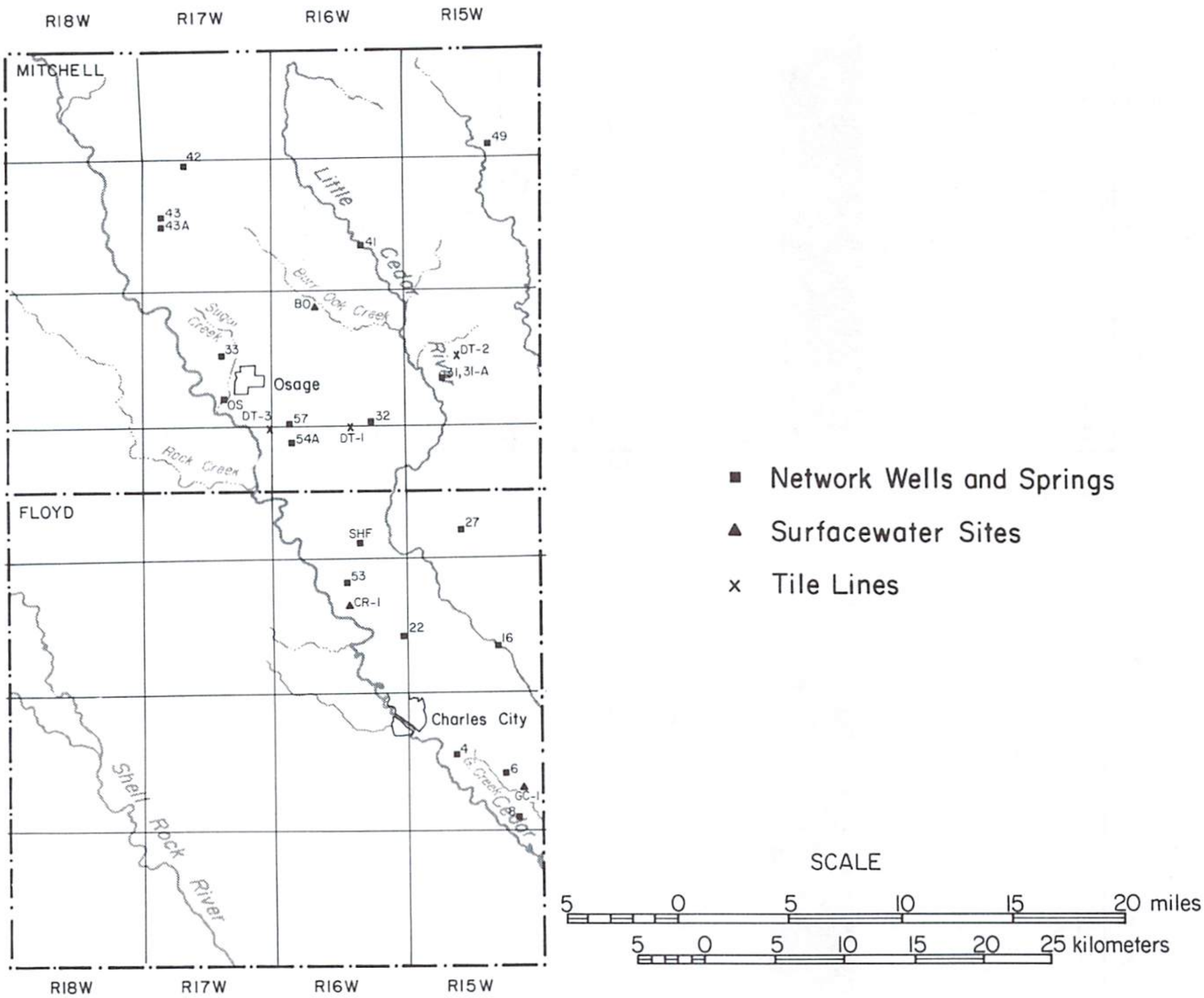

Figure 16. Location of monthly-monitoring water-quality sites.

Nitrate Analyses

Summary statistics from the monthly monitoring of individual network wells are tabulated in Table 6. Table 7 summarizes these data by geologic regions for the water-year, and also summarizes the data from tile lines and surfacewater sites. A total of 277 samples were analyzed for nitrates; including 223 groundwater samples and 54 samples from surfacewater and tile-line sites.

Monthly nitrate levels from the Deep Bedrock region are clearly differentiated from those present in the less protected regions. The mean nitrate concentration from all Deep Bedrock wells is <5 mg/l, the detection limit for the standard nitrate analysis at UHL. More detailed analyses (major ion analyses from mineral scans) indicate nitrate levels in the Deep Bedrock region range from 0.2 to 5 mg/l. The monitoring results are consistent with the data from the water-quality inventory of this area. The results are also consistent with the monthly monitoring of similarly "protected" wells in the Big Spring area of Clayton County and other areas in northeastern Iowa (Hallberg et al., 1983a, b; Hallberg and Hoyer, 1982); in both areas, any seasonal increases or fluctuations in nitrate levels are not noticable, using a 5 mg/l detection limit.

Monitoring results from the less protected regions show elevated nitrate levels, relative to the Deep Bedrock region. Mean concentrations for all wells in the Shallow Bedrock, Karst, and Incipient Karst regions were 22 mg/l, 41 mg/l, and 68 mg/l, respectively (Table 7). The significantly higher mean nitrate concentration of groundwater in the Incipient Karst area relative to the "open" Karst area may be, in part, a function of the small number of sampling points involved (5 Karst region wells and 4 Incipient Karst wells). The various miscellaneous samples collected (see Appendix 2) support these differences, however. These data do serve to show, as have prior studies (Hallberg et al; 1983a), that delivery of nitrate to a karst-carbonate aquifer is mainly an infiltration process, and therefore does not require the presence of open sinkholes. Both the "open" Karst and Incipient Karst regions are areas of high infiltration where contamination of groundwater by nitrate (and other surficially-derived, soluble and thus, leachable chemicals) may occur. The above discussion is also applicable to the Shallow Bedrock region. As mentioned, the mean of monthly nitrate levels in this geologic region is lower than those in the Karst regions (Tables 6, 7, and 8), a reflection of the thicker protective cover present in some parts of the Shallow Bedrock region. The Shallow Bedrock area was defined as having a maximum of 50 feet (15 m) of Quaternary deposits over bedrock, while in the Karst areas bedrock is often within 25 feet (7.5) of the surface.

Mean nitrate concentration and ranges from monthly sampling of surface-waters and tile lines are also given in Table 7. In this area the tile lines are generally 2-4 feet (0.5-1.2 m) below the land surface, and samples of tile discharge are good indicators of the quality of downward moving, shallow-groundwater recharge in agricultural areas. The mean and range of nitrate concentrations is similar to, although somewhat higher than, the means and ranges from well samples in the Karst/Incipient Karst regions. While this similarity must be viewed in light of the small number of sampling sites involved, it again indicates the utility of using tile-line effluent as proxy indicators of the chemical quality of shallow groundwater which is delivered to the groundwater system by infiltration processes.

Monthly monitoring of the network wells in the Karst-Incipient Karst-Shallow Bedrock regions shows that wide variations in nitrate concentrations occur in groundwater, among individual wells located within the same geologic region (Table 6-8). For example, the mean of monthly samples for individual wells within the Shallow Bedrock region varies from 6 mg/l at site 32, to 53 mg/l at site 41. A more striking example of this variability occurs between two Karst region wells. The highest mean nitrate concentration for a Karst region well was 76 mg/l at site 54-A, while the lowest was 17 mg/l at site 57; these wells supply adjacent farms, and are located about 1000 feet (300 m) apart. The range of monthly nitrate levels at site 54-A was 34-119 mg/l, but only 16-23 mg/l at site 57. Relatively high, variable nitrate concentrations, such as these from site 54-A, generally correspond to wells intersecting the more open, solutionally enlarged parts of the karst-carbonate aquifer. Relatively low, stable nitrate levels, such as from site 57, are common in wells

Table 6. Summary statistics for nitrate data (mg/l) for monthly monitoring network wells by geologic region.

Site No. Wells	Mean	s. d.	Range mg/l
DEEP			
16	<5	0	0.2 - <5
27	<5	0	0.4 - <5
31	<5	0	<5 - 5
31-A	<5	0	0.2 - <5
SHALLOW			
4	11	2	6 - 13
6	34	2	32 - 38
8	19	4	8 - 23
32	6	4	<5 - 13
41	53	4	45 - 58
49	11	4	7 - 20
KARST			
22	52	5	43 - 58
53	29	4	22 - 33
54-A	76	30	34 - 119
57	17	2	16 - 23
SHF-A	27	5	19 - 32
INCIPIENT KARST			
33	26	0.8	25 - 28
42	65	4	57 - 71
43	82	8	71 - 92
43-A	116	27	56 - 132

Table 7. Summary statistics for Water-year 1983.

Geologic Regions		NO_3 mg/l		BACT MPN	
Wells	No. Samples	Mean	Range	Md.	Range
DEEP	44	<5	0-5	0	0-9.2
SHALLOW	66	22	<5-58	0	0-16+
KARST	44	41	16-119	5.1	0-16+
INCIPIENT KARST	40	68	25-132	0	0-16+
TILE LINES	19	74	42-127	Not Applicable	
SURFACEWATER SITES	32	30	<5-67	Not Applicable	

producing groundwater from minor fractures that have not been significantly enlarged by carbonate dissolution. The water-quality differences between these well waters, both of which lie in close proximity to open sinkholes, underscore the complexity of karst-carbonate aquifer hydrogeology. Wells which tap groundwater from more open parts of the aquifer (e.g., 54-A) show wide variations in water-quality related to such things as short-term influxes of surfacewater into the groundwater system.

Monthly sampling at Osage Spring consistently produced nitrate concentrations of less than 5 mg/l. A single more precise analysis indicated 0.4 mg/l nitrate. The consistently low nitrate concentrations in the water at this site indicate the spring is a discharge point for a relatively deep, protected flow system. General head relationships suggest that Osage Spring is discharging groundwater from the deep, "lower aquifer" (Spillville Formation; see figure 6).

The median nitrate concentration for network surfacewater sites was 30 mg/l. The median nitrate concentration at Burr Oak Creek, in the northern part of the area was 42 mg/l, and at Goose Creek, in the southern part of the area 23 mg/l. The difference in nitrate levels at these sites may relate to several factors. Burr Oak Creek drains the large, relatively flat divide between the Cedar and Little Cedar Rivers, an area that is extensively row-cropped. Goose Creek flows subparallel and relatively close to the Cedar River, and drains an area with greater topographic relief, which contains more woodlots, pastures, etc., and less intensive row-crop agriculture, relative to Burr Oak Creek. Goose Creek's basin likely receives less chemical fertilizer than does Burr Oak Creek's basin.

Table 8. Monthly summary statistics of nitrate and bacteria for network wells, subdivided by geologic regions (Md-median).

Date	NO_3 mg/l								Bacteria MPN							
1982	DEEP		SHALLOW		KARST		INCIPIENT KARST		DEEP		SHALLOW		KARST		INCIPIENT KARST	
	Md	Range	Md	Range	Md	Range	Md	Range	Md	Range	Md	Range	Md	Range	Md	Range
12/14	<5	<5-10	23	8-27	30	23-50	61	27-92	0	0-9.2	2.2	0-9.2	16+	0-16+	0	0
1983																
2/26	<5	<5-8	20	<5-57	28	23-34	66	26-81	0	0-2.2	0	0-9.2	9.2	0-16+	16+	0-16+
4/4	<5	<5-9	18	11-52	37	19-110	63	27-92	0	0	0	0-2.2	9.2	0-16+	2.2	0-2.2
4/17	3	0.2-8	17	13-47	37	17-119	57	26-92				No Analyses				
5/31	<5	<5-8	12	8-56	30	16-85	76	26-132	0	0-2.2	0	0-16	16+	0-16+	5.1	0-16+
7/6	<5	<5-9	15	5-53	26	27-113	74	26-129	0	0	0	0-2.2	9.2	0-16+	2.2	0-16+
8/2	<5	<5-12	21	<5-54	26	16-55	69	26-127	0	0	0	0	5.1	0-16+	0	0-2.2
8/30	<5	<5-7	22	<5-53	46	27-56	71	26-120	0	0	0	0-5.1	16+	0-16+	0	0
9/27	<5	<5-18	22	<5-58	45	32-70	62	27-82	0	0	16	0-16+	9.2	0-16+	2.2	0-16+
10/27	<5	<5-20	22	6-50	44	17-66	75	28-122	0	0	0	0-16+	16	0-16+	2.2	0-16+
12/6	<5	<5-15	18	<5-45	29	18-46	69	25-123	0	0	0	0-16+	5.1	0-16+	2.2	0-16

Samples of Cedar River water had a mean nitrate concentration of 27 mg/l. The Cedar River is one of the master streams that act as discharge zones for the Devonian aquifer, and samples from the river serve as good indicators of regional groundwater quality. Thus, the monthly sampling record from the river is used as the starting point for an analysis of temporal trends within the components of the hydrologic system.

Temporal Trends in Nitrate Concentrations

Figure 17 shows the discharge and nitrate concentrations for the Cedar River. The nitrate data show seasonal changes similar to those seen elsewhere in northeastern Iowa (Hallberg et al., 1983b): nitrate concentrations are low in the late-winter and snowmelt period, they increase during spring and early summer, and decrease during late summer. Nitrate concentrations increase again in fall, but recede somewhat with very cold, early winter conditions. These trends in nitrate concentrations correlate to the overall trends in discharge. River discharge is high during spring when significant amounts of precipitation becomes infiltration. The infiltrating water leaches nitrate from the soil and delivers the nitrate to the groundwater system. Groundwater discharges to the Cedar River, forming the baseflow of the river. During the late summer growing season, high evapotranspiration potential inhibits infiltration, and therefore nitrate leaching, and thus both nitrate levels and discharge in the Cedar River recess. During fall, much lower evapotranspiration caused by cooler temperatures and especially decreased plant-water requirements allows precipitation to again infiltrate and leach nitrates.

Table 8 summarizes the well network nitrate data on a monthly basis, by geologic region. Figure 18 shows the monthly median and quartiles of the nitrate concentrations from the well network, with the Cedar River data for comparison. (Unfortunately, as noted in the Appendix, the February 6, 1983 data had to be dropped from the record because of likely analytical problems.) Monthly variations in the aggregate well data statistics are subtle (in part because of the well-selection criteria), but show the same general trends as the river with higher nitrate concentrations occurring in spring/early summer and fall, and lower concentrations occurring during late-summer and winter.

Monthly median nitrate concentrations for the network wells only varied from 17 to 27 mg/l. The first quartile of the well-groundwater data is strongly influenced by Deep bedrock region wells, and was above detection limits only for samples collected between 4/4 and 7/5. The third quartile is influenced by Karst/Incipient Karst regions wells, and exceeds the 45 mg/l nitrate drinking water standard for samples collected between 5/31 and 10/28.

Figure 19 shows nitrate concentrations from Goose Creek, Burr Oak Creek, and the tile lines, again with the Cedar River data for comparison. The same seasonal trends in nitrate levels are present in these components of the hydrologic system. The late summer data (8/2-30/83) are especially compelling. Tile lines stopped flowing, indicating that soil moisture was low, and shallow water tables had dropped below the shallow soil horizons where much of the nitrate (and its source) is contained. Small streams such as Burr Oak and Goose Creek, which derive their baseflow from the shallow groundwater system, show dramatic decreases in nitrate concentrations. Master streams, such as the Cedar River which act as groundwater discharge zones, also show a large decrease in nitrate concentration. The overall drop in nitrate levels is also reflected in groundwater from well samples, the least responsive part of the hydro-

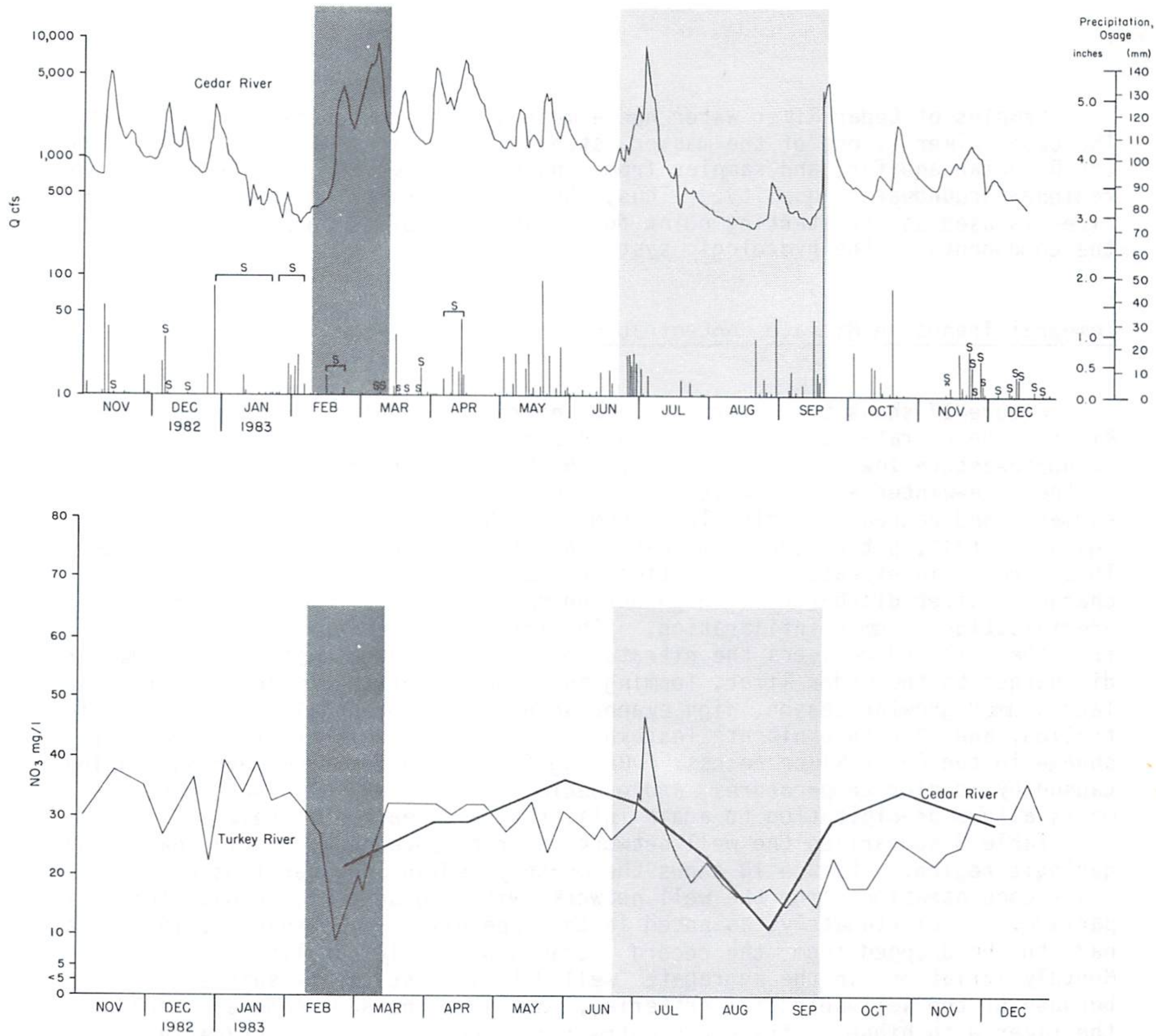

Figure 17. Cedar River discharge hydrograph and nitrate concentrations in the Cedar River and Turkey River (at Big Spring).

logic system. Similar trends for all parts of the hydrologic system were noted by Hallberg and other (1983b) in the Big Spring area. While the magnitude and details of these trends will vary with geologic setting and climatic conditions, the overall seasonal response of nitrate levels in soil water, groundwater, and surfacewater appears to be consistent.

Figure 17 also shows the nitrate concentrations over time for the Cedar River, and the Turkey River (at Big Spring) for the year of study, along with the Cedar River discharge hydrograph. As previously discussed the discharge records from these areas are strikingly similar. The nitrate concentrations from these sites are equally comparable, showing the same seasonal trends, and are quite similar even in magnitude. The similarity in hydrologic and water-

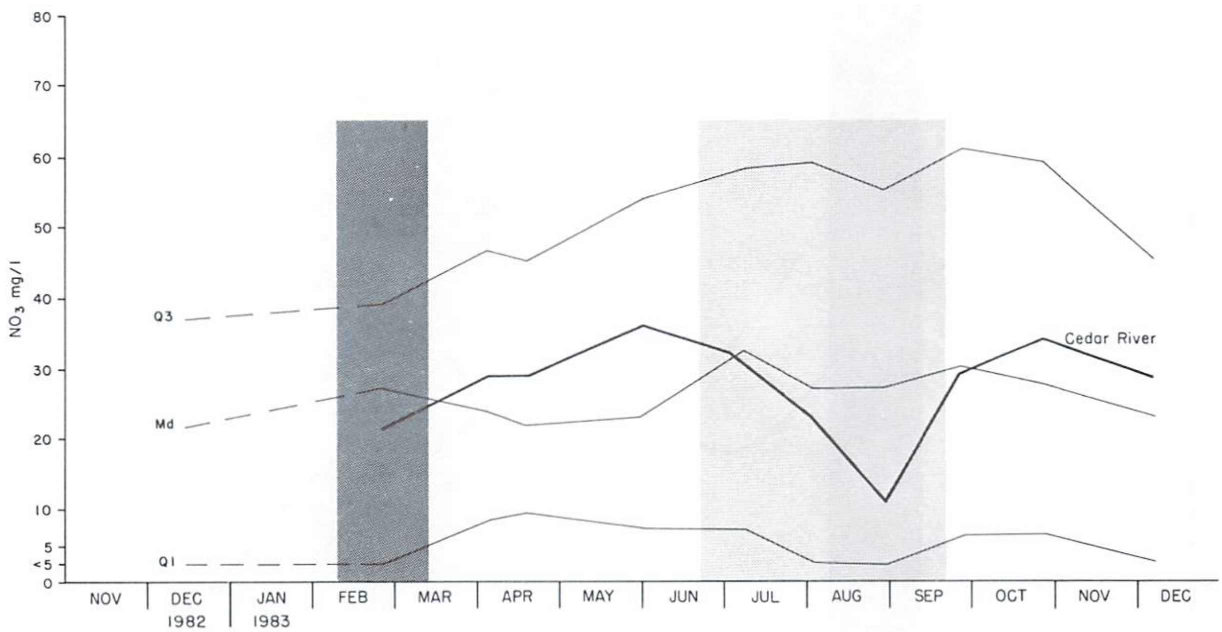

Figure 18. Median and quartile nitrate concentrations from the well-monitoring network and the nitrate concentration in the Cedar River.

quality responses between the Big Spring area and the Floyd-Mitchell County region further reinforce the broad applicability of the finding from these various studies to the whole of the karst-carbonate aquifer regions.

Bacteria Monitoring

Table 6 summarizes coliform-bacteria concentrations for network well samples by geologic region. Median bacteria levels, were zero for all geologic regions except the Karst region. The direct connection between the open parts of the aquifer and the land surface in the Karst area gives surficially-derived bacterial contaminants an open pathway into the aquifer, causing elevated levels of coliform bacteria in the Karst area wells (see also, Hallberg et al., 1983b). Table 8 is a summary of monthly bacteria data from the well network. The median bacteria MPN for Deep Bedrock region wells was consistently zero, and Shallow Bedrock region wells exceeded zero only twice. The open nature of the Karst region is reflected in the monthly summary statistics; monthly medians for bacteria in the Karst region wells consistently exceeded 5.1 MPN. Incipient Karst region wells generally showed MPN of 0 or 2.2, with occasional higher values. There is some correspondence of high coliform counts with periods of higher nitrate levels and wet-runoff periods, but no significant seasonal trend is apparent in the data.

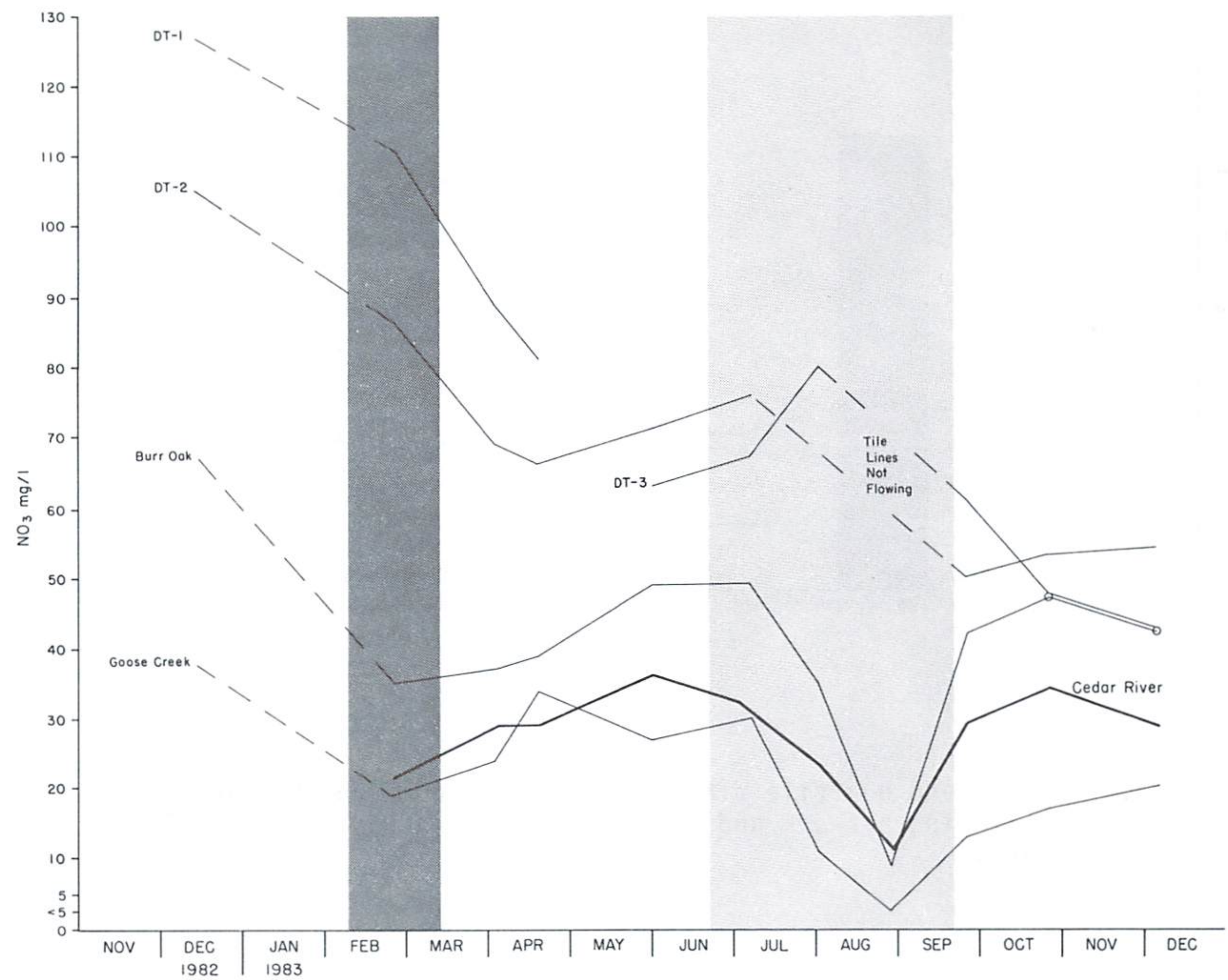

Figure 19. Nitrate concentrations from surfacewater and tile-line monitoring sites and the Cedar River.

Pesticide Monitoring

Pesticide data accumulated during this study are tabulated in Tables 9, 10, and 11, and Appendices 1 and 2. In total, 121 water samples (and 4 soil samples) were analyzed for pesticides. Ninety-three samples were from groundwater from wells and springs; 44% of these samples contained detectable pesticides. Eleven samples of tile line discharge were analyzed, all of which contained detectable pesticides. Of 17 surfacewater samples, 88% contained detectable pesticides.

Table 9 summarizes the pesticide data for samples collected from network wells, by geologic regions. Pesticides were not detected in Deep Bedrock region well samples during the course of monitoring, with the exception of one sample collected on 8/2, from site 31-A. This well was drilled as a replacement for well 31, is located about 20 feet from well 31, and is of generally similar depth and construction. The sample that contained pesticides was col-

Table 9. Summary of pesticide analyses from network wells in Floyd and Mitchell Counties in μg/l (micrograms per liter).[1]

Well Sites/ Geologic Region	2/26	4/3	4/18	5/31	7/6	8/2	9/27	10/27	12/6
DEEP BEDROCK: >50' Depth to bedrock									
16	*	*	ND	ND	ND	ND	*	ND	*
27	*	*	ND	*	ND	ND	*	ND	*
31	*	*	ND	*	ND	*	*	*	*
31-A	*	*	*	*	*	0.29B	*	ND	*
SHALLOW BEDROCK: <50' Depth to bedrock									
4	*	*	0.34A	0.38A	0.25A	0.31A	*	0.39A	*
6	0.19A	0.12A	0.15A	*	0.46A	0.85A	*	0.68A	0.51A
8	*	*	ND	ND	ND	ND	*	ND	*
32	*	*	ND	*	ND	0.12A	*	0.16A	*
41	*	*	ND	*	ND	ND	*	ND	*
49	*	*	0.21A	*	ND	0.25A	*	0.10A	*
KARST									
22	*	*	0.15A	ND	ND	ND	*	0.25A	0.1A
53	*	*	ND	0.10L 0.09S	0.10A 0.15S	ND	*	ND	*
54-A	ND	1.20S	1.50S	1.1S	1.00S	0.17S	*	1.80S	*
57	*	*	*	*	*	0.17A	*	ND	*
SHF-A	*	*	*	*	ND	ND	*	*	ND
INCIPIENT KARST									
33	*	*	0.10A 0.12B 0.11D	*	ND	ND	*	ND	*
42	*	*	3.30L 1.20S	*	9.50L 0.24B 1.70S	7.50L 0.23B 1.20S	16.60L 0.45B 4.0S	16.00L 0.48B 4.35S	13.00L 0.41B 4.30S
43	ND	ND	ND	ND	ND	ND	*	ND	*
43-A	*	*		*	ND	ND	*	ND	*

[1] All analyses expressed in micrograms/l (parts per billion): A--Atrazine; L--Lasso; S--Sencor; B--Bladex; R--Furadan; D--Dual; ND--None detected.

* No sample taken.

lected from well 31-A about two weeks after the well was drilled. Samples from well 31 showed no detectable pesticides during two prior samplings. Another sample from well 31-A (10/27) also contained no detectable pesticides. The sample which showed detectable pesticides may reflect contamination arising during drilling and finishing of the well. Samples from four of the six Shallow Bedrock region network wells had detectable levels of pesticides at least once during the year. Atrazine was the only pesticide found in these groundwater samples, at concentrations ranging from 0.10 to to 0.85 µg/l. There are no sinkholes adjacent to or upgradient from these wells, and thus the pesticides detected must have been delivered to groundwater through infiltration processes.

Pesticides were detected at least once in four of the five Karst region wells, with site SHF-A being the exception (Table 9). Samples from three of the four wells contained atrazine; two wells also showed Sencor, a common soybean herbicide. Relatively high concentrations of Sencor, generally above 1 µg/l, were noted at site 54-A. Evidence previously discussed indicated this well intersects a relatively open part of the karst aquifer. Reported turbidity problems during wet periods of the year indicate this well receives some surface runoff via the karst system. Runoff commonly contains high levels of pesticides, relative to infiltration, and runoff recharge may account for the high Sencor concentrations from this well (runoff would include surfacewater baseflow as well as stormflow). This is supported by the low concentrations (0.17 µg/l) observed in August, following a hot, dry period where little recharge occured. The water produced by the well in August originated as infiltration during a prior recharge event, and was delivered to the well through the more diffuse-flow parts of the aquifer. Concentrations at other Karst region wells ranged up to 0.25 µg/l total pesticides.

Two network wells from the Incipient Karst region produced samples with detectable pesticides (Table 9). A wide variety of pesticides were present in samples from these wells, including atrazine, Bladex, Lasso, Sencor and Dual. The pesticide concentrations in groundwater from well-site 42 in the Incipient Karst area have been unusually high, with Lasso concentrations ranging from 3.3 to 16.6 µg/l, and total pesticide concentrations ranging from 4.5 to 21.0 µg/l (Table 9). The highest concentrations of total pesticides in groundwater detected by prior sampling in northeast Iowa (Big Spring's area and Dutton's Cave Spring) range from about 6 to 17 µg/l, but these occurred during very short-lived events involving surface runoff. Site 42 exhibits these concentrations year round. There have been no known siphoning accidents or spills in the area. (The year-round persistence argues against such a short-term effect.) The well construction and placement are optimal to avoid contamination. The well is located in a high area in the grassy lawn around the farmhouse. No seepage can get to the well and it is well-constructed. However, it is only 50 feet deep (15 m), and depth to rock in the immediate area ranges from 5 to 25 feet (1-7 m) . The static water level in the aquifer is only 10-15 feet (3-5 m) below landsurface.

The monthly changes in pesticide concentrations at site 42 mimics the seasonal changes in nitrate concentrations, and thus suggests that infiltration is the primary mechanism delivering the pesticides to the groundwater. Also, the three pesticides present in the groundwater (Lasso, Sencor, and Bladex) are the same pesticides that the farm operator had used on the surrounding soybean fields for the past two years.

Additional sampling was done in the area of site 42 to provide some further insight. On December 6, 1983, the three farm wells closest to site 42 were sampled. These wells (sites 42-A, B, and C, Appendix 2) range from about 0.25 to 1 mile (0.4 -1.6 km) in distance from site 42. These wells are also

Table 10. Pesticide concentrations in soil samples at site 42 in Mitchell County, taken 12/6/83.[1]

Site	Depth (in.)	Pesticide[2] Concentration µg/kg	Comments
S-42-1	0-6"	50.0L 14.0B 15.0S	Sample from Ap horixon about 300 ft east of site.
S-42-2	18-26"	6.0L 5.0S	Sample from top of B-horizon .
S-42-3	52-60"	ND	Sample from top of C-horizon.
S-42-4	0-12"	45.0L 15.0B 5.0S	Ap sample from 300 ft. SE of site.

[1] Soil samples were collected from soybean field surrounding farmstead at site 42.
[2] Pesticide concentrations; L--Lasso; B--Bladex; S--Sencor; ND--none detected.

finished at a shallow depth in the upper aquifer, and the water samples showed nitrate concentrations nearly equal to site 42 (59 to 64 mg/l). There are more corn fields adjacent to these farmsteads than site 42. All three well-water samples contained pesticides, but principally atrazine, and in much lower concentrations than site 42. These samples showed from 0.17 to 0.3 µg/l atrazine and 0.1 µg/l Sencor. These values are more typical of the persistent concentrations of pesticides being detected regionally in groundwater, in the Karst and Shallow Bedrock regions.

Some soil samples were also taken from the soybean fields on the farm at site 42. Pesticide concentrations in the plow-layer (Ap) ranged from 45.0 - 50.0 µg/kg Lasso, 14.0 -15.0 µg/kg Bladex, and 5.0--15.0 µg/kg Sencor (Table 10). There are few data available for comparison and perspective. A number of soil samples have been analyzed from the Big Spring basin. These samples were collected in the fall of 1982 and 1983, and thus also represent the pesticide residues remaining after the growing season (5-8 months after application). In the Big Springs basin these herbicides were applied on corn acreage, generally as combinations of Bladex and Lasso, or in combination with atrazine (no Sencor is used with corn). However, recommended application rates are similar. In the Big Spring samples, post-growing season residues in the Ap horizon, range from 2.0 -2.3 µg/kg Lasso, and Bladex was less than 6.0 mg/kg, and often not detected. The pesticide concentrations in the soil around site 42 are more than double the maximum values recorded elsewhere.

The farmer at site 42 does not feel that excessive amounts (above recommended levels) of pesticides were used. However, these bean fields are 'very

Table 11. Summary of pesticide analyses from network tile lines, surfacewaters, and springs.

Site I.D.	2/26	4/3	4/18	5/31	7/6	8/2	9/27	10/27	12/6
TILE LINES									
DT-1	1.00A	0.40A	0.54A	*	*	*	*	*	*
DT-2	0.58A	*	0.70A	*	0.74A 0.52R 0.54D	*	*	0.33A	*
DT-3	*	*	*	0.26A	0.29A 0.38L 0.18S	0.12A	*	0.25A	*
SURFACEWATER SITES									
BO	0.29A	0.40A	0.43A 0.70B 0.33D	*	1.10A 0.23L 0.47B 2.30S 0.70D	0.28A	*	0.36A 0.22S	*
GC-1	0.27A	*	0.24A	*	3.00A 0.18L 0.22B 0.34D	ND	*	0.42A	*
CR-1	0.40A	*	0.37A 0.21D	0.69A 1.20L 0.29B	3.10A 3.00L 0.89B 0.63S 0.60D	ND	*	0.12A	*
SPRING SITE									
OS	ND		ND	*	ND	ND		ND	

[1] All analyses expressed in micrograms/l (parts per billion): A--Atrazine; L--Lasso; S--Sencor; B--Bladex; R--Furadan; D--Dual; ND--None detected.
* No sample taken.

clean', and no stands of weeds were noted even in the fence rows or adjacent to farm buildings near the bean fields. This all suggests that heavy applications of the herbicides were used, and that the high concentrations in the groundwater are simply derived from local, direct infiltration.

Table 11 summarizes all pesticide analyses from Osage Spring, surfacewaters, and drainage tiles. Five samples from Osage Spring indicated no detectable pesticides, again suggesting the spring discharges water from a relatively deep, protected flow system.

All samples from drainage tiles contained detectable levels of pesticides, with total pesticide concentrations ranging between 0.1 and 1.75 µg/l. Atrazine was the most commonly identified product in tile-line discharge; however the July samples, collected a few days after a major rainstorm (see figure 17), also contained Dual, Lasso, Sencor, and the insecticide Furadan. The July samples also showed the highest total pesticide levels, reflecting increased pesticide leaching following this major precipitation event. In general, pesticide concentrations in tile-line discharge are similar to levels in groundwater in the Shallow Bedrock, Karst, and Incipient Karst regions, again indicating that tile line samples are good indicators of the quality of infiltrating groundwater.

Temporal Trends

There is not sufficient pesticide data at most sites to allow for a detailed analysis of temporal trends in pesticide concentrations. However, a few points merit discussion. In general, pesticide levels follow the same seasonal trends as nitrate concentrations, with high values during wetter periods of the year. For example, fall rains generated relatively high levels of pesticides in well samples collected in September and October, and the large rainstorm of early July caused high levels in the fast-responding parts of the hydrologic system: tile lines and surfacewaters. Winter and late summer months are characterized by lower pesticide concentrations. These relationships are not as clearly defined as those describing nitrate concentrations, however.

One other important seasonal aspect of the pesticide data relates to samples collected on or before 4/18 (Tables 9 and 10). These samples were collected prior to spring pesticide applications. Atrazine was commonly present in tile and surfacewater samples, and detected in well site 6, on 2/26 and 4/3. The period before the 4/18 sampling was rainy, providing both infiltration and runoff, as indicated by the Cedar River discharge hydrograph (figure 17). A range of concentrations of a wide variety of pesticides occurred in the tile lines, surfacewaters, and wells during this sampling (Tables 9 and 10). Water samples from half of the network wells from the Shallow Bedrock, Incipient Karst, and Karst Regions showed detectable pesticide levels. The occurrence of the herbicides --atrazine, Bladex, Dual, Lasso, and Sencor --in these pre-application samples from all components of the hydrologic system indicates that these chemicals are persisting in the environment year-round. The existence of pesticides in well samples indicates persistence in groundwater, and the existence of pesticides in stream and tile line samples indicates persistence in shallow soil horizons, as well.

The data collected on pesticide occurrences and concentrations from the Floyd-Mitchell county study is similar to pesticide data from the Big Spring area of Clayton County (Hallberg et al., 1983b). Drainage-tile effluent generally contains approximately 1 µg/l or less total pesticides, with higher values occurring after major precipitation or snowmelt events. Through most of the year pesticide levels in surfacewaters are similar to, though somewhat higher than, tile-line pesticide concentrations. However, following climatic events causing runoff, streamwater pesticide levels are often an order of magnitude greater than tile lines. In both the Floyd-Mitchell area and the Big Spring area, widespread occurrences of low levels of pesticides were noted in well-water, groundwater samples. In general, pesticide levels in well water are somewhat higher in the Floyd-Mitchell area, reflecting more intense row-crop agriculture, relative to the Big Spring area. Also, a wider variety of pesticides are present in the Floyd-Mitchell area. This results from differences in crop types grown, and hence, chemicals applied. Soybeans are a common crop (Table 1) in the Floyd-Mitchell County area, and soybean herbicides are commonly found in the groundwater. Differences in climatic conditions in 1982 versus 1983, agricultural practices, and the affects of the PIK program limit more specific comparisons between the two areas.

Nitrate-Pesticide Relationships

This study and previous work by Hallberg and others (1983b) have indicated in northeastern Iowa the major source for nitrates and pesticides in groundwater (as well as other components of the hydrologic system) is row-cropped land receiving applications of N-fertilizer and pesticides. As the source of both these contaminants is the land-surface, it would not be unreasonable to expect that some relationships exist between the concentrations of nitrates and pesticides in the hydrologic system. This should be particularly true in groundwater, where in the absence of open sinkholes, both nitrates and pesticides are delivered through infiltration. This has been suggested by work in other areas (Spalding et al., 1980). Figure 20 is a plot of the results from all pesticides analyses for the Floyd-Mitchell area, versus corresponding nitrate concentrations. No clear-cut relationship is discernable in the data. In groundwater samples with detectable pesticides, there is a trend indicating high pesticide concentrations occurring with high nitrate concentrations. However, well samples with no detectable pesticides showed nitrate levels ranging from <5 mg/l to over 120 mg/l. High nitrate concentrations in well water can indicate the potential for the presence of pesticides, but do not serve as a predictive indicator of pesticide contamination. Nitrate-pesticide relationships in surfacewaters and tile lines are also ambiguous. There are several reasons for the lack of correspondence between nitrate and pesticide levels. Constant proportions of nitrogen and pesticides are not applied to all cropped fields because of different crop types (corn vs. soybeans) and fertilizer-pesticide management practices. This was especially true during the course of the present study, because of the effects of the PIK program. Additionally, varying amounts of nitrate and pesticides will remain in storage in the soil, through periods when no infiltration takes place, or when land is taken out of production, because of the varying rates of leaching and degradation among the different pesticides, and between the pesticides and nitrates.

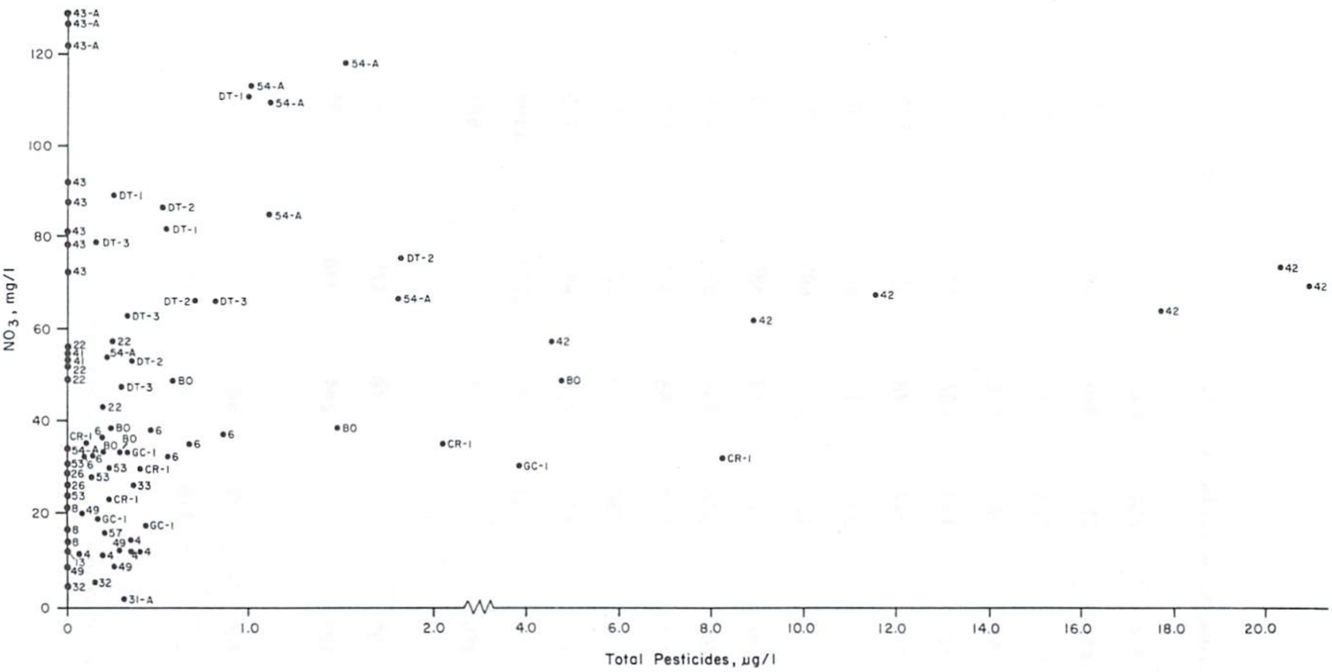

Figure 20. Plot of nitrate versus pesticide concentrations from water-quality monitoring data.

Major Ion Chemistry

Mineral scan analyses for major dissolved ions were collected on 4/18 from the monitoring network. Results are given on Table 12. The chemistry of waters from the various geologic regions, surfacewaters, and tile lines were generally similar. Total dissolved solids (TDS) in network wells varied between 200 and 850 mg/l, with the majority of the analyses indicating 250-450 mg/l TDS. Calcium and bicarbonate are the dominate ions in solution, as is typical of relatively shallow carbonate aquifers. These ions, along with magnesium, are derived from solution of the carbonate rock matrix and the carbonate minerals contained in the overlying unconsolidated materials. Sodium and potassium concentrations are generally below 10 mg/l. Sulfate, chloride, and nitrate are present in variable concentrations. Prior studies have suggested that chloride (Saffigna and Keeney, 1977; Hill, 1982; Hallberg et al., 1983b) and to a lesser extent, sulfate (Langmuir, 1971; Hallberg et al., 1983b) concentrations are often related to nitrate levels, suggesting a similar, surficial source for these ions in relatively shallow aquifers. As previously noted, groundwater in the Deep Bedrock region generally contains less than 5 mg/l nitrate and no detectable pesticides. The mineral scan data from wells in this region indicates nitrate concentrations of 0.5 to 5 mg/l, averaging 1.5 mg/l; chloride concentrations of 0.5 to 5 mg/l, averaging 2 mg/l; and sulfate concentrations of 22-48 mg/l, averaging 36 mg/l. As groundwater in the deep bedrock region is protected from surficial contaminants, these concentrations of nitrate, chloride, and sulfate reflect contributions from natural

Table 12. Chemical analyses of groundwaters and surfacewaters, in Floyd and Mitchell Counties, 4/18/83.[1]

Site	Field Temp.	Ca^{++}	Mg^{++}	Na^{+}	K^{++}	Mn^{+}	Fe	HCO_3^-	$SO_4^=$	Cl^-	NO_3^-	F^-	pH	SiO_2	Hardness	Alkalinity	TDS	Lab Conductivity	Field Conductivity
4	12.5°	120	21	7.8	1.2	<0.01	0.21	305	90	20	13	0.2	7.45	15	376	250	463	1600	760
6	12.0°	75	24	4.4	4.2	<0.01	0.03	272	29	8.5	36	0.3	7.5	11	286	223	360	570	585
8	12.0°	73	20	2.5	0.9	<0.01	<0.01	248	30	4.5	17	0.4	7.5	13	265	203	282	510	450
16	9.5°	78	23	11	3.0	0.02	1.2	304	48	0.5	0.2	0.7	7.45	12	292	249	338	570	590
22	10.0°	76	9.6	5.4	1.4	<0.01	0.04	187	51	13	43	0.1	7.15	17	229	153	287	470	485
27	11.5°	70	23	9.1	3.7	0.02	1.2	295	30	0.5	0.4	0.8	7.45	10	272	242	278	530	520
31	11.0°	80	25	22	4.6	0.27	1.5	376	44	4.5	5.0	0.4	7.4	14	306	308	419	680	690
32	10.0°	84	22	24	1.2	0.03	0.04	251	88	21	13	0.3	7.5	15	300	206	456	680	730
41	13.5°	76	26	5.6	2.6	<0.01	<0.01	270	24	10.5	47	0.2	7.35	17	297	221	359	580	580
42	12.0°	71	22	6.5	0.6	0.01	0.42	211	35	13	57	0.1	7.7	15	269	173	359	550	570
43	12.0°	68	21	7.0	<0.1	<0.01	0.12	159	38	19	91	0.1	7.6	13	256	130	355	550	575
49	10.0°	48	6.3	3.1	4.3	<0.01	0.24	159	17	4.5	8.1	<0.1	6.9	9.4	146	130	209	320	340
53	9.0°	120	12	6.3	3.8	<0.01	0.27	354	23	24	30	<0.1	7.1	17	354	290	426	680	730
54-A	9.5°	180	21	28	22	0.48	0.14	428	51	60	120	0.1	6.9	18	522	351	832	1200	1100
OS	12.0°	73	20	4.4	1.8	0.03	0.56	290	22	4.0	0.4	0.25	7.9	13	266	238	315	510	525
Surfacewater Sites																			
BO	10.0°	53	15	4.5	3.4	0.02	0.29	159	15	17.5	39	0.1	7.6	5.6	195	130	278	420	440
GC-1	9.5°	57	11	5.3	2.0	0.05	0.18	157	22	13	34	0.2	7.6	9.6	188	129	244	390	390
Tile Lines																			
DT-1	7.0°	98	39	8.7	1.4	<0.01	0.03	279	35	58	81	0.2	7.1	18	405	229	580	850	880
DT-2	6.5°	70	13	7.6	<0.1	<0.01	<0.01	142	22	38	66	0.3	7.0	9.3	228	116	361	540	550

[1] All analyses expressed as milligrams per liter except: Temperature - degrees centigrade; pH - standard units; Lab - Field conductivity - μmhos/cm^2

subsurface sources or long-term surficial sources (such as natural soil and precipitation inputs). These sources provide insignificant amounts of nitrate and chloride. Sulfate concentrations, however, indicate a small yet significant natural source, probably scattered inclusions of gypsum, anhydrite, or sulfide minerals, such as pyrite, within the aquifer matrix.

The data from the Deep Bedrock region suggest a surficial source for the high concentrations of both nitrate and chloride found in the groundwater of the other geologic regions. Saffigna and Keeney (1977) and Hill (1982) showed that relatively constant ratios of C/NO_3-N in groundwater samples from shallow aquifers underlying agricultural areas were derived from N and KCl fertilizers, respectively. Their Cl/NO_3-N ratios varied between 0.8 and 3.5. Data from the Big Spring area of northeast Iowa showed a similar relationship, but with more variable Cl/NO_3-N values. The variations were ascribed to differing agricultural practices between the Big Spring area and the areas described by Saffigna and Keeney, and Hill (Hallberg et al., 1983b). Table 13 gives the Cl/NO_3-N ratio for network wells in the Floyd-Mitchell area. Wells in the Shallow, Karst, and Incipient Karst areas vary from 0.9 to 7.3, with most below 3.5. Samples taken from individual wells in April and August show very consistent Cl/NO_3-N ratios over time. This suggests a similar source for chloride and nitrate, and that the source is variable geographically. This is consistent with a surficial-fertilizer source; variable levels of N and KCl are applied to row crops in the Floyd-Mitchell area, depending on crop type, cropping history, and management practices. The distribution of PIK acres may also have contributed to this variability.

Miscellaneous Sampling

A number of samples for nitrate, bacteria, and pesticide analyses were taken from miscellaneous wells, tile lines, and surfacewaters within and adjacent to the primary area of study. These data, tabulated in Appendix 2, are consistent with the data generated during the inventory and monitoring phases of this study. The monitoring network was sampled once for metals analysis. These samples were collected and analyzed as a cooperative effort with UHL to compile additional background data on water quality in the Devonian aquifer, in part because of concerns with the LaBounty waste-disposal site in Floyd County. Results are given in Appendix 2. The network was also sampled once for dissolved radon gas. The radon analysis was conducted by Mr. Richard Lively of the Minnesota Geological Survey, and the results are given in Appendix 2.

Stratigraphic Controls on Groundwater Flow and Quality

Evidence from a number of network wells, miscellaneous samples, head data from existing wells, and stratigraphic analysis gives an initial evaluation of the stratigraphic controls on groundwater movement in the study area. Stratigraphic analysis (Witzke and Bunker, this report) suggests that the "Rapid shale" and shales within the Wapsipinicon Formation may act as confining beds within the Devonian sequence, creating a three-part aquifer system. Wells with known completion intervals yield water quality or head data that may in-

Table 13. Chloride/nitrate-nitrogen (Cl/NO_3-N) ratios for network wells.

Well Sites/ Geologic Region	4/18	8/1
Deep		
16	11.2	NA
27	5.6	NA
31/31A	4.1	NA
Shallow		
4	6.9	6.9
6	1.1	1.2
8	1.2	1.3
32	7.3	NA
41	1.0	1.0
49	2.5	1.5
Karst		
22	1.4	1.4
53	3.6	3.1
54A	2.2	1.6
57	NA	4.3
Incipient Karst		
33	NA	2.2
42	1.0	1.0
43	0.9	0.4
43A	NA	0.6

NA -Indicates either NO_3 or Cl values reported as less than 5mg/l; no sample taken; or analytical error.

dicate the effectiveness of these potential confining beds, and the nature of the groundwater flow system within the intervening aquifers. The majority of the wells from the Shallow Karst and Incipient Karst regions were completed in the upper aquifer. However, two wells were included in the network because of their known completion in the middle aquifer, below the "Rapid shale." These were sites 4 and 6, located in the Shallow Bedrock Region (figure 10). (Monitoring data from these wells are compiled in Appendix I.) Monitoring at site 4 showed nitrate levels of 6 to 13 mg/l, and pesticide concentrations of 0.25 to 0.39 µg/l. At site 6, nitrate concentrations ranged between 32 and 38 mg/l, and pesticides from 0.19 to 0.85 µg/l. These data suggest the "Rapid shale" is not an effective protective layer in the areas adjacent to and upgradient from these wells. However, as stated in the discussion of the inventory results, the "Rapid shale" is absent immediately upgradient from these wells; and farther upgradient, depth to bedrock increases to over 50 feet. If the "Rapid shale" is an effective barrier to groundwater flow, then recharge to these wells must largely occur in the zone where bedrock is "shallow" and the shale is absent, with laterally moving groundwater delivering infiltration-derived contaminants to the middle aquifer, below the shale. Well 53 is open to parts of both the middle and upper aquifers. Nitrate concentrations at this site vary between 23 and 33 mg/l; pesticides, from below detection limits to 0.30 µg/l. Additional data is needed to better evaluate the effectiveness of the "Rapid shale" as a confining bed and barrier to infiltrating contaminants.

Osage Spring (OS) and flowing well 16 are located in discharge zones along major streams, and produce water that contains no surficial contaminants but that does contain H_2S gas. A flowing well located just north of Charles City (Miscellaneous sampling site DW-1, Appendix 2) also produces H_2S-bearing water with less than 5 mg/l nitrates and no coliform bacteria. The completed intervals of these wells and the stratigraphic source of Osage Spring are not precisely known. However, the lack of surficial contaminants, presence of H_2S, and strong upward gradients (resulting in artesian flows) suggest the groundwater is rising from depth, possibly from confined conditions. The topographic position of these sites, at low elevations near major streams, is consistent with upward groundwater flow from depth.

Data from the LaBounty Site in Charles City indicates a head difference of about 10 feet (3 m) is present above and below the "Rapid shale," with higher heads below the shale (Munter, 1980). However, head measurements of the site were taken from a well open to both the middle and lower aquifers. The resulting head is therefore an integration of heads for both aquifers. Down-hole flowmeter tests indicated the strongest flows of water within the sequence below the "Rapid shale" were from the lower aquifer (B. Bunker, personal communication, 1984). This suggests that a significant amount of the head difference that occurs in the sequence above and below the "Rapid shale" may actually originate in the lower aquifer.

Data from a new well, drilled as a replacement for well 54A, and the Orchard public supply wells (PSW) give further indications of head and contaminant distributions across potential confining beds. The replacement well at site 54A has an open interval beginning about 50 feet below the "Rapid shale," and extending downward an additional 75 feet, encompassing parts of both the middle and lower aquifers. The static water elevation in this well is about 1100 feet. The static water elevation in well 54A, completed in the upper aquifer, was estimated to be about 1080 feet, based on comments from the owner. Orchard PSW #1, located about one mile to the southeast, is open to parts of the upper and middle aquifers, and has a static water elevation of about 1065 feet. This again suggests an upward gradient, even though these wells are located in the uplands, about 75 feet higher in elevation than the nearby Cedar River, the ultimate discharge point for much of the aquifer system. Unfortunately, the completion of these wells in multiple aquifers does not isolate the effects of the individual confining beds. Water-quality data from these wells stand in marked contrast. The well tapping the middle/lower aquifer has no detectable nitrates, pesticides, or coliform bacteria. Orchard PSW #1 experienced an increase in nitrate concentrations from 21 mg/l in 1959 to 47 mg/l in 1979. Where upward gradients are present, the lower and possibly the middle aquifer will be protected from surficial contamination. However, it is not known whether these head relationships are widespread or not. Downward gradients likely exist on topographic highs, which act as recharge areas. Of particular importance are the vertical gradients beneath the Incipient Karst region, where high rates of infiltration recharge and associated contaminant leaching occur. The analysis of the head and contaminant distribution is hampered by a lack of wells completed within the individual aquifers. Additional data on stratigraphy, heads, and water quality, derived from test wells with known completion intervals, are needed to refine the understanding of the groundwater system in the area.

DISTRIBUTION OF CONTAMINANTS

The distribution of surficially-derived contaminants within a karst-carbonate aquifer may exhibit a great deal of variation. A complex set of variables interacts to produce the concentrations of contaminants which are measured at any individual point location, such as a well. The depth within the aquifer and the thickness of the aquifer tapped by a particular well affect the quality of the integrated sample taken. The quality of this groundwater that interacts with the well is affected by various environmental and land-use factors, by hydrogeologic factors, such as the local aquifer properties and nature of the flow-system, and by the stability of the contaminants in the groundwater.

The data from this study, as from the prior studies in northeastern Iowa (Hallberg and Hoyer, 1982; Hallberg et al., 1983b), show a general, inverse relationship between nitrate concentration and depth within the aquifer, as indicated by well depth or casing depth. This is a common feature of nitrate contamination of groundwater in agricultural areas that has been noted in studies world-wide (e.g., Larson and Henley, 1966; NRC, 1978; Singh and Sekon, 1978; Zaporozec, 1982, 1983; Alfoldi, 1983; Jacks and Sharma, 1983; Young, 1983; Ritter and Chirnside, 1984; Hill, 1982; Freeze and Cherry, 1979). In general this relationship is viewed as a function of time and rates. In many areas, nitrates in groundwater have only become a problem in recent decades with the more concentrated use of N-fertilizers (e.g., see Singh and Sekon, 1978; Hill, 1982; Young, 1983; Alfoldi, 1983; Vrba, 1983). In the Big Spring basin the authors have shown that the nitrate concentrations in groundwater increased over 200% between 1968 and 1982, from about 12 to 40 mg/l (Hallberg et al., 1983b; 1984). In a study in Europe, nitrates in groundwater increased from about 5 to 65 mg/l over a 10 year period, related to high rates of N-fertilization of corn. In many aquifers lateral and vertical transport rates are low, and nitrate will accumulate in the upper zone of the aquifer, with a slow gradual movement downward, by mass flux, diffusion, and hydrodynamic dispersion. In many settings there has simply not been sufficient time for nitrates to move great distances into an aquifer.

However, in karst-carbonate aquifers, such as those present in northeastern Iowa, groundwater flow rates may be very high locally. This is one factor which complicates analysis. In the Big Spring basin karst-conduit development penetrates the full thickness of the Galena aquifer and consequently there is no consistent relationship between nitrate concentration and well depth (Hallberg et al., 1983b). The most clear-cut relationship in the data from the Floyd-Mitchell County area (see figure 13) is that elevated concentrations of nitrate will likely occur in areas where bedrock is less than 50 feet deep (15m). However, within this and similar relationships developed by the authors for other local and regional areas (Hallberg and Hoyer, 1982;

Hallberg et al., 1983a, b, 1984) there is considerable variation, which warrants further discussion.

Local Environmental Factors

As described in several prior studies (Hallberg and Hoyer, 1982; Hallberg et al., 1983a, b) local well and water-system construction and well-placement problems can contribute to water-quality problems, such as nitrate contamination, as measured at a particular well. However, even in data sets such as the Floyd-Mitchell County data, where these problems have been carefully eliminated, there is still considerable variation (e.g., in the range of nitrate concentrations found in groundwater in areas of less than 50 feet, 15m, to bedrock). Many other local factors may contribute to these variations.

In recent years, numerous studies in all parts of the world, and on various scales from controlled plot studies to basin-size inventories, have shown that nitrate concentrations in groundwater (in shallow, fresh-water aquifers) can be directly related to landuse. Nitrate concentrations in groundwater (and tile effluents) under forest, unfertilized (or low-level fertilization) pastures, meadows, and grasslands are cited as less than 10 mg/l and generally less than 5 mg/l, whereas nitrate concentrations under fertilized crops and intensive animal production areas are greater than 10 mg/l, generally greater than 30 mg/l, and ranging up to 500 mg/l nitrate (e.g., Steward et al., 1968; Viets, 1971; Young and Hall, 1977; Baker and Johnson, 1977; Young and Gray, 1978; Anderson et al., 1980; Hill, 1982; Hallberg and Hoyer, 1982; Smith-Carington et al., 1983; Jacks and Sharma, 1983; Young, 1983; Lowrance et al., 1984; Hubbard et al., 1984). Many of these studies show a range from a 3 to a 60-fold increase in nitrate concentrations in groundwater between forested-pasture-grassland areas and intensively cultivated and fertilized areas. Many variables affect the resultant concentrations of nitrate that reach groundwater, but most of these studies indicate that, over the long term, there are three primary controlling factors -- the amount of N-source available, the amount of infiltrating or percolating water (and the hydraulic-conductivity of the material), and the potential for nitrate-reduction and/or denitrification. Numerous studies show a direct relationship between nitrate concentrations in groundwater and nitrogen-fertilization rates and/or fertilization history (Olson et al., 1970; Peele and Gillingham, 1972; Nightengale, 1972; Atkins, 1976; Singh and Sekon, 1976; Safinga and Keeney, 1977; Anderson et al., 1980; Csaki and Endredi, 1981; Young, 1981; Hill, 1982; Gustafson, 1983; Hallberg et al., 1983b; Hubbard and Sheridan, 1983; Young, 1983).

The nitrates in groundwater sampled at any particular well, or point-location, will reflect the interaction of these various local-source factors, the intricacies of the local groundwater flow-system, and how the open portion of the well is related to them. One well may be receiving predominantly local recharge from heavily-fertilized corn acreage, and exhibit high levels of nitrate. An adjacent well may be receiving recharge from moderately-fertilized and forested areas and show much lower nitrate concentrations. Slight differences in well, or casing depth, may result in the well tapping a substantially different part of the flow-system, particularly in a carbonate aquifer. How these factors integrate in the subsurface can never be satisfactorily worked out on a point location basis.

Hydrogeologic Factors

As inferred above, the intracacies of the groundwater-flow system from recharge area to well is one source of variation in water quality. Other hydrogeologic factors also contribute to this variability.

Physical Properties

As described previously, in a carbonate aquifer large differences in groundwater quality may occur areally (between closely adjacent wells), or seasonally (in a single well), depending upon what part of the aquifer the well is open to. In a karst-carbonate aquifer the effective, or interconnected, pore space, through which groundwater moves, is comprised principally of various kinds of secondary fractures and bedding planes and related solutional features. For discussion, the nature of a karst-carbonate aquifer may be described in terms of three conditions: 1) the "matrix" of the aquifer, marked by very small, to microscopic fractures and pores, and thus, low interstitial permeability; 2) the very open, "conduit" portions of the aquifer, marked by large, solutionally widened conduits, which often connect with sinkholes at the landsurface; and 3) "intermediate" portions of the aquifer, where the fracture and solutional porosity grades from one of the above end members to the other, but clearly includes many small, but macroscopic, horizontal and vertical fractures and fissures. The "intermediate" condition (albeit rather nebulously defined) is likely dominant areally, and plays a major role in water movement in the aquifer as a whole. Rates of groundwater (and solute) movement, hydraulic conductivity, and related properties also vary from one end member to the other; from very slow in the matrix portion to very fast in the conduit portion. Water quality will vary depending on what conditions are intercepted by a particular well boring, and, as described above, what type of landuse occurs in the recharge area.

Assuming uniform landuse over an area, in this case intensive row-cropping, these hydrologic conditions will exhibit a major effect on water quality. Wells which tap the matrix and intermediate portions of a carbonate aquifer will have relatively stable water quality seasonally, because they are recharged principally by infiltration. However, wells finished in the matrix will often have much lower nitrate concentrations. The macropores and fractures in the intermediate portion of the aquifer will promote more direct and more rapid recharge into the aquifer than can occur in the matrix portions of the aquifer. Larger volumes of infiltrating soil water, which will have a high nitrate concentration (analogous to a tile line), will be carried through the intermediate fissures to depth in the aquifer. Because the matrix portion of the aquifer has much lower hydraulic conductivities, infiltrating water with high nitrate concentrations will move very slowly down into the aquifer matrix. This nitrate-enriched groundwater will only slowly displace the pre-existing matrix water, which at one point contained little or no nitrate. Some of the nitrate will move ahead of the displacement-groundwater by diffusion and dispersion. Thus, groundwater within deeper parts of the matrix may not yet contain nitrates. The juxtaposition of higher nitrate concentrations in macropore-fracture groundwater (intermediate conditions) with low-nitrate water in the matrix will result in the diffusion of nitrates from the intermediate areas back into the matrix. Wells finished principally in the matrix will show relatively low nitrate concentrations in their groundwater. Wells recharged more from intermediate conditions will show higher concentrations of nitrate, and larger seasonal fluctuations as soil water more readily recharges this portion of the aquifer.

In England, in analagous karst-carbonate aquifers, such mechanisms of solute transport and transfer between fracture and matrix water have been described from studies of pore-water and well-water nitrate concentrations and isotope distributions (Young et al., 1977; Foster and Smith-Carrington, 1980; Barker and Foster, 1981; Young, 1983; Foster and Bath, 1983). Data from controlled-packer pump testing presented by Hallberg and others (1983a) show a direct relationship between specific capacity/foot of carbonate aquifer and nitrate concentration in the groundwater. This relationship also supports the above interpretations; i.e.--the more conductive zones that interact with the landsurface transmit water with higher nitrates, while the lower conductivity aquifer matrix still has low (or no) nitrates, at least locally.

As noted before, the open conduit portions of the aquifer will show great variations in water quality. During runoff periods surfacewater, which is low in nitrate, may "run-in" to the aquifer through sinkholes and actually dilute and lower nitrate concentrations (yet likely increase pesticide concentrations; Hallberg et al., 1983b). The "run-in" water may cause a sharp rise in head in the groundwater in the conduit zone, which will force water from the conduit zone into the intermediate and matrix portions of the aquifer. This water may re-enter the conduit as return-flow as the head difference declines. A complex interaction of displacement and diffusion of groundwater and solutes can occur among the various portions of the aquifer. As surfacewater "run-in" recedes, interflow and tile-drainage entering the sinkhole may cause a sharp rise in nitrate concentrations. In periods between runoff events the groundwater in the conduit portion (and wells tapping it) may be recharged primarily by water from the intermediate portions of the aquifer.

Obviously, a karst-carbonate aquifer is comprised of a continuum of conditions between the matrix and conduit end members. In different areas, and at different times, various processes may dominate or converge; in some areas solute movement by displacement through the matrix and intermediate portions may dominate, whereas in many regions the fracture flow is dominant (Young, 1983). These general concepts help to understand how even closely spaced wells of similar depth in the carbonate aquifer can have such wide variations in hydraulic properties and water quality. Wells depicting these variations in hydrologic regimen and water quality have been described in this study and other studies by the authors (Hallberg et al., 1983a, b, Hallberg and Hoyer, 1982).

Flow-system

The head distribution, particularly in relation to the nature of vertical flow components within the aquifer, will obviously affect water quality. Strong downward gradients will help to displace surficial contaminants, such as nitrates, deeper into the aquifer. Conversely, upward flow will prevent surficial contaminants from penetrating to depth in the aquifer, at least by processes of displacement flow or mass flux (i.e., diffusion may still occur). When aquitards occur they will promote more lateral or horizontal flow, and they may help prevent, or retard, the influx of nitrates into subjacent aquifers.

Such may, in part, be the case in the Devonian aquifer in Floyd-Mitchell Counties. Stratigraphic analysis and various head data suggests that the lower aquifer (Spillville Formation) is at least partially confined, resulting in a sub-regional flow system. Thus, in the basin in Floyd County, where the lower (Spillville) aquifer wedges out, strong upward groundwater flow likely occurs, and water quality in the lower aquifer is good (<1 mg/l NO_3), even though the upper aquifer shows high concentrations of nitrates. The hydrologic setting in this area will preclude substantial downward flux of surficial contaminants. However, it may only be a matter of time before surficial contaminants, such as nitrates and pesticides arrive in the deeper portions of the lower aquifer by lateral influx.

As described, nitrates and pesticides are found in both the upper and middle aquifers. Even if partially confined, downward groundwater flow, or leakage, into the lower aquifer will occur across their broad area of occurrence (see figures 6 and 7). More direct influx of surficial contaminants into the lower aquifer occurs in its outcrop area, to the northeast of the Floyd-Mitchell County area (figure 7). As noted, in this area the Spillville Formation is exhumed from beneath the younger Devonian rocks, and is in a Shallow Bedrock and Karst setting, where nitrates and pesticides will directly enter the aquifer. For example, the Dutton's Cave spring discharges groundwater draining from both the lower-Devonian aquifer and the Silurian aquifer. Water-quality data (presented in Hallberg and Hoyer, 1982, and Hallberg et al., 1983b) shows high concentrations of both nitrates and pesticides in the groundwater. In other words, such surficial contaminants have already entered the lower aquifer where it forms the bedrock in Winneshiek, Howard, and Chickasaw Counties. These contaminants will move downflow in the aquifer and eventually will reach the Floyd-Mitchell County area, unless they degrade or are naturally removed by such processes as denitrification. This will be discussed below.

As discussed, few wells could be located that allowed isolation of water samples from the middle aquifer to evaluate the effectiveness of the "Rapid shale" as an aquitard. Wells that were sampled showed that groundwater below the shale contained nitrates and pesticides. However, where these wells were located the "Rapid shale" is at a very shallow depth, and locally may be absent. The data may suggest that the "Rapid shale" is not as effective an aquitard as originally suspected, but further hydrogeologic analysis will be necessary to make an evaluation. Such analysis would require controlled test-drilling and properly finished observation wells.

Time and Denitrification

As noted above, the removal of nitrate from the soil or groundwater by denitrification may also affect the delivery of nitrate to groundwater, and its concentration or longevity in groundwater. Denitrification, a complicated mechansism which reduces nitrate to elemental nitrogen or nitrous oxide, which may then be given off as a gas, requires reducing conditions. Denitrification, however, is an indirect mechanism, and even though the proper redox conditions may be present the reaction still requires the presence of oxidizable or biodegradable carbon and biologic (microbial) mediation (Stumm and Morgan, 1970; Singh and Sekhon, 1978).

Little is known about denitrification in groundwater. The redox potential in groundwater will evolve toward conditions suitable for denitrification (Freeze and Cherry, 1979; Stumm and Morgan, 1970); however, it is not clear if the groundwater environment contains sufficient sources of carbon and microbial mediators which are needed to catalyze the reaction (Viets and Hagemen, 1971). This limits the rate of denitrification, even when suitable redox conditions exist. Appropriate bacteria have been reported from depths up to 150 feet (50 m) in the unsaturated zone in carbonate aquifers in England (Whitelaw and Rees, 1980), but there is no evidence to show that microbial dentrification could or does proceed under these generally oxidizing conditions (Young, 1983). Evidence for denitrification in groundwater, in limited areas, has been documented or suggested (Gillham and Cherry, 1978; Gambell et al., 1975; Steenvoorden, 1976; Vogel et al., 1981), but this has generally been in confined aquifers, and/or slow-moving flow systems. It has also been suggested that chemical reduction of nitrate may be catalyzed by other reactions in the groundwater (Anderson et al., 1980). However, the pervasive nature of nitrate problems world-wide, in various types of aquifers (see Singh and Sekon, 1978; Young, 1983, Vrba, 1983) suggest that denitrification is not significant enough to naturally resolve the problem.

Data from a carbonate aquifer in England (Smith-Carrington et al., 1983), from a study analogous to the authors' work in northeastern Iowa, shows that as the aquifer becomes confined down dip, reducing conditions develop in the groundwater. Sulfate is depleted in this area, and H_2S gas appears, suggesting microbial reduction. This suggests that denitrification may also be possible. Nitrate is not present in the reducing area. However, nitrate is also absent immediately upgradient, in a zone where dissolved-oxygen is still present; that is, a "marginally" aerobic zone. Thus, it is likely that the downgradient decrease in nitrate concentrations are related to dilution, and time, not denitrification. The situation is analogous to the findings, in this report, regarding the partially confined flow in the lower Devonian aquifer. In groundwater from this deep flow system hydrogen-sulfide was noted, again suggesting that denitrification may be possible. However, as expressed in the study of the British carbonate aquifer, the system may not be capable of denitrifying the high nitrate concentrations that will eventually arrive because of limitations on the oxidizable organic carbon and bacterial populations.

The potential for degradation of pesticides in groundwater is even more unclear. The data from the various studies of the authors show that at least low-concentrations of some pesticides are stable, and can persist in groundwater year round. Undoubtedly, various breakdown or daughter-products also occur in groundwater. Their nature, concentrations, and potential health effects need further research also.

The potential for denitrification in soils also deserves comment. Undoubtedly, denitrification occurs in particular, appropriate soil environments, however, it has seldom been measured in the field. Yet many field studies have invoked high rates of denitrification and volatilization of N-fertilizer to explain unaccounted-for nitrogen in total N-balances. These losses have seldom been measured, and in many studies the possibility of large leaching losses is not even considered. Losses of N of 30% or higher, by denitrification, are often cited (e.g., Kurtz, 1970). Many field N-balance studies also only measure N-transformations in the upper 6 to 24 inches (15-60 cm) of the soil profile, before making such conclusions. Such claims have been made even though studies of tile effluent and deep soil cores (e.g., Baker and Johnson, 1981; Gast et al., 1978) have shown substantial leaching of nitrogen, as nitrate, below the root zone.

More recent studies using N-isotope tracers show that substantial downward leaching of fertilizer-N occurs (Priebe, Blackmer, and Bremner, 1983), with loss rates ranging from 15 to 65% dependent on rate and time of application (Buzicky et al., 1983). In the range of application rates common in northeast Iowa, shallow-leaching losses of nitrate-N ranged from 30 to 50% of applied fertilizer-N (Buzicky et al., 1983; Nelson and Randall, 1983; Rice and Smith, 1983). These studies dealt only with leaching losses to tile drainage or to "depth" in the soil. However, as discussed here and in Hallberg and others (1983b) these settings are excellent indicators of what is being delivered to groundwater in shallow unconfined aquifers, such as the carbonate aquifers of northeastern Iowa. It is of interest to note the general correspondence of these figures with the total N-discharge measured in the Big Spring Basin, which was equivalent to 30 to 40% of fertilizer-N applied.

Studies in England also are worthy of review. Various studies have directly related fertilizer useage to the amount of nitrate leached to the unsaturated zone and to groundwater, on a basin-wide basis as well as on small-scale experimental farm plots (e.g., Young, 1981, 1983; Foster and Bath, 1983; Smith-Carrington et al., 1983). These studies also show that the nitrate delivered to groundwater in a given year is equivalent to 25 to 50% of the fertilizer-N applied, and that a significant build-up of nitrate-N (locally over 1,000 lbs/ac; 1,100 kg/ha) may accumulate in the unsaturated zone, waiting to be leached. Models calibrated from groundwater data, from experimental farm studies, instead of assuming large denitrification, assume that 50% of the applied fertilizer is leached annually below the root zone (Oakes, 1982; Young, 1981, 1983). Assumptions that denitrification in the soil generally will remove large quantities of nitrate from the soil-water system are not supported by studies which have actually measured the resulting leachate. Denitrification in the soil environment will occur, but is likely restricted in regional signficance to only areas where shallow anerobic conditions dominate year-round.

SUMMARY AND DISCUSSION

This study provides an assessment of the hydrogeology and groundwater quality in the Devonian-carbonate aquifers of the Floyd-Mitchell County area. The hydrogeology cannot be defined in the same detail as in the Big Spring basin study. However, in concert with the findings from the Big Spring study and other regional studies on the karst-carbonate aquifers in northeastern Iowa, these data from the Floyd-Mitchell County region provide valuable additional insights on the relationships between agriculturally-related chemicals and groundwater quality. The area of study was confined to the northeastern side of the Cedar River, to keep the sampling within one part of the groundwater flow system. All of the area monitored is underlain by portions of the upper aquifer. Through careful well-selection, a review and reevaluation of the hydrogeology, and delineation of pertinent surficial-geologic regions, the groundwater monitoring data can be used to further evaluate, on a broad scale, the delivery mechanisms of surface-applied chemicals to the groundwater system.

Reevaluation of existing data, new field work, and biostratigraphic analysis of the Devonian stratigraphy in the region provide a refined interpretation of the Devonian carbonate-aquifer in the Floyd-Mitchell County area. The Devonian aquifer is better described as a three-part system: a lower aquifer formed by the newly-defined Spillville Formation; a middle aquifer composed of the Wapsipinicon Formation and the Cedar Valley Formation below the "Rapid shale"; and an upper aquifer composed of the remainder of the Cedar

Valley Formation and the "Upper Cedar Valley" limestones. The base of the aquifer system is confined by the shales of the Maquoketa Formation. The lower, middle, and upper aquifers are separated, and at least partially confined, by shales in the lower Wapsipinicon Formation, and by the "Rapid shale," respectively. The lower aquifer is erosionally truncated, stratigraphically and structurally confined within a basin in the Floyd-Mitchell County study area. Extant data and limited observations of head differences and water quality indicate at least a partially-confined, deep, flow system in the lower aquifer, with strong upward flow components. The effectiveness of the "Rapid shale" as a confining bed or aquitard is unclear on a regional scale. Further detailed work is needed to clarify and confirm these observations.

Regionally, the distribution of surficial karst topography and sinkholes is controlled by the distribution of particular Devonian rocks. Where limestone rock units are near the landsurface, concentrations of sinkholes occur. The prominent Karst and Incipient Karst areas in Floyd-Mitchell Counties occur where "Upper Cedar Valley" limestones form the near-surface bedrock. In other Shallow Bedrock areas, dolomitic rock units form the bedrock, or because of facies changes, the "Upper Cedar Valley" is dolomitized, and few sinkholes are apparent and karst development less pronounced.

Four different geologic regions are delineated in the Floyd-Mitchell study area: 1) Deep Bedrock regions--areas where the carbonate aquifer is buried by greater than 50 feet (15m) of Quaternary surficial materials; 2) Shallow-Bedrock regions--areas where the aquifer is buried by less than 50 feet (15 m) of Quaternary materials (often less than 25 feet, 7.5 m), and where few sinkholes are found; Karst regions--areas of very shallow bedrock (less than 50 feet or 15 m, and generally less the 25 feet or 7.5 m, to bedrock), where numerous, open sinkholes occur; and 4) Incipient Karst regions --areas of very shallow bedrock (generally 5 to 15 feet, 1.5 -4.5 m depth) and numerous "incipient," soil-mantled sinkholes on broad, very low-relief, upland divides. These areas present unique interrelationships between surficial geology and hydrology, and the resultant groundwater quality.

The Deep Bedrock areas provide a background for the evaluation of groundwater quality in the Devonian aquifer. As in past studies (Hallberg and Hoyer, 1982; Hallberg et al., 1983a, b), the groundwater from properly-constructed wells in these regions contains <5 mg/l nitrate, no bacteria, no pesticides, and low levels of other surficially-derived dissolved-solids, such as chloride (Table 14). The thick mantle of Quaternary deposits is comprised dominantly of fine-grained tills with very low hydraulic conductivities, which act as an aquitard. This has protected the carbonate aquifers from the influx of surficial contaminants, primarily because there has not been enough time for these contaminants to penetrate the till. The slow-rate of downward leakage through the till may also afford more opportunities for degradation and possibly adsorption of some of these contaminants. However, in other areas, shallow wells completed in sand zones within the till are also showing elevated levels of nitrate (Hallberg and Hoyer, 1982).

The groundwater quality data from the Shallow Bedrock, Karst, and Incipient Karst regions are in total agreement, and amplify the conclusions of the authors' prior studies in northeastern Iowa (Hallberg and Hoyer, 1982; Hallberg et al., 1983a, b). The Incipient Karst areas, which must be marked by very high-infiltration recharge, show the highest, constant, concentrations of nitrate (68 mg/l, annual mean; see Table 14) in groundwater. As noted in the Big Spring region, the largest quantities and highest concentrations of nitrate are delivered to groundwater simply by infiltration (Hallberg et al., 1983b). The Karst area groundwater shows the next highest nitrate concentration (41 mg/l). Karst area wells also show the greatest variation in nitrate

Table 14. Summary of mean-annual groundwater quality data by geologic region from Floyd and Mitchell County monitoring network.

Geologic Regions	Mean NO_3 mg/l	Median Bacteria MPN	Wells With Pesticides
Deep	<5	0	0%
Shallow	22	0	70%
Karst	41	5.1	80%
Incipient Karst	68	0	70%

concentration, both seasonally and areally, reflecting the various recharge mechanisms in the open-karst system. Karst area wells may be recharged by various combinations of infiltration (high to very high nitrate concentrations), landsurface runoff which enters sinkholes and the conduit system (low nitrates), and direct tile drainage and shallow interflow which enters sinkholes (very high nitrates). Depending upon what portion of the aquifer the well is open to (i.e., larger, open conduits, versus the matrix of the rock with only small fractures), the water quality will vary. With the direct influx of surfacewater into the system, Karst area wells also show the highest bacteria levels.

The Shallow Bedrock regions show lower (yet significantly elevated over the Deep Bedrock region) nitrate concentrations in the groundwater (annual mean, 22 mg/l). The Shallow Bedrock regions vary in the thickness of Quaternary materials over bedrock, from areas where the cover is very thin allowing infiltration of surface chemicals, to areas where the thickness approaches 50 feet (15m) and the aquifer is relatively protected.

Pesticides

Various pesticides were detected in groundwater in all three of the relatively "unprotected" geologic regions--Shallow Bedrock, Karst, and Incipient Karst (Table 14). The herbicides atrazine, Lasso, Bladex, Sencor, and Dual were all detected in groundwater (in concentrations ranging from 0.11 to 3.30 µg/l) prior to their 1983 application, illustrating, as in the Big Spring study that these herbicides are persisting in groundwater (and/or the soil that they are infiltrating from) year round. Table 15 summarizes the range of pesticide concentrations detected in groundwater in these areas. The data from the Floyd-Mitchell area also amplify the Big Spring study findings in several respects. Soybeans are grown extensively in the Floyd-Mitchell County area and the common soybean herbicides, Sencor and Lasso, were commonly found

Table 15. Summary of pesticide concentrations detected in groundwater from the Big Spring area (1982-83) and the Floyd-Mitchell County area (1983). Pesticide concentrations in µg/l.

	Big Spring Area	Floyd-Mitchell Area
Herbicides*		
Atrazine	0.04 - 10.0	0.10 - 1.6
Bladex (cyanazine)	0.07 - 1.2	0.12 - 0.48
Dual (metochlor)	0.25 - 0.62	0.11
Lasso (alachlor)	0.05 - 6.0	0.10 - 16.6
Sencor (metribuzon)	---	0.09 - 4.35
Insecticides		
Dyfonate (fonofos)	0.11	---
(Dieldrin - attached to sediment)	(8.0)	---

*All herbicides listed have been found in winter, or pre-application groundwater samples.

in groundwater. The Floyd-Mitchell County area is somewhat more intensively row-cropped than the Big Spring basin, and pesticide concentrations in groundwater in the Floyd-Mitchell region are generally 2 to 5 times higher than in the Big Spring basin (even ignoring well site #42).

The persistence and movement of pesticides in groundwater is also reinforced by the detection of pesticides in Shallow Bedrock area wells (Table 14) which are located in towns (such as McIntire) one-half mile (0.8 km) from the nearest cultivated field.

The behavior of agricultural chemicals can be broadly grouped into three categories: 1) chemicals that move principally in infiltration or subsurface flow, the non-adsorbed and highly soluble compounds, particularly ions such as NO_3 which actually form in the soil from other compounds; 2) chemicals that move principally with runoff water, such as the more-soluble pesticides that are not readily adsorbed, and are generally surface applied (or only incorporated to a very shallow depth); and 3) chemicals that move primarily with the sediment in overland flow, such as the strongly adsorbed pesticides and PO_4. Many of the widely-used herbicides in Iowa fall in category 2. In the Big Spring basin study the highest concentrations of pesticides detected in groundwater occur during very short intervals, associated with the inclusion of surface-runoff water and high turbidity which entered the groundwater system through sinkholes (Hallberg et al., 1983b, and reports in preparation). However, well site 42 in the Incipient Karst area of Mitchell County, from this study, shows the highest routine and persistent concentrations of pesticides (over 20 µg/l) in groundwater that the authors' have recorded (other than with spills or accidents). All evidence suggests that these concentrations are simply derived from local infiltration recharge, from surrounding soybean fields, which received high-application rates. Also, as a whole, pesticide concentrations fluctuate seasonally, similar to nitrates. These results should not be surprising. The solubility of most of these common pesticides (the herbicides particularly) is great enough (in relation to applied concentrations) that they should clearly behave in a fashion similar to nitrates. The leaching of low concentrations of atrazine and Lasso to groundwater concurrent with nitrate has been noted in other studies, but principally in relation to irrigation (Lavy, 1977; Spalding et al., 1980). Spalding and others (1980) report a significant correlation between nitrate and atrazine concentrations in groundwater. The data from this study and the Big Spring basin also show a significant positive relationship between nitrate concentrations and pesticides, but the relationship does not offer any accurate predictability. There are too many local variables related to application rates, degradation rates, seasonal variations, etc., which complicate the relationship. The best that can be said at this stage is that if elevated nitrates are detected in the groundwater there is a possibility that pesticides will also occur in detectable amounts during some portion of the year. As shown on Table 14, pesticides have been noted in 70-80% of the the wells sampled in the Karst-Incipient Karst-Shallow Bedrock regions during some portion of the year.

Depth Distribution of Contaminants

Concentrations of surficial contaminants in groundwater, such as nitrate, generally decrease with depth within the karst-carbonate aquifers of northeastern Iowa. The areal distribution of nitrates in groundwater also can be directly related to different geologic regions, reflecting near-surface conditions which influence recharge to these shallow aquifers. However, there is considerable variation in nitrate concentrations among individual groundwater (well-water) samples, within these general relationships, even when such factors as seasonal variation and well-construction problems are accounted for. Such variability is the rule, not the exception, in data from all the regional and local studies conducted by the authors, and in most similar data in the literature.

The interrelationship of the three-dimensional groundwater-flow system with the hydraulic properties of the aquifer will influence the distribution of surficial contaminants. Strong, upward, groundwater flow may prevent the influx of surficial contaminants to depth in the aquifer. Conversely, where karst-conduit development fully penetrates an aquifer, and this is coupled with strong, downward groundwater flow, nitrates and pesticides will penetrate the full-thickness of the aquifer, and little or no relationship with depth may be apparent.

On the very local level, groundwater flow, in a karst-cabonate aquifer, will be localized along the often, rectilinear arrangement of fracture and solutional openings. The water quality measured in any particular well will, in part, be related to what conditions in the aquifer the well dominantly intercepts; e.g., the matrix, the intermediate macropore-fracture portion, and/or larger, open conduits.

The concentration of contaminants delivered to the aquifer in an area over time will be related to the land-use, the application rates of nitrogenous materials and pesticides, the nature and thickness of materials overlying the aquifer, and the amount of infiltration. When these land-use and treatment variables interact with the complexity of influx mechanisms into the karst-carbonate aquifer, and its complex flow system, a great range of variation in water quality is possible in point-specific samples such as wells. Water quality in closely-spaced wells which are open to the water-table may reflect very local differences in landuse and treatment. Water from wells finished deeper in the aquifer may reflect the influence of recharge from broader, undefined areas. Even slight differences in depth or location may allow a well to encounter very different physical conditions in the aquifer, resulting in very different water quality. Concentrated "plumes" of surficial contaminants may not disperse in a karst-carbonate aquifer, but may locally be confined to a particular conduit or fracture-macropore that is encountered in one well but not another.

All of these variables can seldom be sorted out satisfactorily to explain the water-quality variations of point-specific locations. However, such variation can, at least, be comprehended within this framework, and with areally distributed well-water quality data such variation should be expected. Such variation does not obviate the statistical validity, or the conclusions derived from the general relationship in the groundwater-quality data that have been repeated in study after study in this area.

Seasonal and Regional Relationships

Seasonal variations in hydrologic responses and nitrate concentration, though different in magnitude, are identical in trend in the soil-water (tile drainage), surfacewater, and groundwater data. The same parallelism has been shown in the Big Spring basin, and again illustrates how interconnected and responsive the entire hydrogeologic system is in the karst-carbonate aquifer regions of northeastern Iowa. Similiar relationships have been noted in other shallow, unconfined groundwater systems, in areas of heavy chemical fertilization (Smith et al., 1975; Smith-Carrington et al., 1983).

The similarity in water quality between tile-line effluent and shallow groundwater shown in this study and the Big Spring study illustrate that data from tile-drainage water can be used as a proxy indicator of what is leaching into the shallow, unconfined, groundwater system. Such insights will be useful in predicting chemical losses to groundwater in other settings. In northeast Iowa most tile-drainage water tends to have higher nitrate concentrations than most wells. The tile-drainage water generally shows concentrations of pesticides which are very comparable to those found in groundwater on a regional basis.

The regional correspondence in hydrologic and water-quality responses between the Big Spring area and the Floyd-Mitchell County region further reinforce the broad applicability of the findings from these various studies to the whole of the karst-carbonate aquifer region. The trends and concentrations of nitrates and pesticides are similar in all parts of the hydrogeologic system between the two areas. Pesticide concentrations in groundwater are generally higher in the Floyd-Mitchell County area, reflecting the more intensive row-cropping in this area. The seasonal variation in nitrate concentrations between the Cedar River and Turkey River are strikingly similar both in trend and concentration. The discharges of these rivers are also quite similar. These similarities clearly suggest that the losses of nitrogen and pesticides are also very similar, on a regional basis.

These regional relationships, and particularly the confirmation of the presence of pesticides in the groundwater of the Shallow Bedrock regions, affirm the conclusions of Hallberg and Hoyer (1982): the groundwater quality in the combined Karst-Shallow Bedrock regions of northeastern Iowa is clearly being degraded by the infiltration of surface-applied chemicals. These combined regions constitute over 6,800 square miles (17,600 sq. km) of land area overlying the carbonate aquifers of northeastern Iowa, and any strategies which may be developed for the protection of groundwater resources in these areas must consider this total region and not just the "sinkhole" or Karst areas.

Groundwater Quality and ADWs

The data on hydrogeology and groundwater quality collected for this study is also necessary to provide a framework for the evaluation of the potential impacts of ADWs on groundwater quality. As discussed, the few known, or suspected, ADWs in the area studied for this report are either sinkholes that have been modified to permanently take surface drainage, or ADWs that occur on the edge of Karst and Shallow Bedrock regions. Thus, the impact of these ADWs on groundwater quality will be indiscernible from the more areally extensive and quantitatively greater impacts of infiltration and "run-in" of agricultural chemicals in the Karst-Incipient Karst-Shallow Bedrock regions. As noted, ADWs may locally affect groundwater quality, but on the regional scale in this sampling area their impact is overshadowed by these other sources of contamination.

The majority of the known or reported ADWs in the general region occur in, and around the margin, of the Deep Bedrock region in southern Floyd County. The data collected in this study, and prior studies by the authors, indicate that the groundwater in this region should be characterized by good water quality, with <5 mg/l nitrate and no pesticides. ADWs are essentially man-made sinkholes; drilled shafts which inject surfacewater and tile drainage into the carbonate aquifer below. This surface-drainage water entering the ADWs is essentially the same as that draining into sinkholes; often exhibiting high nitrate concentrations and variable concentrations of pesticides (see Musterman et al., 1981, Hallberg and Hoyer, 1982). Thus, potentially the ADWs will degrade the groundwater quality in this Deep Bedrock region (e.g., <5 mg/l NO_3) to conditions similar to the Karst or Shallow Bedrock region (e.g., 20-40 mg/l NO_3 and variable concentrations of pesticides), at least locally. A well-sampling network could be developed in this area to test this hypothesis. If possible, this sampling should be done in conjunction with controlled test-drilling and groundwater sampling because of the limited hydrogeologic information available in this area.

CONCLUSIONS

The assessment of the hydrogeology and groundwater quality in the Devonian aquifers in the Floyd-Mitchell County area provide the following major conclusions:

1) The Devonian carbonate-aquifer may be better described as three aquifers, which are partially confined by shales;
2) However, the effectiveness of the shales as aquitards needs further investigation.
3) Delineation of surficial-geologic regions, as originally utilized by Hallberg and Hoyer (1982), provides a valid means of defining areas with unique relationships among the surficial geology, hydrology, and resultant groundwater quality. In the Floyd-Mitchell County study, the standard Deep Bedrock, Shallow Bedrock, and Karst regions were delineated. An Incipient-Karst region was also defined, as a subdivision of the Karst areas. The Incipient Karst areas are marked by high-rates of infiltration recharge and little, if any, surfacewater, "run-in" recharge.
4) As in past studies, the groundwater quality in the carbonate aquifers of the Deep Bedrock regions is unaffected (at present) by surficially-derived contaminants. The groundwater in these regions contains <5 mg/l nitrate, no bacterial problems, and no detectable pesticides.
5) Groundwater from wells in the Shallow Bedrock, Karst, and Incipient Karst areas exhibits significant concentrations of surficially-derived contaminants; mean-annual nitrate concentrations were: 22 mg/l in the Shallow Bedrock region; 44 mg/l, Karst; 68 mg/l, Incipient Karst. In all three areas, 70-80% of the wells sampled detectable concentrations of pesticides during the water year.
6) The herbicides atrazine, Lasso, Bladex, Sencor, and Dual were all detected in groundwater prior to their 1983 application showing that these pesticides persist in the groundwater system year round. On the local level, concentrations as high as 20 µg/l total pesticides were detected.
7) The highest, persistent concentrations of surficially-derived contaminants in groundwater are related to simple infiltration recharge.
8) These conclusions confirm the findings of Hallberg and Hoyer (1982): the groundwater quality in the combined Karst-Shallow Bedrock regions of northeastern Iowa is clearly being degraded by the infiltration of surface-applied chemicals. These combined regions constitute over 6,800 square miles (17,600 sq. km) of land area overlying the carbonate aquifers of northeastern Iowa, and any strategies which may be developed for the protection of groundwater resources in these areas must consider this total region and not just the "sinkhole" or Karst areas.

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APPENDIX I

WATER-QUALITY ANALYSES

FROM MONITORING NETWORK SITES

(Note: Nitrate data from 2/2/83 not included in statistical summaries, because of apparent analytical problems.)

Table 1-1. Water analyses for well 4.

Date	NO_3 mg/l	Bac. MPN	Temp °C	Cond. Microhs/cm[2] @ 25°C	N-Series[3] NO_3-N Org-N Amm-N mg/l	Cl^- mg/l	Pest[4] µg/l	Other[5] Min or M	Notes
1982									
12/14	11	2.2	12.0	825					
1983									
*2/2	(25)	0	12.0	860					
2/26	13	0	12.0	780					
4/4	11	2.2	12.0	802				R	
4/18	13[1]		12.5	760			0.34A	Min	
5/31	12	5.1	11.0	715		20[1]	0.38A		
7/6	11	0	9.0				0.25A		
8/2	12	0	12.0	725		18[1]	0.31A		
8/30	11	0	11.0	790					
9/27	6	9.2	13.0	800				M	
10/27	12	0	12.0	775			0.39A		
12/6	9	2.2	9.0	1000					

NO_3	Bac.	Cond.
N 11	Q_1 0	N 11
$\bar{X}$ 11	Md 0	$\bar{X}$ 803
S 2	Q_3 2.2	S 77
CV 18		CV 10

[1] From mineral scan analysis.
[2] From nitrogen-series analysis.
[3] Nitrogen-series analysis; values from top to bottom are: Nitrate-N, Organic-N, Ammonia-N; note nitrate expressed as N in this column, shown as NO_3 in first column.
[4] Pesticide concentrations; A--Atrazine; B--Bladex; L--Lasso; S--Sencor; D--Dual; R--Furadan; ND--none detected; blank--no analysis.
[5] Other--Radon (R), mineral scan (Min), and metals (M) analysis on separate table.

*See comment on 2/2/83 nitrate data in introduction to this Appendix.

Table 1-2. Water analyses for well 6.

Date	NO_3 mg/l	Bac. MPN	Temp °C	Cond. Microhs/cm^2 @ 25°C	N-Series[3] NO_3-N Org-N Amm-N mg/l	Cl^- mg/l	Pest[4] µg/l	Other[5] Min or M	Notes
1982									
12/14	32	9.2	11.5	600					
1983									
*2/2	(52)	0	11.0	622			0.19A		
2/26	32	9.2	11.0	585					
4/2	32	0	12.5	585			0.12A	R	
4/18	36[1]		11.5	585		8.5[1]	0.15A	Min	
5/31	38	0	11.0	600					
7/6	37	2.2	11.0				0.46A		
8/2	37	0	12.0	575		9.5[1]	0.85A		
8/30	35	0	12.5	580					
9/27	33	16+	13.0	580				M	
10/27	35	16+	11.0	600			0.68A		
12/5	32	16+	9.0	595			0.51A		

N 11	Q_1 0	N 11
$\overline{X}$ 34	Md 5.1	$\overline{X}$ 592
S 2	Q_3 16+	S 14
CV 6		CV 2

[1] From mineral scan analysis.
[2] From nitrogen-series analysis.
[3] Nitrogen-series analysis; values from top to bottom are: Nitrate-N, Organic-N, Ammonia-N; note nitrate expressed as N in this column, shown as NO_3 in first column.
[4] Pesticide concentrations; A--Atrazine; B--Bladex; L--Lasso; S--Sencor; D--Dual; R--Furadan; ND--none detected; blank--no analysis.
[5] Other--Radon (R), mineral scan (Min), and metals (M) analysis on separate table.

*See comment on 2/2/83 nitrate data in introduction to this Appendix.

Table 1-3. Water analyses for well 8.

Date	NO_3 mg/l	Bac. MPN	Temp °C	Cond. Microhs/cm[2] @ 25°C	N-Series[3] NO_3-N Org-N Amm-N mg/l	Cl^- mg/l	Pest[4] µg/l	Other[5] Min or M	Notes
1982									
12/14	23	0	11.5	520					
1983									
*2/2	(36)	0	10.0	520					
2/26	20	0	11.5	518					
4/4	18	0	12.0	510				R	
4/18	17[1]		12.0	450		4.5[1]	ND	Min	
5/31	8	0	12.0	490			ND		
7/6	15	0	12.0				ND		
8/2	21	0	13.0	475		6[1]	ND		
8/30	22	5.1	11.5	495					
9/27	22	16	12.0	495				M	
10/27	22	0	9.0	480			ND		
12/5	18	0	9.0	510					

NO_3	Bac.	Cond.
N 11	Q_1 0	N 11
$\bar{X}$ 19	Md 0	$\bar{X}$ 497
S 4	Q_3 0	S 22
CV 21		CV 4

[1] From mineral scan analysis.
[2] From nitrogen-series analysis.
[3] Nitrogen-series analysis; values from top to bottom are: Nitrate-N, Organic-N, Ammonia-N; note nitrate expressed as N in this column, shown as NO_3 in first column.
[4] Pesticide concentrations; A--Atrazine; B--Bladex; L--Lasso; S--Sencor; D--Dual; R--Furadan; ND--none detected; blank--no analysis.
[5] Other--Radon (R), mineral scan (Min), and metals (M) analysis on separate table.

*See comment on 2/2/83 nitrate data in introduction to this Appendix.

Table 1-4. Water analyses for flowing well 16.

Date	NO_3 mg/l	Bac. MPN	Temp °C	Cond. Microhs/cm[2] @ 25°C	N-Series[3] NO_3-N Org-N Amm-N mg/l	Cl^- mg/l	Pest[4] µg/l	Other[5] Min or M	Notes
1982									
12/14	<5	0	9.0	605					
1983									
*2/2	(14)	0	8.0	608					
2/26	<5	0	11.0	590					
4/3	<5	0	10.0	590				R	
4/18	0.2[1]		9.5	590		<0.5[1]	ND	Min	
6/1	<5	0	11.0	570			ND		
7/6	<5	0	12.0				ND		
8/1	<5	0	15.0	580		0.5[1]	ND		
8/29	<5	0	10.0	555					
9/27	<5	0	12.0	385				M	
10/27	<5	0	9.0	380			ND		
12/5	<5	0	7.0	595					

	NO_3		Bac.		Cond.
N	11	Q_1	0	N	11
$\overline{X}$	<5	Md	0	$\overline{X}$	583
S	0	Q_3	0	S	147
CV	0			CV	25

[1] From mineral scan analysis.
[2] From nitrogen-series analysis.
[3] Nitrogen-series analysis; values from top to bottom are: Nitrate-N, Organic-N, Ammonia-N; note nitrate expressed as N in this column, shown as NO_3 in first column.
[4] Pesticide concentrations; A--Atrazine; B--Bladex; L--Lasso; S--Sencor; D--Dual; R--Furadan; ND--none detected; blank--no analysis.
[5] Other--Radon (R), mineral scan (Min), and metals (M) analysis on separate table.

*See comment on 2/2/83 nitrate data in introduction to this Appendix.

Table 1-5. Water analyses for well 22.

Date	NO_3 mg/l	Bac. MPN	Temp °C	Cond. Microhs/cm[2] @ 25°C	N-Series[3] NO_3-N Org-N Amm-N mg/l	Cl^- mg/l	Pest[4] µg/l	Other[5] Min or M	Notes
1982									
12/14	50	16+	10.0	565					
1983									
*2/2	(69)	0	9.0	587					
2/27	58	0	10.0	575					
4/2	52	0	9.5	520				R	
4/18	43[1]		10.0	485	9.5	13[1]	0.15A	Min	
	43[2]				<0.01				
					<0.01				
5/31	49	0	10.5	490			ND		
7/6	52	0	11.5				ND		
8/1	55	0	13.0	530		17[1]	ND		
8/29	56	0	10.5	475					
9/27	56	0	12.0	570				M	
10/27	57	0	10.0	500			0.25A		
12/5	46	0	7.0	550					

N 11	Q_1 0		N 11
$\bar{X}$ 52	Md 0		$\bar{X}$ 532
S 5	Q_3 0		S 40
CV 10			CV 8

[1] From mineral scan analysis.
[2] From nitrogen-series analysis.
[3] Nitrogen-series analysis; values from top to bottom are: Nitrate-N, Organic-N, Ammonia-N; note nitrate expressed as N in this column, shown as NO_3 in first column.
[4] Pesticide concentrations; A--Atrazine; B--Bladex; L--Lasso; S--Sencor; D--Dual; R--Furadan; ND--none detected; blank--no analysis.
[5] Other--Radon (R), mineral scan (Min), and metals (M) analysis on separate table.

*See comment on 2/2/83 nitrate data in introduction to this Appendix.

Table 1-6. Water analyses for well 27.

Date	NO_3 mg/l	Bac. MPN	Temp °C	Cond. Microhs/cm^2 @ 25°C	N-Series[3] NO_3-N Org-N Amm-N mg/l	Cl^- mg/l	Pest[4] µg/l	Other[5] Min or M	Notes
1982									
12/14	<5	0	10.0	560					
1983									
*2/2	(14)	0	9.5	560					
2/26	<5	0	11.0	535					
4/2	<5	0	11.0	535				R	
4/18	0.4[1]		11.5	520		0.5[1]	ND		
6/1	<5	0	11.0	520					
7/6	<5	0	10.5				ND		
8/2	<5	0	11.0	560		<0.5[1]	ND		
8/29	<5	0	10.5	530					
9/27	<5	0	13.0	530				M	
10/2	<5	0	10.5	540			ND		
12/5	<5	0	9.0	570					

	NO_3	Bac.	Cond.
	N 11	Q_1 0	N 11
	$\overline{X}$ <5	Md 0	$\overline{X}$ 542
	S 0	Q_3 0	S 18
	CV 0		CV 3

1 From mineral scan analysis.
2 From nitrogen-series analysis.
3 Nitrogen-series analysis; values from top to bottom are: Nitrate-N, Organic-N, Ammonia-N; note nitrate expressed as N in this column, shown as NO_3 in first column.
4 Pesticide concentrations; A--Atrazine; B--Bladex; L--Lasso; S--Sencor; D--Dual; R--Furadan; ND--none detected; blank--no analysis.
5 Other--Radon (R), mineral scan (Min), and metals (M) analysis on separate table.

*See comment on 2/2/83 nitrate data in introduction to this Appendix.

Table 1-7. Water analyses for well 31.

Date	NO_3 mg/l	Bac. MPN	Temp °C	Cond. Microhms/cm[2] @ 25°C	N-Series[3] NO_3-N Org-N Amm-N mg/l	Cl^- mg/l	Pest[4] µg/l	Other[5] Min or M	Notes
1982									
12/14	<5	9.2	8.0	670					
1983									
*2/2	(16)	5.1	9.0	680					
2/26	<5	2.2	11.0	660					
4/2	<5	0	10.0	690				R	
4/18	5.0[1]		11.0	690			ND	Min	
6/1	<5	2.2	11.0						**

	NO_3	Cond.
N	5	5
$\overline{X}$	<5	678
S	0	13
CV	0	2

1 From mineral scan analysis.
2 From nitrogen-series analysis.
3 Nitrogen-series analysis; values from top to bottom are: Nitrate-N, Organic-N, Ammonia-N; note nitrate expressed as N in this column, shown as NO_3 in first column.
4 Pesticide concentrations; A--Atrazine; B--Bladex; L--Lasso; S--Sencor; D--Dual; R--Furadan; ND--none detected; blank--no analysis.
5 Other--Radon (R), mineral scan (Min), and metals (M) analysis on separate table.

*See comment on 2/2/83 nitrate data in introduction to this Appendix.
**Well dismantled as a result of casing problems. See replacement well 31-A.

Table 1-8. Water analyses for well 31-A.

Date	NO_3 mg/l	Bac. MPN	Temp °C	Cond. Microhs/cm[2] @ 25°C	N-Series[3] NO_3-N Org-N Amm-N mg/l	Cl^- mg/l	Pest[4] µg/l	Other[5] Min or M	Notes
1983									
8/2	<5	2.2	10.0	640		<0.5[1]	0.29B		New
8/29	<5	0	9.5	630					well
9/27	<5	0	12.5	645				M	drilled to re-
10/27	<5	0	11.0	650			ND		place
12/6	<5	2.2	8.0	690					site 31
	N 5			N 5					
	$\bar{X}$ <5			$\bar{X}$ 651					
	S 0			S 23					
	CV 0			CV 4					

1 From mineral scan analysis.
2 From nitrogen-series analysis.
3 Nitrogen-series analysis; values from top to bottom are: Nitrate-N, Organic-N, Ammonia-N; note nitrate expressed as N in this column, show NO_3 in first column.
4 Pesticide concentrations; A--Atrazine; B--Bladex; L--Lasso; S--Sencor; D--Dual; R--Furadan; ND--none detected; blank--no analysis.
5 Other--Mineral scan (Min), and metals (M) analysis on separate table.

Table 1-9. Water analyses for well 32.

Date	NO_3 mg/l	Bac. MPN	Temp °C	Cond. Microhs/cm[2] @ 25°C	N-Series[3] NO_3-N Org-N Amm-N mg/l	Cl- mg/l	Pest[4] µg/l	Other[5] Min or M	Notes
1982									
12/14	8.0	5.1	9.0	675					
1983									
*2/2	(20)	0	8.5	640					
2/26	<5	0	8.0	660					
4/2	13	0	8.0	790				R	
4/19	13[1]		10.0	730		21[1]	ND	Min	
5/31	10	16.0	11.0	630					
7/6	5	0	12.0				ND		
8/2	<5	0	12.0	590		10[1]	0.12A		
8/29	<5	0	12.0	590					
9/27	<5	2.2	11.0	640				M	
10/27	6	0	10.0	630			0.16A		
12/5	<5	0	8.0	700					

NO_3	Bac.	Cond.
N 11	Q_1 0	N 11
$\bar{X}$ 6	Md 0	$\bar{X}$ 661
S 4	Q_3 2.2	S 60
CV 67		CV 9

[1] From mineral scan analysis.
[2] From nitrogen-series analysis.
[3] Nitrogen-series analysis; values from top to bottom are: Nitrate-N, Organic-N, Ammonia-N; note nitrate expressed as N in this column, shown as NO_3 in first column.
[4] Pesticide concentrations; A--Atrazine; B--Bladex; L--Lasso; S--Sencor; D--Dual; R--Furadan; ND--none detected; blank--no analysis.
[5] Other--Radon (R), mineral scan (Min), and metals (M) analysis on separate table.

*See comment on 2/2/83 nitrate data in introduction to this Appendix.

Table 1-10. Water analyses for well 33.

Date	NO_3 mg/l	Bac. MPN	Temp °C	Cond. Microhs/cm[2] @ 25°C	N-Series[3] NO_3-N Org-N Amm-N mg/l	Cl⁻ mg/l	Pest[4] µg/l	Other[5] Min or M	Notes
1982									
12/14	27	0	10.0	540					
1983									
*2/2	(41)	0	11.0	618					
2/26	26	0	11.0	545					
4/2	27	0	10.0	580				R	
4/18	26[1]		10.5	570		12[1]	0.10A 0.12B 0.11D	Min	
6/1	26	16+	9.5	530					
7/5	26	2.2	10.0				ND		
8/1	26	0	12.5	575		13[1]	ND		
8/29	26	0	13.0	530					
9/27	27	0	11.0	580				M	
10/27	28	0	10.0	565			ND		
12/6	25	0	9.0	575					

NO_3	Bac.	Cond.
N 11	Q_1 0	N 11
$\overline{X}$ 26	Md 0	$\overline{X}$ 565
S 0.8	Q_3 0	S 26
CV 3		CV 5

[1] From mineral scan analysis.
[2] From nitrogen-series analysis.
[3] Nitrogen-series analysis; values from top to bottom are: Nitrate-N, Organic-N, Ammonia-N; note nitrate expressed as N in this column, shown as NO_3 in first column.
[4] Pesticide concentrations; A--Atrazine; B--Bladex; L--Lasso; S--Sencor; D--Dual; R--Furadan; ND--none detected; blank--no analysis.
[5] Other--Radon (R), mineral scan (Min), and metals (M) analysis on separate table.

*See comment on 2/2/83 nitrate data in introduction to this Appendix.

Table 1-11. Water analyses for well 41.

Date	NO_3 mg/l	Bac. MPN	Temp °C	Cond. Microhs/cm[2] @ 25°C	N-Series[3] NO_3-N Org-N Amm-N mg/l	Cl^- mg/l	Pest[4] µg/l	Other[5] Min or M	Notes
1982									
12/14	57	0	8.0	605					
1983									
*2/1	(76)	0	10.0	650					
2/26	57	5.1	10.0	650					
4/2	52	0	10.0	630				R	
4/18	47[1]		13.5	580		10.5[1]	ND	Min	
6/1	56	0	10.0	600					
7/6	53	0	11.0				ND		
8/1	54	0	11.5	620		12[1]	ND		
8/29	53	0	9.0	610					
9/27	58	16	13.0	620				M	
10/27	50	0	11.0	620			ND		
12/5	45	0	8.0	720					

	NO_3	Bac.	Cond.
	N 11	Q_1 0	N 11
	$\bar{X}$ 53	Md 0	$\bar{X}$ 630
	S 4	Q_3 0	S 37
	CV 8		CV 6

[1] From mineral scan analysis.
[2] From nitrogen-series analysis.
[3] Nitrogen-series analysis; values from top to bottom are: Nitrate-N, Organic-N, Ammonia-N; note nitrate expressed as N in this column, shown as NO_3 in first column.
[4] Pesticide concentrations; A--Atrazine; B--Bladex; L--Lasso; S--Sencor; D--Dual; R--Furadan; ND--none detected; blank--no analysis.
[5] Other--Radon (R), mineral scan (Min), and metals (M) analysis on separate table.

*See comment on 2/2/83 nitrate data in introduction to this Appendix.

Table 1-12. Water analyses for well 42.

Date	NO_3 mg/l	Bac. MPN	Temp °C	Cond. Microhs/cm[2] @ 25°C	N-Series[3] NO_3-N Org-N Amm-N mg/l	Cl- mg/l	Pest[4] µg/l	Other[5] Min or M	Notes
1982									
12/14	61	0	10.0	545					
1983									
*2/2	(81)	0	10.5	600					
2/26	66	16+	12.0	590					
4/2	63	2.2	12.0	590				R	
4/19	57[1]		14.0	570		13[1]	3.30L 1.20S	Min	
5/31	65	0	12.0	560					
7/5	68	0	11.0				9.50L 0.24B 1.70S		
8/1	64	0	11.5	525		14[1]	7.50L 0.23B 1.20S		
8/29	69	0	10.0	475					
9/27	68	0	12.0	580			16.50L 0.45B 4.00S	M	
10/27	71	0	11.0	575			16.00L 0.48B 4.30S		
12/6	64	0	9.0	630			13.00L 0.41B 4.30S		
	N 11	Q_1 0		N 11					
	$\overline{X}$ 65	Md 0		X 567					
	S 4	Q_3 0		S 41					
	CV 6			CV 7					

[1] From mineral scan analysis.
[2] From nitrogen-series analysis.
[3] Nitrogen-series analysis; values from top to bottom are: Nitrate-N, Organic-N, Ammonia-N; note nitrate expressed as N in this column, shown as NO_3 in first column.
[4] Pesticide concentrations; A--Atrazine; B--Bladex; L--Lasso; S--Sencor; D--Dual; R--Furadan; ND--none detected; blank--no analysis.
[5] Other--Radon (R), mineral scan (Min), and metals (M) analysis on separate table.
*See comment on 2/2/83 nitrate data in introduction to this Appendix.

Table 1-13. Water analyses for well 43.

Date	NO_3 mg/l	Bac. MPN	Temp °C	Cond. Microhs/cm[2] @ 25°C	N-Series[3] NO_3-N Org-N Amm-N mg/l	Cl^- mg/l	Pest[4] µg/l	Other[5] Min or M	Notes
<u>1982</u>									
12/14	92	0	11.0	570					
<u>1983</u>									
*2/2	(92)	0	10.0	595					
2/26	81	16+	12.0	570			ND		
4/2	92	2.2	12.0	590			ND	R	
4/19	92[1]		14.0	575		19[1]	ND	Min	
5/31	87	0	11.0	550			ND		
7/5	79	0	12.0				ND		
8/1	73	0	12.5	500		15[1]	ND		
8/29	72	0	10.0	545					
9/27	82	2.2	14.0	680				M	
10/27	78	5.1	11.0	550			**		
12/6	73	16	9.0	640					

	NO_3	Bac.	Cond.
	N 11	Q_1 0	N 11
	$\overline{X}$ 82	Md 0	$\overline{X}$ 579
	S 8	Q_3 2.2	S 49
	CV 10		CV 8

[1] From mineral scan analysis.
[2] From nitrogen-series analysis.
[3] Nitrogen-series analysis; values from top to bottom are: Nitrate-N, Organic-N, Ammonia-N; note nitrate expressed as N in this column, shown as NO_3 in first column.
[4] Pesticide concentrations; A--Atrazine; B--Bladex; L--Lasso; S--Sencor; D--Dual; R--Furadan; ND--none detected; blank--no analysis.
[5] Other--Radon (R), mineral scan (Min), and metals (M) analysis on separate table.

*See comment on 2/2/83 nitrate data in introduction to this Appendix.
**Sample broken in lab.

Table 1-14. Water analyses for well 43-A.

Date	NO_3 mg/l	Bac. MPN	Temp °C	Cond. Microhs/cm[2] @ 25°C	N-Series[3] NO_3-N Org-N Amm-N mg/l	Cl^- mg/l	Pest[4] μg/l	Other[5] Min or M	Notes
1983									
5/31	132	16	9.0	740					Live-stock well
7/5	129	2.2	11.0				ND		
8/1	127	2.2	12.0	610		1.7[1]	ND		
8/29	120	0	8.0	760					
9/27	56	16+	11.0	680				M	
10/27	122	16+	10.0	740			ND		
12/6	123	5.1	7.0	800					
	N 7	Q_1 2.2		N 6					
	$\overline{X}$ 116	Md 5.1		$\overline{X}$ 722					
	S 27	Q_3 16		S 67					
	CV 23			CV 9					

1 From mineral scan analysis
2 From nitrogen-series analysis
3 Nitrogen-series analysis; values from top to bottom are: Nitrate-N, Organic-N, Ammonia-N; note nitrate expressed as N in this column, shown as NO_3 in first column
4 Pesticide concentrations; A--Atrazine; B--Bladex; L--Lasso; S--Sencor; D--Dual; R--Furadan; ND--none detected; blank--no analysis
5 Other--Mineral scan (Min) and metals (M) analysis on separate table

Table 1-15. Water analyses for well 49.

Date	NO_3 mg/l	Bac. MPN	Temp °C	Cond. Microhs/cm[2] @ 25°C	N-Series[3] NO_3-N Org-N Amm-N mg/l	Cl- mg/l	Pest[4] µg/l	Other[5] Min or M	Notes
1982									
12/14	10	0	8.0	345					
1983									
*2/2	(19)	0	10.0	380					
2/27	8	0	10.0	378					
4/2	9	0	10.0	345				R	
4/19	8.1[1]		10.0	340		4.5[1]	0.21A	Min	
5/31	8.0	0	10.5	350					
7/5	9.0	0	13.0				ND		
8/1	12	0	11.5	400		4[1]	0.25A		
8/29	7	0	10.0	500					
9/27	18	0	13.0	380				M	
10/27	20	0	12.0	370			0.10A		
12/5	15	0	8.5	410					
	N 11	Q_1 0		N 11					
	$\bar{X}$ 11	Md 0		$\bar{X}$ 382					
	S 4	Q_3 0		S 46					
	CV 36			CV 12					

[1] From mineral scan analysis.
[2] From nitrogen-series analysis.
[3] Nitrogen-series analysis; values from top to bottom are: Nitrate-N, Organic-N, Ammonia-N; note nitrate expressed as N in this column, shown as NO_3 in first column.
[4] Pesticide concentrations; A--Atrazine; B--Bladex; L--Lasso; S--Sencor; D--Dual; R--Furadan; ND--none detected; blank--no analysis.
[5] Other--Radon (R), mineral scan (Min), and metals (M) analysis on separate table.

*See comment on 2/2/83 nitrate data in introduction to this Appendix.

Table 1-16. Water analyses for well 53.

Date	NO_3 mg/l	Bac. MPN	Temp °C	Cond. Microhs/cm[2] @ 25°C	N-Series[3] NO_3-N Org-N Amm-N mg/l	Cl^- mg/l	Pest[4] µg/l	Other[5] Min or M	Notes
<u>1982</u>									
12/14	30	0	8.5	755					
<u>1983</u>									
*2/2	(47)	0	9.0	718					
2/26	33	16	6.0	750					
4/2	22	0	8.5	750				R	
4/19	30[1]		9.0	730		24[1]	ND	Min	
5/31	30	0	11.0	710			0.10L		
							0.09S		
7/6	28	0	10.5				0.10A		
							0.15S		
8/2	23	0	11.0	625		16[1]	ND		
8/29	27	16+	13.0	690					
9/27	33	16+	11.0	710				M	
10/27	30	9.2	9.0	745			ND		
12/6	29	5.1	8.0	815					

NO_3	Bac.	Cond.
N 11	Q_1 0	N 11
$\overline{X}$ 29	Md 2.2	$\overline{X}$ 727
S 4	Q_3 16	S 47
CV 14		CV 6

[1] From mineral scan analysis.
[2] From nitrogen-series analysis.
[3] Nitrogen-series analysis; values from top to bottom are: Nitrate-N, Organic-N, Ammonia-N; note nitrate expressed as N in this column, shown as NO_3 in first column.
[4] Pesticide concentrations; A--Atrazine; B--Bladex; L--Lasso; S--Sencor; D--Dual; R--Furadan; ND--none detected; blank--no analysis.
[5] Other--Radon (R), mineral scan (Min), and metals (M) analysis on separate table.

*See comment on 2/2/83 nitrate data in introduction to this Appendix.

Table 1-17. Water analyses for well 54-A.

Date	NO_3 mg/l	Bac. MPN	Temp °C	Cond. Microhs/cm^2 @ 25°C	N-Series[3] NO_3-N Org-N Amm-N mg/l	Cl- mg/l	Pest[4] µg/l	Other[5] Min or M	Notes
<u>1982</u>									
12/14									
<u>1983</u>									
*2/2	(58)	2.2	9.0	810					
2/27	34	5.1	10.5	815			ND		
4/4	110	16+	9.0	1118			1.20S	R	
4/19	119[1]		9.5	1100	26.4	60[1]	1.50S	Min	
	119[2]				0.69				
					0.14				
5/31	85	16+	10.0	900			1.10S		
7/6	113	16+	10.0				1.00S		
8/1	54	16+	12.0	850		19[1]	0.17S		
8/29	46	16+	11.0	810					
9/27	70	16+	11.0	810				M	
10/27	66	16+	9.5	895			1.80S		
	N 10	Q_1 10.5		N 10					
	$\bar{X}$ 76	Md 16+		X 871					
	S 30	Q_3 16+		S 150					
	CV 39			CV 17					
12/6	<5	2.2	8.0	600			ND		**

1 From mineral scan analysis.
2 From nitrogen-series analysis.
3 Nitrogen-series analysis; values from top to bottom are: Nitrate-N, Organic-N, Ammonia-N; note nitrate expressed as N in this column, shown as NO_3 in first column.
4 Pesticide concentrations; A--Atrazine; B--Bladex; L--Lasso; S--Sencor; D--Dual; R--Furadan; ND--none detected; blank--no analysis.
5 Other--Radon (R), mineral scan (Min), and metals (M) analysis on separate table.

*See comment on 2/2/83 nitrate data in introduction to this Appendix.
**A new well was drilled in December 1983 at 54-A. The water-quality analyses taken on 12/6/83 at 54-A are the results from the new well. Drillers record show--rock at 4', well depth 278', casing depth 203'; the well is grouted to 202'.

Table 1-18. Water analyses for well 57.

Date	NO_3 mg/l	Bac. MPN	Temp °C	Cond. Microhs/cm^2 @ 25°C	N-Series[3] NO_3-N Org-N Amm-N mg/l	Cl- mg/l	Pest[4] µg/l	Other[5] Min or M	Notes
1983									
2/27	23	16+	10.0	740					
4/4	19	16+	8.0	660				R	
4/19	17	16+	8.75	615					
5/31	16	16+	12.0	610					
7/6									No Sample
8/2	16	9.2	12.5	605		15[1]	0.17A		
8/29									No Sample
9/27									No Sample
10/27	17	16+	11.0	780			ND		
12/6	18	16+	9.0	725					
	N 6	Q_1 16+		N 7					
	$\overline{X}$ 17	Md 16+		$\overline{X}$ 676					
	S 2	Q_3 16+		S 72					
	CV 6			CV 11					

1 From mineral scan analysis.
2 From nitrogen-series analysis.
3 Nitrogen-series analysis; values from top to bottom are: Nitrate-N, Organic-N, Ammonia-N; note nitrate expressed as N in this column, shown as NO_3 in first column.
4 Pesticide concentrations; A--Atrazine; B--Bladex; L--Lasso; S--Sencor; D--Dual; R--Furadan; ND--none detected; blank--no analysis.
5 Other--Radon (R), mineral scan (Min), and metals (M) analysis on separate table.

Table 1-19. Water analyses for well SHF-A.

Date	NO_3 mg/l	Bac. MPN	Temp °C	Cond. Microhs/cm[2] @ 25°C	N-Series[3] NO_3-N Org-N Amm-N mg/l	Cl^- mg/l	Pest[4] µg/l	Other[5] Min or M	Notes
1983									
5/31	19	16+							
7/6	27	16+					ND		
8/2	26	5.1	10.5	725		26[1]	ND		
8/30									No Sample
9/27									No Sample
10/27	32	0	9.5	895			ND		
12/6	29	2.2	8.0	770					
	N 5			N 3					
	X̄ 27			X̄ 797					
	S 5			S 88					
	CV 19			CV 11					

[1] From mineral scan analysis.
[2] From nitrogen-series analysis.
[3] Nitrogen-series analysis; values from top to bottom are: Nitrate-N, Organic-N, Ammonia-N; note nitrate expressed as N in this column, shown as NO_3 in first column.
[4] Pesticide concentrations; A--Atrazine; B--Bladex; L--Lasso; S--Sencor; D--Dual; R--Furadan; ND--none detected; blank--no analysis.
[5] Other--Mineral scan (Min) and metals (M) analysis on separate table.

Table 1-20. Water analyses for Osage Spring, site OS.

Date	NO_3 mg/l	Bac. MPN	Temp °C	Cond. Microhs/cm[2] @ 25°C	N-Series[3] NO_3-N Org-N Amm-N mg/l	Cl^- mg/l	Pest[4] µg/l	Other[5] Min or M	Notes
1982									
12/14	<5	0							
1983									
*2/2	(13)	0	8.0	540					
2/26	<5	0	9.0	545					
4/3	<5	0	8.5	540				R	
4/19	0.4[1]		12.0	525		4.0[1]	ND	Min	
5/31	<5	0	9.5	480					
7/5	<5	0	10.5				ND		
8/2	<5	0	11.0	560		4.0[1]	ND		
8/29	<5	0	11.0	515					
9/27	5	0	9.5	530				M	
10/27	<5	0	9.0	545			ND		
12/6	<5	0	7.0	570					

NO_3	Bac.	Cond.
N 11	Q_1 0	N 10
$\bar{X}$ 2	Md 0	$\bar{X}$ 535
S 1	Q_3 0	S 25
CV 50		CV 5

[1] From mineral scan analysis.
[2] From nitrogen-series analysis.
[3] Nitrogen-series analysis; values from top to bottom are: Nitrate-N, Organic-N, Ammonia-N; note nitrate expressed as N in this column, shown as NO_3 in first column.
[4] Pesticide concentrations; A--Atrazine; B--Bladex; L--Lasso; S--Sencor; D--Dual; R--Furadan; ND--none detected; blank--no analysis.
[5] Other--Radon (R), mineral scan (Min), and metals (M) analysis on separate table.

*See comment on 2/2/83 nitrate data in introduction to this Appendix.

Table 1-21. Water analyses for surfacewater site BO (Burr Oak Creek).

Date	NO_3 mg/l	Bac. MPN	Temp °C	Cond. Microhs/cm[2] @ 25°C	N-Series[3] NO_3-N Org-N Amm-N mg/l	Cl- mg/l	Pest[4] µg/l	Other[5] Min or M	Notes
1982									
12/14	67	16+							
1983									
*2/2	(63)	16+	1.0	540			0.29A		
2/26	35	16+	2.0	480					
4/3	37	16+	4.5	455			0.4A	R	
4/19	39[1]		10.0	440		17.5[1]	0.43A 0.70B 0.33D	Min	
5/31	49	16+	14.0	510					
7/6	49	16+	20.0				1.1A 0.23L 0.47B 2.3S 0.70D		
8/1	35	16+	27.0	525		18[1]	0.28A		
8/29	9	16+	30.0	485					
9/27	42	16+	18.0	570				M	
10/27	47	16+	9.0	575			.36A .22S		
12/5	42	16+	0	710					
	N 12 $\bar{X}$ 42 S 15 CV 36	Q_1 16+ Md 16+ Q_3 16+		N 10 $\bar{X}$ 529 S 78 CV 15					

[1] From mineral scan analysis.
[2] From nitrogen-series analysis.
[3] Nitrogen-series analysis; values from top to bottom are: Nitrate-N, Organic-N, Ammonia-N; note nitrate expressed as N in this column, shown as NO_3 in first column.
[4] Pesticide concentrations; A--Atrazine; B--Bladex; L--Lasso; S--Sencor; D--Dual; R--Furadan; ND--none detected; blank--no analysis.
[5] Other--Radon (R), mineral scan (Min), and metals (M) analysis on separate table.

*See comment on 2/2/83 nitrate data in introduction to this Appendix.

Table 1-22. Water analyses for surfacewater site GC-1 (Goose Creek).

Date	NO_3 mg/l	Bac. MPN	Temp °C	Cond. Microhs/cm[2] @ 25°C	N-Series[3] NO_3-N Org-N Amm-N mg/l	Cl⁻ mg/l	Pest[4] µg/l	Other[5] Min or M	Notes
<u>1982</u>									
12/14	38	16+							
<u>1983</u>									
*2/2	(31)	16+	0	490			0.27A		
2/27	19	16+	4.0	340					
4/4	24	16+	4.0	320				R	
4/19	43[1] 34[2]		9.5	390	7.5 0.38 0.05	13[1]	0.24A	Min	
5/31	27	16+	13.0	410					
7/6	30	16+	18.0				3.00A 0.18L 0.22B 0.34D		
8/1	11	16+	23.5	450		12[1]	ND		
8/30	<5	16+	26.5	495					
9/27	13	16+	17.0	405				M	
10/27	17	16+	10.5	440			0.42A		
12/6	20	16+	0	540					

	NO_3	Bac.	Cond.
	N 12	Q_1 16+	N 10
	$\overline{X}$ 23	Md 16+	$\overline{X}$ 428
	S 11	Q_3 16+	S 69
	CV 48		CV 16

[1] From mineral scan analysis.
[2] From nitrogen-series analysis.
[3] Nitrogen-series analysis; values from top to bottom are: Nitrate-N, Organic-N, Ammonia-N; note nitrate expressed as N in this column, shown as NO_3 in first column.
[4] Pesticide concentrations; A--Atrazine; B--Bladex; L--Lasso; S--Sencor; D--Dual; R--Furadan; ND--none detected; blank--no analysis.
[5] Other--Radon (R), mineral scan (Min), and metals (M) analysis on separate table.

*See comment on 2/2/83 nitrate data in introduction to this Appendix.

Table 1-23. Water analyses for surfacewater site CR-1 (Cedar River).

Date	NO_3 mg/l	Bac. MPN	Temp °C	Cond. Microhs/cm[2] @ 25°C	N-Series[3] NO_3-N Org-N Amm-N mg/l	Cl- mg/l	Pest[4] µg/l	Other[5] Min or M	Notes
1982									
12/14									
1983									
*2/2									
2/26	21	16+	1.5	420			0.40A		
4/3	29	16+	4.5	440				R	
4/19	29	16+	8.5	470			0.37A		
5/31	36	16+	13.0	600			0.69A		
							1.20L		
							0.29B		
7/6	32	16+	19.0				3.10A		
							3.00L		
							0.89B		
							0.63S		
							0.60D		
8/2	23	16+	23.0	450		20[1]	ND		
8/30	11	16+	25.5	500					
9/27	27	16+	15.0	625				M	
10/27	34	16+	9.0	650			.12A		
12/6	29	16+	0	970					
	N 10	Q_1 16+		N 9					
	$\overline{X}$ 27	Md 16+		$\overline{X}$ 570					
	S 7	Q_3 16+		S 173					
	CV 26			CV 30					

[1] From mineral scan analysis.
[2] From nitrogen-series analysis.
[3] Nitrogen-series analysis; values from top to bottom are: Nitrate-N, Organic-N, Ammonia-N; note nitrate expressed as N in this column, shown as NO_3 in first column.
[4] Pesticide concentrations; A--Atrazine; B--Bladex; L--Lasso; S--Sencor; D--Dual; R--Furadan; ND--none detected; blank--no analysis.
[5] Other--Radon (R), mineral scan (Min), and metals (M) analysis on separate table.

*See comment on 2/2/83 nitrate data in introduction to this Appendix.

Table 1-24. Water analyses for tile line, site DT-1.

Date	NO_3 mg/l	Bac. MPN	Temp °C	Cond. Microhs/cm[2] @ 25°C	N-Series[3] NO_3-N Org-N Amm-N mg/l	Cl- mg/l	Pest[4] µmg/l	Other[5] Min or M	Notes
1982									
12/14	127	16+							
1983									
*2/2									Not Flowing
2/27	111	16+	2.0	1105			0.58A		
4/3	89	16+	5.0	908			0.40A	R	
4/19	81[1]		7.0	880		58[1]	0.54A		
5/31									No Sample, Tile washed-out during a storm
	N 4			N 3					
	X̄ 102			X̄ 964					
	S 21			S 122					
	CV 21			CV 13					

[1] From mineral scan analysis.
[2] From nitrogen-series analysis.
[3] Nitrogen-series analysis; values from top to bottom are: Nitrate-N, Organic-N, Ammonia-N; note nitrate expressed as N in this column, shown as NO_3 in first column.
[4] Pesticide concentrations; A--Atrazine; B--Bladex; L--Lasso; S--Sencor; D--Dual; R--Furadan; ND--none detected; blank--no analysis.
[5] Other--Radon (R), mineral scan (Min), and metals (M) analysis on separate table.

*See comment on 2/2/83 nitrate data in introduction to this Appendix.

Table 1-25. Water analyses for tile line, site DT-2.

Date	NO_3 mg/l	Bac. MPN	Temp °C	Cond. Microhs/cm[2] @ 25°C	N-Series[3] NO_3-N Org-N Amm-N mg/l	Cl⁻ mg/l	Pest[4] µg/l	Other[5] Min or M	Notes
1982									
12/14	105	16+							
1983									
*2/2									Not Flowing
2/27	86	16+	3.0	650			0.58A		
4/4	69	16+	4.0	585				R	
4/19	66[1]		6.5	550	0.01 0.04	38[1]	0.70A	Min	
5/31	71	16+	12.0	500					
7/6	76	16+	15.0				0.74A 0.52R 0.54D		
8/2									Not Flowing
8/30									Not Flowing
9/27	50	16+	15.5	580				M	
10/27	53	16+	12.5	555			0.33A		**
12/5	54	16+	3.0	720					
	N 9 $\overline{X}$ 70 S 18 CV 26	Q_1 16+ Md 16+ Q_3 16+		N 7 $\overline{X}$ 592 S 73 CV 12					

[1] From mineral scan analysis.
[2] From nitrogen-series analysis.
[3] Nitrogen-series analysis; values from top to bottom are: Nitrate-N, Organic-N, Ammonia-N; note nitrate expressed as N in this column, shown as NO_3 in first column.
[4] Pesticide concentrations; A--Atrazine; B--Bladex; L--Lasso; S--Sencor; D--Dual; R--Furadan; ND--none detected; blank--no analysis.
[5] Other--Radon (R), mineral scan (Min), and metals (M) analysis on separate table.

*See comment on 2/2/83 nitrate data in introduction to this Appendix.
**Snow conditions prevented direct sampling from the tile line (DT-2). This sample was collected from the drainage ditch into which DT-2 empties.

Table 1-26. Water analyses for tile line, site DT-3.

Date	NO_3 mg/l	Bac. MPN	Temp °C	Cond. Microhs/cm[2] @ 25°C	N-Series[3] NO_3-N Org-N Amm-N mg/l	Cl- mg/l	Pest[4] µg/l	Other[5] Min or M	Notes
1983									
5/31	63	16+	10.5	640			0.26A		
7/6	67	16+	15.5				0.29A 0.38L 0.18S		
8/2	80	16+	19.0	680		21[1]	0.12A		
8/30									Not Flowing
9/27	61	16+	14.0	750				M	
10/27	47	16+	11.0	770			0.25A		
12/6	42	16+	7.0	850					
	N 6	Q_1 16+		N 5					
	$\bar{X}$ 60	Md 16+		$\bar{X}$ 738					
	S 14	Q_3 16+		S 82					
	CV 23			CV 11					

[1] From mineral scan analysis
[2] From nitrogen-series analysis
[3] Nitrogen-series analysis; values from top to bottom are: Nitrate-N, Organic-N, Ammonia-N; note nitrate expressed as N in this column, shown as NO_3 in first column
[4] Pesticide concentrations; A--Atrazine; B--Bladex; L--Lasso; S--Sencor; D--Dual; R--Furadan; ND--none detected; blank--no analysis
[5] Other--Mineral scan (Min) and metals (M) analysis on separate table

APPENDIX II

MISCELLANEOUS WATER ANALYSES

Table 2-1. Miscellaneous water analyses from wells and surface-water sites in Floyd and Mitchell Counties.

Date	Geologic Region/ Site	T	R	S	NO_3 mg/l	BAC MPN	Temp °C	Cond. Microhos/cm² @ 25°C	Pesticide[1]	Notes/ Sample Location
	Deep									
										Flowing well
4/18	DW-1	96	16	35	<5	0				
7/6	GES-1	98	15	21	<5	2.2				House Tap
	GES-2	98	15	21	<5	0				House Tap
	Shallow									
4/4	54-B	97	16	7	58	16+				Outside Hydrant
	55	99	15	3	58	0			1.6A	House Tap
	56	--	--	--	36	16				Outside Hydrant
	60	--	--	--	43	16+				Outside Hydrant
	Karst									
4/4	58	98	17	28	43	0				
5/31	SHF-B	96	16	3	5	0				House Tap
7/6	SHF-B	96	16	3	31	2.2	9.0			House Tap
9/27	SHF-C	96	16	3	36	5.5	13.0	700		Outside Hydrant
10/27	CAT	98	17	36	41	16+				Outside Hydrant
	Incipient Karst									
12/6	42-A	99	17	5	59	0	6.0	635	0.3A	Outside Hydrant
	42-B	99	17	4	64	16+	9.0	825	0.2A 0.1S	Outside Tap
	42-C	99	17	4					0.17A	House Tap
	Surfacewater Sites									
10/27	LCR	96	15	23	32	16+	11.0	520		Little Cedar River
12/6	LCR	96	15	3	29	16+	0	595		Little Cedar River

[1]Pesticide concentrations μg/l; A--atrazine; S--Sencor; Blank--no analysis.

Table 2-2. Radon analyses from Floyd and Mitchell Counties, 4/3/83.[1]

Geologic Region/ Site	Radon piCi/l
Network Well	
Deep	
16	430±44
27	38±13
31	330±38
Shallow	
6	240±30
8	520±54
32	510±52
41	1300±120
49	390±38
Karst	
22	240±29
53	440±45
54-A	460±44
57	390±39
Incipient Karst	
33	660±63
42	530±55
43	950±90
Surfacewater Sites	
CR-1	24±7
GC-1	170±21
BO	150±18
Tile Lines	
DT-1	1200±110
DT-2	700±67
Osage Spring	280±30

Site	Radon piCi/l
Misc. Well Sites	
54-B	300±32
55	470±50
56	210±26
58	1200±110
60	420±45

[1]All analyses expressed as picoCuries per liter.

Table 2-3. Metal analyses from wells, surfacewaters, and tile lines in Floyd and Mitchell Counties, 9/27/83.

Site	As	Ba	Cd	Cr	Cu	Pb	Hg	Se	Ag	Zn	Ni
Wells											
4	<0.01	<0.01	<0.001	<0.01	0.02	<0.01	<0.001	<0.01	<0.01	0.04	<0.1
6	<0.01	<0.1	<0.001	<0.01	0.09	<0.01	<0.001	<0.01	<0.01	0.36	<0.1
8	<0.01	<0.1	<0.001	<0.01	<0.01	<0.01	<0.001	<0.01	<0.01	0.04	<0.1
16	<0.01	<0.1	<0.001	<0.01	<0.01	<0.01	<0.001	<0.01	<0.01	<0.01	<0.1
22	<0.01	0.2	<0.001	<0.01	<0.01	<0.01	<0.001	<0.01	<0.01	0.52	<0.1
27	<0.01	<0.1	<0.001	<0.01	<0.01	<0.01	<0.001	<0.01	<0.01	0.03	<0.1
31-A	<0.01	0.2	<0.001	<0.01	0.01	<0.01	<0.001	<0.01	<0.01	<0.01	<0.1
32	<0.01	0.3	<0.001	<0.01	0.04	<0.01	<0.001	<0.01	<0.01	0.08	<0.1
33	<0.01	<0.1	<0.001	<0.01	0.01	<0.01	<0.001	<0.01	<0.01	<0.01	<0.1
41	<0.01	<0.1	<0.001	<0.01	<0.01	<0.01	<0.001	<0.01	<0.01	0.02	<0.1
42	<0.01	<0.1	<0.001	<0.01	0.03	<0.01	<0.001	<0.01	<0.01	<0.01	<0.1
43	<0.01	<0.1	<0.001	<0.01	<0.01	<0.01	<0.001	<0.01	<0.01	0.14	<0.1
43-A	<0.01	<0.1	<0.001	<0.01	0.01	<0.01	<0.001	<0.01	<0.01	0.07	<0.1
49	<0.01	<0.1	<0.001	<0.01	0.12	<0.01	<0.001	<0.01	<0.01	1.2	<0.1
53	<0.01	<0.1	<0.001	<0.01	0.09	<0.01	<0.001	<0.01	<0.01	0.01	<0.1
54-A	<0.01	0.2	<0.001	<0.01	0.03	<0.01	<0.001	<0.01	<0.01	0.02	<0.1
OS	<0.01	0.1	<0.001	<0.01	<0.01	<0.01	<0.001	<0.01	<0.01	<0.01	<0.1
Surfacewater Sites											
CR-1	<0.01	<0.1	<0.001	<0.01	<0.01	<0.01	<0.001	<0.01	<0.01	<0.01	<0.1
BO	<0.01	<0.1	<0.001	<0.01	<0.01	<0.01	<0.001	<0.01	<0.01	<0.01	<0.1
GC-1	<0.01	<0.1	<0.001	<0.01	<0.01	<0.01	<0.001	<0.01	<0.01	<0.01	<0.1
Tile Lines											
DT-2	<0.01	0.2	<0.001	<0.01	<0.01	<0.01	<0.001	<0.01	<0.01	<0.01	<0.1
DT-3	<0.01	0.2	<0.001	<0.01	<0.01	<0.01	<0.001	<0.01	<0.01	<0.01	<0.1

II. DEVONIAN STRATIGRAPHY OF NORTH-CENTRAL IOWA: A Geologic Framework for the Devonian Aquifer and Karst Systems in Floyd-Mitchell Counties

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ABSTRACT

New lithostratigraphic interpretations of Middle-Upper Devonian carbonate rocks across north-central Iowa suggest that a three-part aquifer system may exist in this region. Limited observations of potentiometric heads in the Charles City area of Floyd County support this contention. Cored intervals of Devonian strata at Mason City (Cerro Gordo County)and Charles City (Floyd County), as well as numerous exposures across northern Iowa, have been of critical importance for recognizing and defining lithostratigraphic units across a large portion of the area. Devonian rocks in this region are presently divided into five formations, which in ascending order include: the Spillville, Wapsipinicon, Cedar Valley, Shell Rock, and Lime Creek formations.

Fracture permeability of porous, vuggy dolomites of the Spillville Formation results in this interval being utilized as an aquifer, informally termed the "lower aquifer," across much of northern Iowa. The abundance of shaley and argillaceous strata in the overlying Wapsipinicon Formation suggests that it serves as an upper confining unit for the "lower aquifer." The apparent high potentiometric surface of the "lower aquifer" in Floyd County, and the westward and southward pinchout beneath the Wapsipinicon Formation, largely restricts vertical groundwater flow in this aquifer.

The Cedar Valley Formation can be informally subdivided into five members, designated in ascending order, Units A through E. Units A, B, and C exhibit a prominent cyclic character, and the stratigraphic contacts between them are drawn at the top of each depositional cycle. Each cycle records a major transgressive-regressive sequence. Fossiliferous dolomitic intervals record

deposition in open-marine carbonate shelf environments during successive transgressive phases, whereas laminated, intraclastic, and brecciated carbonates record deposition in shallow, restricted subtidal and tidal flat settings during each regressive phase. Unit A may represent a separate hydrologic subsystem ("middle aquifer") across most of northern Iowa. It is confined below by shales and shaley carbonates of the Wapsipinicon Formation, and above by the "Rapid shale," which is stratigraphically placed in the upper part of Unit A. Intervening carbonate strata (Units D and E) between the top of Unit C and the base of the Shell Rock or Lime Creek formations are informally included in the "Upper Cedar Valley Formation." Strata (Unit E) included in the "Upper Cedar Valley" may be correlative, in part, with the Shell Rock Formation. "Upper Cedar Valley" and Shell Rock strata in areas of shallow bedrock display prominent to incipient karst development in portions of Floyd and Mitchell counties. These karstified areas are developed in regions where Units D and E are predominantly limestone. The relative vertical continuity of carbonate strata in Units B and C, and "Upper Cedar Valley" (Units D and E) suggest that these strata may form part of a single aquifer system ("upper aquifer") which is confined below by the "Rapid shale."

The Lime Creek Formation is subdivided into three members, which in ascending order include: Juniper Hill, Cerro Gordo, and Owen. The Juniper Hill Shale and the Cerro Gordo Member, where it is predominantly a shale, form a prominent confining unit for the underlying "upper aquifer" (Unit B through Shell Rock) in western Floyd and Cerro Gordo counties. Shales of the Cerro Gordo Member are laterally replaced to the west by carbonates and together with the overlying Owen carbonates may form part of a local aquifer system informally termed the "Lime Creek aquifer." This aquifer is confined beneath Devonian shales of the Yellow Spring Group to the southwest in north-central Iowa.

Cretaceous rocks locally and unconformably overlie Middle and Upper Devonian strata across northern Iowa. These rocks are assigned to the Windrow Formation and include three general lithologies: 1) claystone or mudstone; 2) sandstone; and 3) conglomerates. Where Windrow claystones/mudstones are well developed, they may serve locally to confine the underlying "upper aquifer" or the "Lime Creek aquifer." Local occurrences of friable Windrow sandstones could also conceivably yield water to shallow wells in portions of north-central Iowa.

INTRODUCTION

Although parts of the Devonian stratigraphic sequence in north-central Iowa have been studied in detail, a significant portion has received little study and remains poorly understood. In addition, the relationships between the stratigraphy and geohydrology are not yet well defined. During 1983, as part of a study of the hydrogeology and groundwater quality in the Floyd-Mitchell County area, Devonian stratigraphic studies were conducted in north-central Iowa utilizing both surface exposures and subsurface well data. A summary of these investigations is included in this report. However, many outstanding questions remain, and this summary must be regarded as preliminary in nature.

Although the primary focus of this study has been in Floyd and Mitchell counties, a broader regional perspective was needed to clarify many stratigraphic correlations. Therefore, surface and subsurface investigations of Devonian strata were also conducted in Winneshiek, Fayette, Howard, Chickasaw, and Cerro Gordo counties in northern Iowa, and in adjacent areas of southeastern Minnesota. A cored interval of the Devonian sequence at Mason City, Cerro Gordo County, has been of critical importance for reorganizing and defining stratigraphic units (see Appendix and figure 3). Additional cores from the LaBounty Disposal Site at Charles City, Floyd County (Munter, 1980), have also helped to delimit stratigraphic units within a portion of the Devonian sequence.

Preliminary biostratigraphic studies were also undertaken to help provide a basis for correlations within the Devonian sequence. Conodonts (phosphatic tooth-like microfossils) were recovered from formic acid residues of samples collected at surface exposures and from the Mason City core. Preliminary results are discussed in this report, but details of these studies are forthcoming.

The Devonian sequence in north-central and northeast Iowa is divided into five formations which, in ascending order, include: Spillville, Wapsipinicon, Cedar Valley, Shell Rock, and Lime Creek formations. These formations are further subdivided into members and other informal stratigraphic units. Proceeding to the west in the study area, in general, progressively younger Devonian rock units are encountered at the surface.

SPILLVILLE FORMATION

The Spillville Formation was named by Klapper and Barrick (1983) for the basal Devonian dolomite unit exposed in northeast Iowa and southeast Minnesota. This unit had previously been included within the Cedar Valley Formation (Solon Member) by most geologists prior to the 1980s. Calvin (1903a) described the lower 40 feet (12 m) of this unit, the "Productella beds," as a massive, vesicular dolomite with fossil molds; the upper 15 feet (4.5 m) of bedded dolomite which contained "large included masses of calcite" was termed the "calcite-bearing beds." He correlated the "Productella" and "calcite-bearing beds" with strata in Buchanan County that are now included within the lower portion of the Cedar Valley Formation. Calvin's correlation, now known to be in error, was adapted by Kohls (1961) and Mossler (1978). They termed the basal Devonian dolomite unit in northeast Iowa and adjacent Minnesota the "Solon Member," the basal member of the Cedar Valley Formation. However, Koch and Michael (1965) suggested the possible equivalency of this dolomite unit with the Otis Member (Wapsipinicon Formation) of east-central Iowa. This correlation was later supported by Klapper and Barrick (1983) and Bunker et al. (1983). Nevertheless, Dorheim and Koch (1966) referred this unit back to the Cedar Valley Formation, assigning it to the Solon Member.

The Spillville Formation is a medium- to extremely finely-crystalline dolomite. It is commonly vuggy, and contains scattered to abundant fossil molds (primarily echinoderm debris, brachiopods, and corals). Large masses of calcite locally fill the irregular void spaces in the rock, especially in the upper one-third of the formation. The basal 5 to 30 feet (1.5 to 9 m) of the Spillville across northern Iowa contains varying amounts of silty and sandy argillaceous dolomite, silty to sandy dolomitic or calcitic shale, and sandstone. Basal sandy Spillville strata at Charles City locally contain abundant calcite. Where the Spillville overlies cherty carbonates of the Ordovician Maquoketa Formation (especially the Fort Atkinson Member), the basal few feet may incorporate reworked angular clasts of Maquoketa chert. This clastic-rich basal Spillville interval has been informally termed the "Lake Meyer member" (Bunker et al., 1983). Previous workers assigned clastic-rich strata in Minnesota, which occupy the same general stratigraphic positions as the "Lake Meyer member," to the Ordovician Maquoketa Formation. However, this member unconformably overlies the Maquoketa and is conformable with the overlying Spillville carbonates in Iowa. At most localities the Spillville carbonate rocks are exclusively dolomite. However, some beds of dense dolomitic limestone are locally noted in Minnesota (Mossler, 1978) and in southwest Winneshiek County, Iowa, near the southern extent of the Spillville, where it lies immediately north of the pre-Devonian Silurian escarpment.

Where covered by younger Devonian strata, the Spillville Formation ranges from 50 to 100 feet (15 to 30 m) in thickness, and over most of the study area it typically ranges from 60 to 80 feet (18 to 24 m) in thickness. It is thickest in the Charles City area of Floyd County. The Spillville thins rapidly to the south across southwest Winneshiek, central and southern Chickasaw, southeast Floyd, and northern Butler counties. The Spillville is absent across the "Bremer High," a pre-Devonian Silurian paleoescarpment feature that extends across central to southern Bulter, southeast Chickasaw, Bremer, Fayette, Grundy, and Black Hawk counties (Bunker et al., 1983). The Spillville Formation is constrained to an area north of the pre-Devonian Silurian erosional edge in northern Iowa. Near the Silurian edge, a thinned Spillville Formation locally overlies the Brainard Shale of the Maquoketa Formation; in these areas the Spillville is notably more argillaceous and silty than in areas farther north. Elsewhere the Spillville variably overlies the Fort Atkinson, Clermont, or Elgin members of the Maquoketa, as the Maquoketa sequence is truncated to the north beneath the Devonian. The Spillville ranges from 0 to 70 feet (0 to 21 m) thick within its outcrop belt in western Winneshiek, eastern Howard, and eastern Chickasaw Counties. The formation is primarily a subsurface stratigraphic unit across most of the study area. The Spillville Formation has not been recognized in the subsurface of Cerro Gordo County, where the Wapsipinicon (?) or Cedar Valley Formation directly overlies the Ordovician surface (figure 1). Although the western extent of the Spillville in north-central Iowa is not well defined by available well data, the Spillville apparently pinches out to the west in western Floyd or eastern Cerro Gordo County.

The Spillville Formation is a Middle Devonian rock unit and has yielded conodonts of late Eifelian and early Givetian (?) age (Klapper and Barrick, 1983). It presumably is equivalent to sparsely fossiliferous carbonate rocks

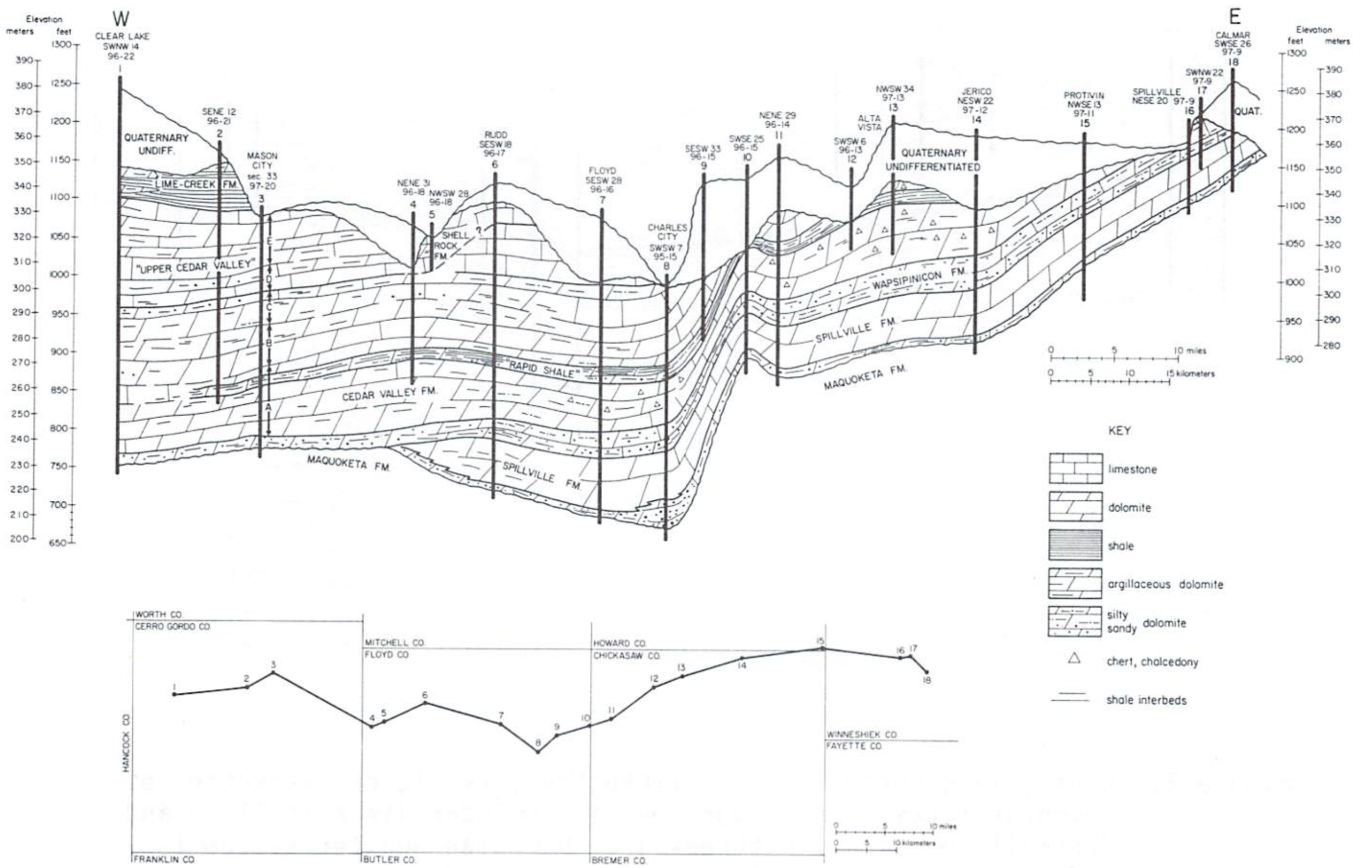

Figure 1. Generalized west-to-east lithostratigraphic cross-section of Devonian rocks across north-central Iowa. Surface and bedrock topography are approximated. Well penetrations denoted by heavy vertical lines. Description of Mason City core (loc. 3) given in Appendix. Loc. 5 is a surface quarry exposure.

of the Otis Member (Wapsipinicon Formation) in east-central Iowa. However, Spillville and Otis strata are not physically connected but are separated by the "Bremer High" (Bunker et al., 1983).

The Spillville Formation contains zones of vuggy porosity. Fracture permeability of the porous dolomites permits the utilization of the Spillville as an important aquifer in much of the study area. If this aquifer is confined to some degree by the overlying shaley Wapsipinicon and underlying Maquoketa or "Lake Meyer" strata, the lower portion of the Devonian aquifer may be separable as a discrete hydrologic unit. Where underlying Maquoketa strata are dominantly carbonates or where the "Lake Meyer" shales are poorly developed, Spillville strata may be hydrologically connected with the Maquoketa carbonates. The Spillville aquifer is informally labelled the "lower aquifer" on figure 2. Flowing wells produce water from the Spillville Forma-

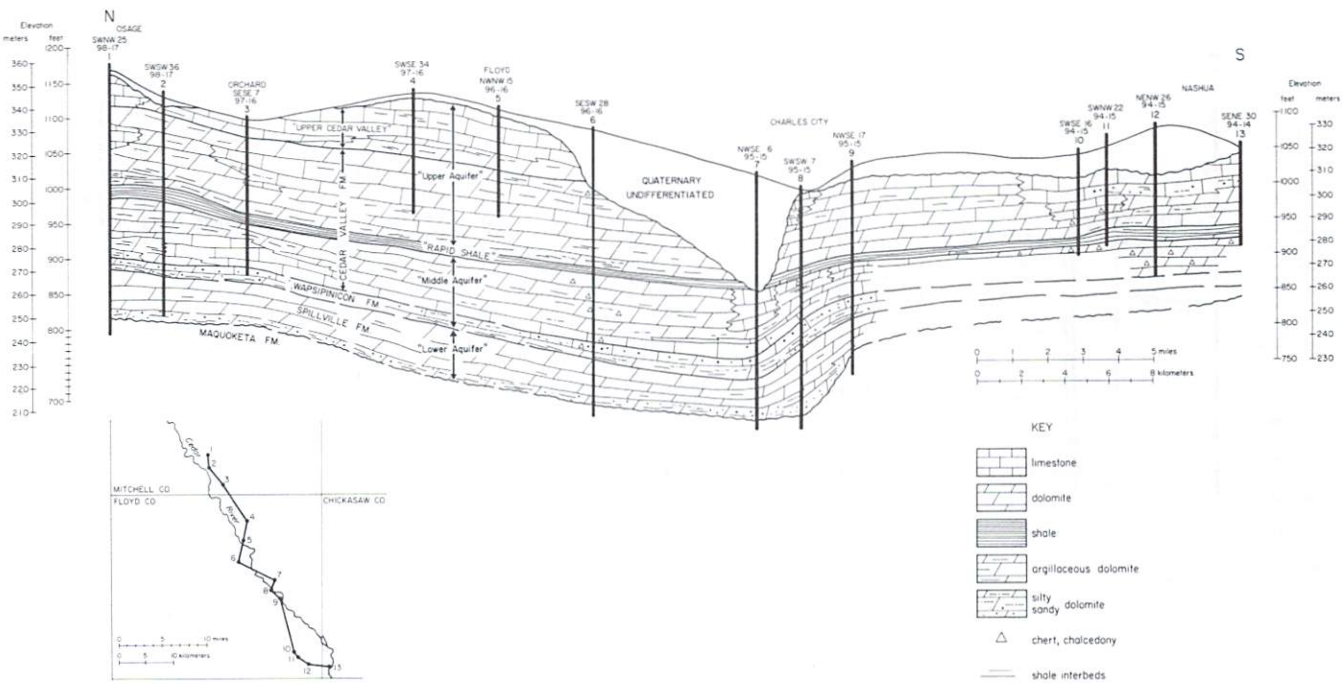

Figure 2. Generalized north-to-south lithostratigraphic cross-section of Devonian rocks along a portion of the Cedar River in Floyd and Mitchell Counties. A three-part, Devonian aquifer system is inferred on this profile. Surface and bedrock topography are generalized. Well penetrations denoted by heavy vertical lines.

tion along the Cedar River in the Charles City area of Floyd County. Flow-meter measurements within a well at the LaBounty Disposal Site in Charles City revealed that the highest rates of groundwater flow in the Devonian aquifer occur near the top of the Spillville Formation. The apparent high potentiometric surface of this lower aquifer in Floyd County, along with its westward and southward pinchout beneath the Wapsipinicon Formation, largely confines groundwater flow in a vertical sense in that area. For a time at least, the head relationship of the lower aquifer may serve to "protect" the aquifer from infiltration of surface contaminants in the Floyd County area. However, large-scale withdrawals from the lower aquifer could conceivably alter future head relationships. Additional investigations are needed to verify these interpretations.

WAPSIPINICON FORMATION

The Wapsipinicon Formation has been recognized as a distinctive rock unit across much of eastern Iowa, where it unconformably overlies Ordovician and

Silurian strata and is disconformably overlain by the Cedar Valley Formation. Previous workers generally have not recognized the Wapsipinicon Formation north of the Silurian zero edge in northeast and north-central Iowa, in part because the underlying Spillville Formation in that area was mistakenly correlated with the Cedar Valley Formation. Nevertheless, the Wapsipinicon Formation is currently recognized as a distinct stratigraphic unit in the subsurface across all of north-central Iowa. Wapsipinicon strata are exposed in portions of Bremer, Fayette, Howard, and Winneshiek (note figure 1) counties in northeast Iowa.

Three members of the Wapsipinicon Formation are recognized in northern Iowa which include, in ascending order, the Kenwood, Spring Grove, and Davenport members. The Wapsipinicon overlies the Spillville Formation with apparent conformity (?) in most of north-central and northeast Iowa, and is disconformably overlain by the Cedar Valley Formation. However, west of the Spillville Formation edge, in western Floyd or eastern Cerro Gordo County, the Wapsipinicon Formation unconformably overlies the Ordovician Maquoketa Formation. The Wapsipinicon Formation unconformably overlies Silurian strata along the trend of the "Bremer High" in northern Iowa (Bunker et al., 1983). The Wapsipinicon generally ranges from 15 to 50 feet (4.5 to 15 m) in thickness across the study area. On the "Bremer High" the Kenwood Member is locally absent, and the Spring Grove or Davenport Members directly overlie Silurian strata. The Wapsipinicon Formation may also be locally absent in portions of Bremer County where the Cedar Valley Formation unconformably overlies the highest portions of an irregular, eroded surface of Silurian dolomite (Dorheim and Koch, 1962). The formation generally thins westward across north-central Iowa (figure 1).

Strata presently assigned to the Wapsipinicon Formation were first recognized in Winneshiek and Howard counties by Calvin (1903a). He identified a poorly exposed interval of "variable strata" above the "calcite-bearing beds" of the Spillville Formation that included lithographic limestones, marly shales, and "crackled beds" (i.e. breccia). However, Calvin correlated this interval with Cedar Valley strata to the south. Koch and Michael (1965) were the first to suggest the possible correlation of these strata with the Wapsipinicon Formation. Stauffer (1922) also recognized a limestone breccia unit above fossiliferous Spillville strata in southeast Minnesota which may correlate to the Wapsipinicon Formation. Good reference exposures of the Wapsipinicon Formation are accessible near Spillville in Winneshiek County (Bunker et al., 1983, p. 29), at Fayette in Fayette County (ibid., p. 37), and near Howard Center in Howard County (NE NE NE sec. 23, T99N, R12W).

The Wapsipinicon Formation in northeast and north-central Iowa is a lithologically variable rock unit, and all three members (Kenwood, Spring Grove, Davenport) cannot be consistently identified at every locality. The Kenwood Member, the basal unit of the Wapsipinicon, is recognizable as a distinct unit across most of the study area. It ranges from about 10 to 20 feet (3 to 6 m) in thickness and is dominated by two general lithologies: 1) dolomite, argillaceous or shaley to varying degrees, commonly silty to sandy; and 2) calcareous or dolomitic shale, generally silty or sandy. Sandstone and dolomitic limestone occur in the Kenwood at some localities, and may locally include abundant calcite spar.

The lithology of the overlying Spring Grove Member, which averages about 13 feet (4 m) thick in outcrop, differs significantly from the Kenwood. The Spring Grove is characteristically identified as a sequence of faintly to prominently laminated carbonate rocks which commonly are of brownish hue and have a petroliferous odor when freshly broken. The composition of the carbonate rocks varies between dolomite, dolomitic limestone, and limestone at various localities. Non-laminated carbonate rocks, which may be argillaceous, also commonly occur in the Spring Grove. At some localities the Spring Grove is a brecciated carbonate, the brecciation probably resulting from solution-collapse of former evaporite (gypsum-anhydrite) layers. Breccia clasts of laminated carbonate rock range from a fraction of an inch up to 3 feet (1 mm to 1 m) in diameter. Breccia beds are known to grade laterally into non-brecciated, laminated carbonates over short distances. Where the Spring Grove Member is brecciated, the contact with the overlying Davenport Member may be obscure.

The Davenport Member varies in thickness from about 10 to 20 feet (3 to 6 m) across most of the study area. Exposures of Davenport strata in northeast Iowa are prominently brecciated, although the extent of brecciation in the subsurface of north-central Iowa is unknown. Exposures in Fayette and Bremer counties in the southern portion of the study area are characterized by breccias of dense lithographic limestone in a matrix of limestone or dolomite; the matrix is variably argillaceous, silty, or sandy. Angular clasts within the breccias range from a fraction of an inch up to 20 inches (1 mm to 50 cm) in diameter. Many of the breccias apparently were formed by dissolution and collapse of interbedded evaporites (gypsum-anhydrite). (The Davenport presently includes evaporites in portions of southeast and central Iowa.) Thin shales and lithographic limestones, and silty argillaceous limestones and dolomites also occur in the sequence. Exposures in Howard and Winneshiek counties in the northeast part of the study area also are characterized by limestone breccias. However, these breccias characteristically lack lithographic limestones, and the contained clasts are primarily composed of very argillaceous dolomite or limestone. The angular clasts range in size from a fraction of an inch up to 3 inches (1 mm to 7 cm) in diameter. The matrix is a limestone or dolomitic limestone. Thin silty shales and laminated limestones also occur locally within the Davenport. Subsurface Davenport strata to the west are of similar lithology and include limestones and dolomites, in part argillaceous, silty, or sandy.

The Wapsipinicon Formation in the subsurface of Cerro Gordo County cannot be subdivided into members. In the Mason City core the thin Wapsipinicon (?) interval (15 ft.; 4.5 m) is primarily an argillaceous, silty to sandy dolomite. Thin-bedded and argillaceous laminated dolomites and thin shales are also noted. Brecciated and intraclastic dolomites occur in the Mason City core (see Appendix); breccia clasts vary from a fraction of an inch to 1 inch (1 mm to 2 cm) in diameter. Most or all of the Wapsipinicon Formation at Mason City probably correlates to the Davenport Member. However, an alternate interpretation of this basal Devonian unit at Mason City is that it may represent a basal clastic-rich unit of the Cedar Valley Formation.

The Wapsipinicon Formation in northern Iowa is characteristically unfossiliferous, although stromatolites occur locally within the Spring Grove Member. Its stratigraphic position between the fossiliferous Spillville and Cedar Valley Formation suggest that the Wapsipinicon in northern Iowa is probably of early to middle Givetian age.

The abundance of shaley and argillaceous strata in the Wapsipinicon Formation of northern Iowa, especially in the Kenwood Member, suggests that it would tend to impede vertical groundwater flow. As noted previously, the Wapsipinicon Formation may serve as a confining unit for the underlying lower aquifer, although further hydrogeologic data is needed to verify this speculation.

CEDAR VALLEY FORMATION

The Cedar Valley Formation forms the bedrock surface over large areas of north-central and northeast Iowa, including portions of Fayette, Winneshiek, Bremer, Chickasaw, Howard, Mitchell, Floyd, Butler, Cerro Gordo, and Worth counties. It is exposed at numerous quarries, road cuts, and river valley outcrops in the area. The Cedar Valley Formation originally was named for the series of exposures of Devonian carbonate rocks along the valley of the Cedar River, although no type locality was designated (McGee, 1891). As originally defined, it included the Devonian sequence above the Silurian unconformity and below the "Hackberry Shale" (Lime Creek Formation). Subsequent recognition of the Wapsipinicon and Shell Rock Formations restricted the Cedar Valley Formation to a position between those two formations.

The Cedar Valley Formation is best known from exposures in the Iowa City area of Johnson County, where the formation is divided, in ascending order, into three members: Solon, Rapid, and Coralville. Miscorrelation of these three members into the Devonian sequence of northern Iowa and southeast Minnesota has persisted until the 1980s. Strata previously included in the "Solon Member" in northeast Iowa and adjacent Minnesota (Mossler, 1978) are now included in the Spillville Formation. "Lower Rapid" strata in the same area (Dorheim and Koch, 1966) are now included in the Wapsipinicon Formation. The lithologic characteristics of rocks included in the Cedar Valley of northern Iowa are different than those of the Cedar Valley in the Iowa City area. Exact regional correlations of the three members of the Cedar Valley Formation are not known with certainty. Thomas (1920, p. 410) also stated that the Cedar Valley subdivisions in Johnson County cannot be applied in northern Iowa. Because of these uncertainties, use of the terms "Solon," "Rapid," and "Coralville" in northern Iowa is discouraged. However, a useful stratigraphic subdivision of the north-central Iowa Devonian can be recognized using the deep core from Mason City (see Appendix and figure 3). Therefore, for the purposes of this report the Cedar Valley Formation is informally subdivided into five members, which are labelled in ascending order, Units A through E. These units probably will be given formal member status pending further studies. Correlation uncertainties in the upper portion of this carbonate sequence (Units D and E) raise doubts concerning the inclusion of this interval within the Cedar Valley Formation. This interval will be discussed in the next section under the heading "Upper Cedar Valley Formation."

Units A, B, and C of the Cedar Valley in northern Iowa exhibit a prominent cyclicity, and the stratigraphic contacts between them are drawn at the top of each depositional cycle. Each of these three cycles are characterized by a similar lithologic sequence, which in ascending order include: 1) fossiliferous dolomites, commonly vuggy; and 2) generally unfossiliferous dolomites and limestones, in part laminated, intraclastic, brecciated, or shaley. Each cycle apparently records a major transgressive-regressive depositional episode. The fossiliferous dolomite intervals record deposition in open-marine, carbonate shelf environments. The laminated, intraclastic, and brecciated carbonate intervals apparently record deposition in shallow, restricted, subtidal and tidal flat settings. Because of the lithologic similarity between Units A, B, and C, the stratigraphic position of individual outcrop sections or short well penetrations is difficult to ascertain. Consequently, previous studies in the area did not identify the stratigraphic sequence discussed in this report.

Where younger Devonian stratigraphic units overlie Unit C, the combined

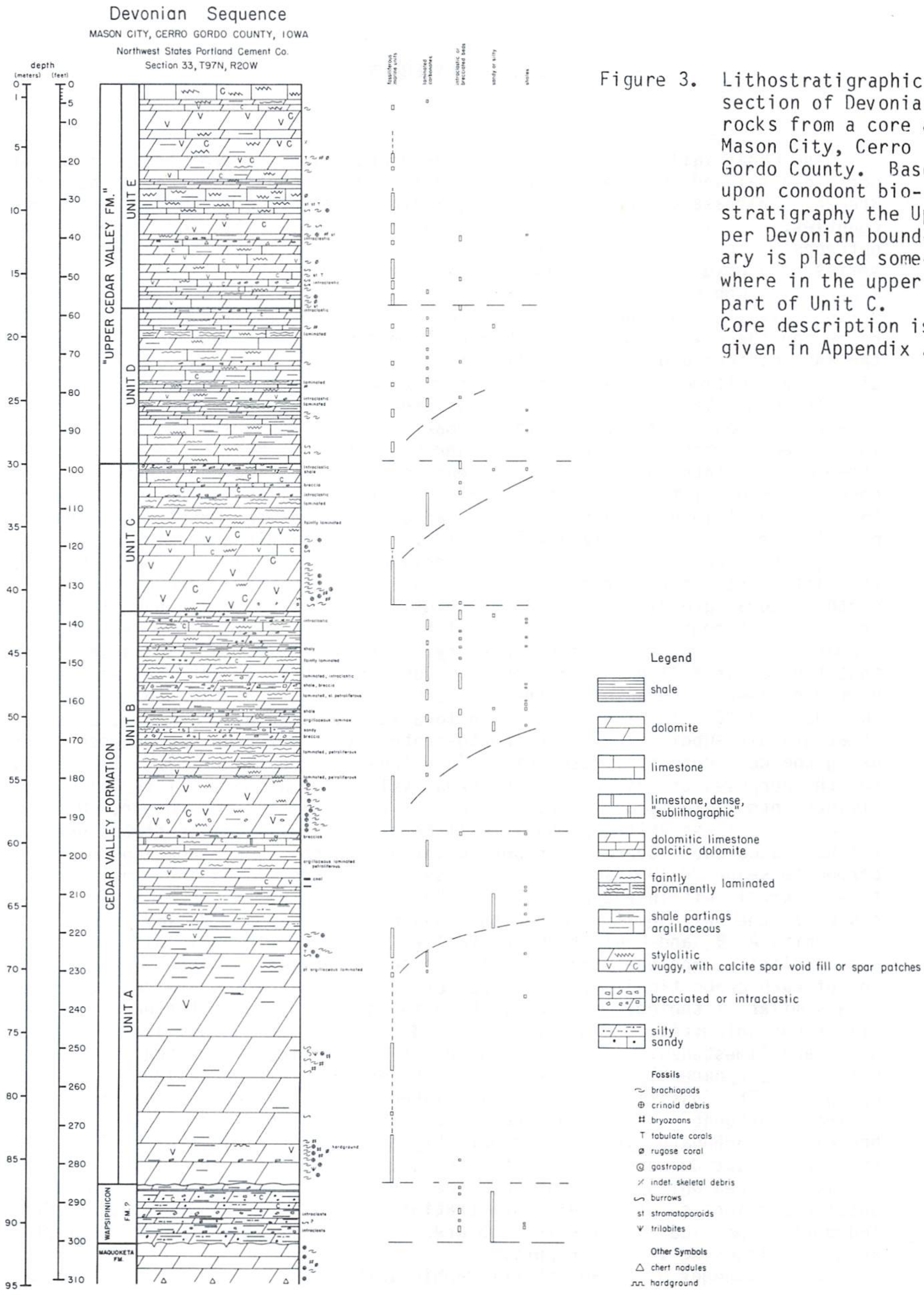

Figure 3. Lithostratigraphic section of Devonian rocks from a core at Mason City, Cerro Gordo County. Based upon conodont biostratigraphy the Upper Devonian boundary is placed somewhere in the upper part of Unit C. Core description is given in Appendix .

thickness of Units A through C ranges from about 175 to 190 feet (53 to 58 m) in the study area. Unit A, B, or C of the Cedar Valley sequence forms the bedrock surface in portions of western Winneshiek, Fayette, Chickasaw, Howard, eastern Floyd, and Mitchell counties (figure 1).

Unit A

Unit A of the lower Cedar Valley Formation, where covered by Unit B, ranges from about 65 to 115 feet (20 to 35 m) in thickness across northeast and north-central Iowa. It averages about 90 feet (27 m) thick in most of the study area. Unit A forms the bedrock surface across portions of western Winneshiek, Fayette, Chickasaw, Howard, and Mitchell counties. A buried bedrock channel in the Charles City area of Floyd County is locally incised into Unit A (figure 2).

Unit A in northern Iowa was incorrectly equated with the "Rapid Member" in previous studies (Kohls, 1961; Mossler, 1978). Mossler (1978) subdivided this interval into a "basal, massive argillaceous dolostone facies" and an overlying "upper laminated argillaceous dolostone facies." The lower portion of Unit A was informally termed the "Salisbury beds" by Klapper and Barrick (1983).

The lower two-thirds to three-quarters of Unit A is characterized by a sequence of thick-bedded dolomite with scattered to abundant fossil molds. It is variably argillaceous, and contains zones of vuggy porosity. Molds of crinoid debris, brachiopods, bryozoans, trilobites, and rugose and tabulate corals are conspicuous in some beds. Limestone and dolomitic limestone beds occur within the lower portion of Unit A in the subsurface of Floyd-Mitchell counties, and limestones (skeletal wackestones-packstones) are also noted east of southeastern Howard County in the outcrop belt (Bunker et al., 1983). Chert occurs within the dolomite sequence in portions of Fayette, Chickasaw, Howard, Bremer, southeastern Mitchell, and eastern Floyd counties. However, chert is absent in Unit A across western Floyd, most of Mitchell, Cerro Gordo, and Worth counties in Iowa, as well as in Minnesota.

The upper one-third to one-quarter of Unit A contains lithologies that differ markedly from those in the lower interval. This upper interval, as recognized in core (figure 3) and outcrop, is characterized by a sequence which includes in ascending order: 1) argillaceous to shaley, silty dolomite and shale; 2) laminated, argillaceous petroliferous dolomite and dolomitic limestone; and 3) dolomite and lithographic limestone, in part laminated, argillaceous, or brecciated. This stratigraphic sequence is virtually indistinguishable from that noted in the Wapsipinicon Formation in northeast Iowa which includes: 1) shaley, silty dolomite and shale (Kenwood Member); 2) laminated petroliferous dolomite and limestone (Spring Grove Member); and 3) brecciated lithographic limestone and dolomite, in part argillaceous (Davenport Member). The close similarity of these two sequences originally created problems in stratigraphic interpretations of the Devonian strata in the subsurface of Cerro Gordo County. However, the recovery of conodonts of Cedar Valley age from lower Unit A strata in that area (Mason City core, figure 3) supports the inclusion of this interval within the Cedar Valley sequence.

The shale and shaley dolomite interval within the upper part of Unit A is a widespread and easily recognized stratigraphic unit in the subsurface of north-central Iowa. This shaley interval has been informally termed the

"Rapid shale" by geologists at the Iowa Geological Survey, and the term has been informally used by hydrogeologists in recent years in the discussions of groundwater problems in Floyd County. Although the exact correlation of this unit to the Rapid Member of the Cedar Valley Formation in east-central Iowa is unclear, the term "Rapid shale" will be used in a tentative and informal manner in this report to refer to this shaley interval in the Cedar Valley sequence of northern Iowa. The interval undoubtedly should be given a new formal stratigraphic name because of its gross lithologic dissimilarity to Rapid strata in eastern Iowa and because of correlation uncertainties. A new name will likely be introduced for this shaley interval, pending further study. The base of the "Rapid shale" has been utilized as a stratigraphic datum to define structure contours in north-central Iowa (figure 4). This structure map delineates the westerly to southwesterly dip of Devonian strata in Chickasaw, Howard, and eastern Floyd counties and the general southward dip of Devonian strata in Mitchell, Cerro Gordo, and western Floyd counties. The "Rapid shale" ranges from about 10 to 20 feet (3 to 6 m) in thickness across the study area. It is generally thickest near its eastern erosional margin. Shale content progressively decreases to the west, and the "Rapid shale" is laterally replaced by an argillaceous to very argillaceous dolomite unit, with only minor shale in Cerro Gordo County. The "Rapid shale" is not recognized with certainty south of the study area, although some shale beds are noted in strata assigned to the upper portion of the Rapid Member (?) in Butler, Buchanan, and Black Hawk counties which may be correlative. The "Rapid shale" of north-central Iowa presumably grades southward into carbonate-dominated facies of the Cedar Valley Formation.

The uppermost portion of Unit A, above the "Rapid shale," includes dolomite, dolomitic limestone, and limestone, in part argillaceous, laminated, and brecciated. Thin seams of black carbonaceous or coaly material locally occur in this interval (figure 3). Laminated and intraclastic strata in Black Hawk and Buchanan counties which have been assigned to the "upper Rapid" member probably correlate to the upper portion of Unit A in north-central Iowa.

Unit A is widely traceable in north-central Iowa. Lithostratigraphic and biostratigraphic studies have been useful for recognizing Unit A strata in areas outside the study area. Strata correlative with Unit A in central Iowa (Dallas and Webster counties) have been described by Klug (1982). The fossiliferous, argillaceous and vuggy dolomite intervals in the lower and middle portion of Unit A corresponds to Klug's units 3 and 4 in the Webster County core sequence. Similar conodont faunas occur in this core and the Mason City core: the faunas are Givetian in age and suggest correlation in part to the Solon Member of the Cedar Valley Formation in Johnson County. The faunas are characterized by *Icriodus brevis* and various species of *Polygnathus* (including *Pol. alveoliposticus* in the lower part). The upper portion of Unit A in the Webster County core (lower unit 5 of Klug, 1982) lacks the "Rapid shale" but contains argillaceous carbonates (in part with evaporite crystal molds) and breccias. Unit A is overlain by fossiliferous Unit B strata that are tentatively correlated with the upper Rapid and lower Coralville members in eastern Iowa. Although the biostratigraphic evidence is not yet definitive, the proposed correlations suggest that the "Rapid shale" may, in fact, correlate to a portion of the Rapid Member in Johnson County.

Unit A is utilized as a source of groundwater in northern Iowa. Vuggy and fractured dolomites form a portion of the Devonian aquifer in this area. Shallow wells are developed in Unit A in areas of northeast Iowa where it forms the bedrock surface. To the west the porous, fossiliferous dolomites of Unit A are confined below by shales and shaley carbonates of the Wapsipinicon

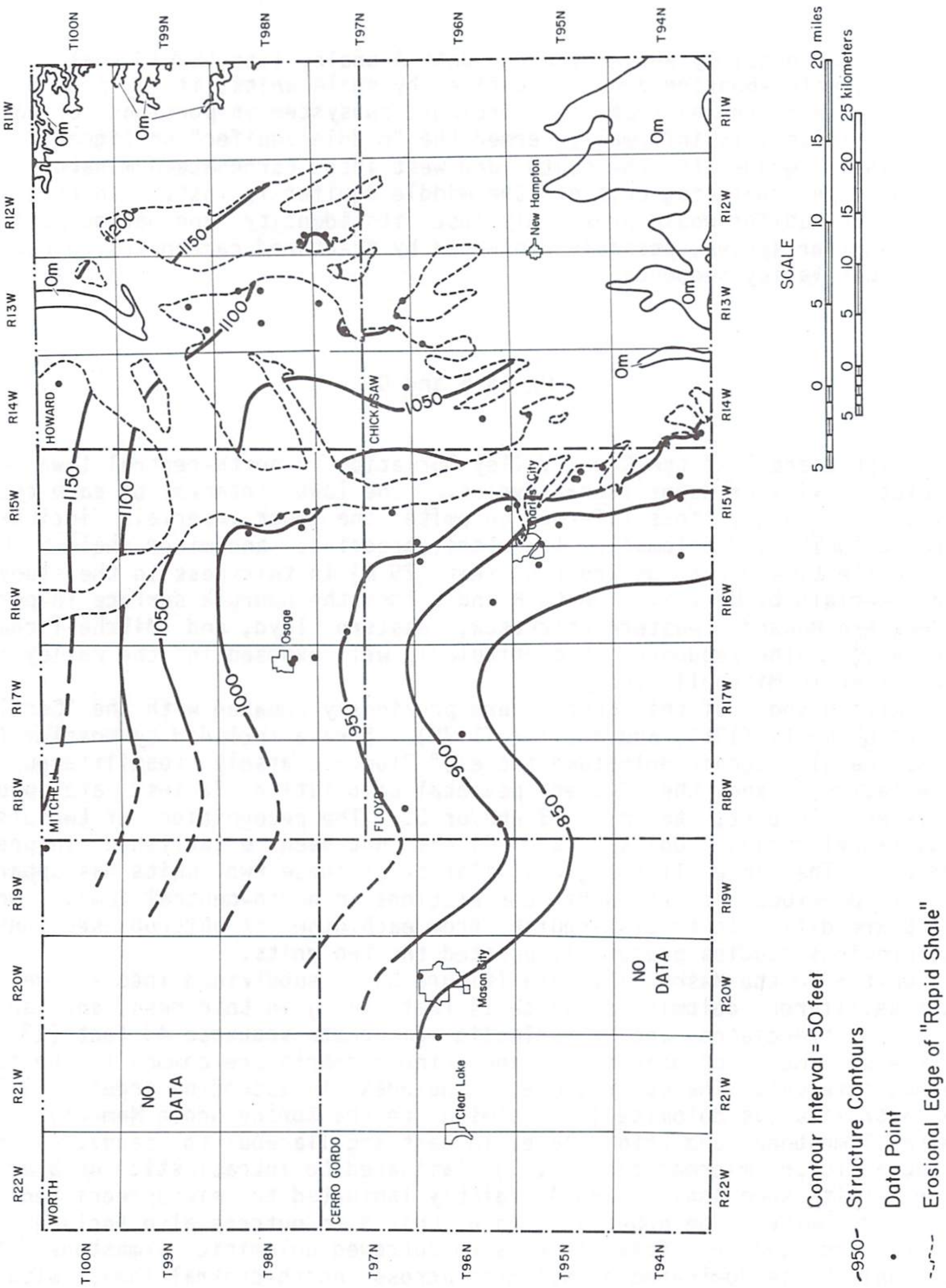

Figure 4. Structure contour map on the base of the "Rapid shale." Interpreted data points across the northern part of the map area are questionable. Some of the northern data points may relate to the Kenwood Member, Wapsipinicon Formation, or other as yet unknown shale intervals in this part of the study area.

Formation and possibly above by upper Unit A shales (the "Rapid shale"). Because this water-bearing zone is confined by shale units, it is proposed that Unit A may represent a separate hydrologic subsystem in portions of northern Iowa. This unit is informally termed the "middle aquifer" on figure 2. The "Rapid shale" grades to the south and west into carbonate-dominated facies, and the upper confining unit of the middle aquifer is lost. In those areas the middle aquifer would presumably lose its identity and become part of a larger aquifer system, possibly connected by fractured carbonates to the overlying Cedar Valley sequence.

Units B and C

Units B and C of the Cedar Valley Formation in north-central Iowa include two closely similar depositional cycles. The lower interval of each cycle is dominated by vuggy, fossiliferous dolomite; the upper intervals include laminated dolomite and dolomitic limestone, breccias, and minor shale. Unit B and C collectively average about 95 feet (29 m) in thickness in the study area where overlain by Unit D. Units B and C form the bedrock surface in portions of western Howard, western Chickasaw, eastern Floyd, and Mitchell counties (figure 1). The sequence is particularly well exposed in the valley of the Cedar River in Mitchell County.

Units B and C of this report were previously equated with the "Coralville Member" by Kohls (1961) and Mossler (1978). Strata included by Mossler (1978) in the "basal biogenic dolostone facies," "lower sparsely fossiliferous dolostone facies," and the "lower pelletal calcilutite facies" are probably equivalent, in part, to Units B and/or C. The recognition of two distinct depositional cycles (Units B and C) has not been established in previous studies. The close lithologic similarity of these two units has apparently hindered previous stratigraphic correlations in north-central Iowa. Units B and C are difficult to distinguish from each other in outcrop sections, and most previous studies presumably equated the two units.

Unit B in the Mason City core (figure 3) is subdivided into a lower vuggy and fossiliferous dolomite sequence 14 feet (4 m) in thickness, and an upper laminated, brecciated, and intraclastic carbonate sequence 43 feet (13 m) in thickness. Molds of brachiopods and crinoid debris are common in the fossiliferous interval. The upper sequence includes, in ascending order: 1) laminated petroliferous dolomite (very similar to the Spring Grove Member); 2) dolomite, limestone, and thin shale, in part argillaceous to sandy, laminated, intraclastic or microbrecciated; 3) laminated to intraclastic or brecciated dolomite with some shale; and 4) faintly laminated to microbrecciated argillaceous dolomite. The upper portion of Unit B in outcrop also includes stromatolites and sparsely fossiliferous to burrowed dolomitic limestones (figure 5). Unit B is dominated by dolomite across north-central Iowa, with minor limestone and shale noted at many localities. Some chert apparently occurs in Unit B in southeastern Floyd County.

Unit C strata closely resembles that of Unit B. However, the lower vuggy fossiliferous dolomite is thicker in Unit C, and the upper laminated and brecciated interval is thinner. In the Mason City core (figure 3) the vuggy fossiliferous dolomite in Unit C is 22 feet (6.7 m) thick and contains common to abundant brachiopod and crinoid debris molds. The upper interval of Unit C at Mason City, which is 16.5 feet (5 m) thick, can be divided into two sub-

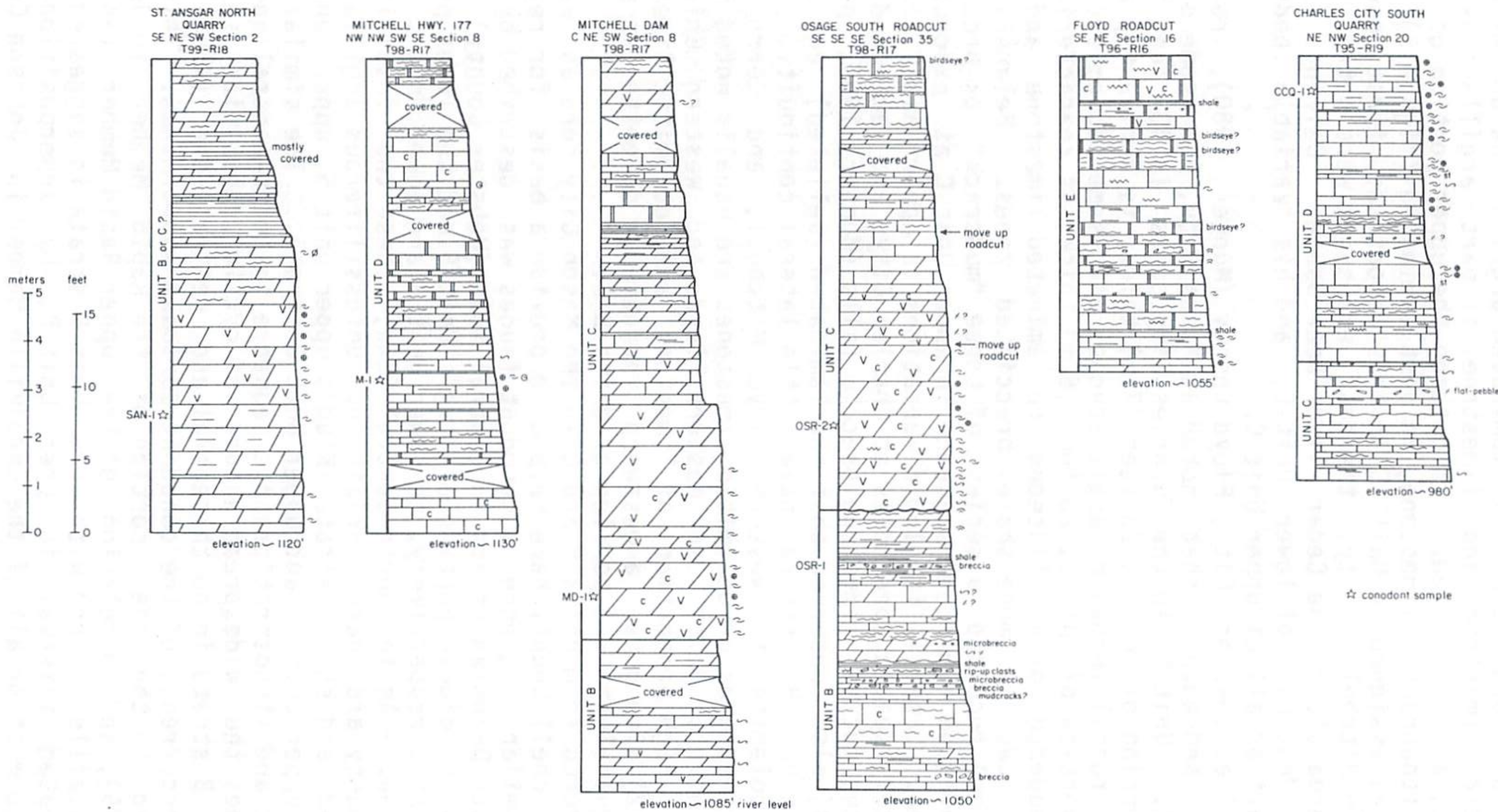

Figure 5. Lithostratigraphic sections of a series of six exposures along the Cedar River in Floyd and Mitchell counties. Unit designations (A through E) are tentatively assigned to each section. Lithologic symbols as in Figure 3.

units, which in ascending order are: 1) laminated argillaceous dolomite, and 2) dolomite, dolomitic limestone, and limestone, in part argillaceous, laminated, intraclastic, and brecciated. In outcrop the upper portion of Unit C also contains some lithographic limestone, in part laminated (figure 5). The stratigraphic interval assigned to Unit C in this report was first described by Calvin (1903b) in Mitchell County; the best exposures were noted in the "Chandler Cliffs" area along the Cedar River near Osage. Calvin's (1903b) "Athyris zone" includes part of lower Unit C, and his "variable beds" apparently comprise part or all of upper Unit C.

Cores of Unit C at Charles City, Floyd County (Munter, 1980), record a similar stratigraphic sequence to that noted at Mason City, but some differences are noteworthy. Unit C in the Charles City cores is 43 feet (13 m) thick. The lower portion of Unit C, 23 feet (7 m) thick, is dominantly a vuggy dolomite, in part fossiliferous or argillaceous, with some dolomitic limestone. The upper portion of Unit C, 20 feet (6 m) thick, is characterized by a highly variable sequence of argillaceous to laminated limestone and dolomitic limestone with two or more shaley brecciated zones. Belanski (unpublished field notes) recorded a series of three "mudcrack" or brecciated zones within the laminated limestone sequence in upper Unit C at exposures in the Charles City area. Lateral lithologic variations in upper Unit C are also apparent in the closely spaced core holes at Charles City, and laminated limestones are locally cut out by limestone breccia fills (Munter, 1980, p. 71). Mossler (1978, p. 14) also observed that the laminated (pelleted) and intraclastic limestones in Unit B-C strata "have little lateral continuity." Unit C is dominated by dolomite in western Floyd, Mitchell, and Cerro Gordo counties, although limestones or dolomitic limestones are usually noted in the upper portion. However, Unit C in eastern Floyd and western Chickasaw counties contains a high proportion of limestone and dolomitic limestone. Mossler (1978, p. 12) also noted a westward increase in dolomite in strata that are probably equivalent to a portion of Units B-C.

Conodonts recovered from Units B and C in the Mason City core as well as from exposures in Mitchell County have helped to provide a basis for regional correlations. A similar sequence of conodont faunas was described by Klug (1982) from subsurface Devonian strata in central Iowa (Webster County). Fossiliferous strata in the middle portion of Klug's Unit 5 and the lower portion of his Unit 6 correlate, respectively, to lower Unit B and lower Unit C strata in north-central Iowa. As in north-central Iowa, these two fossiliferous units in Webster County are each overlain by unfossiliferous argillaceous, laminated, brecciated, and shaley strata (Klug's upper unit 5, upper unit 6), which correlate to upper Unit B and upper Unit C strata. The similarity of the biostratigraphic and lithostratigraphic sequence in north-central and central Iowa establishes the widespread nature of cyclic deposition in these areas. Lower Unit B strata in north-central and central Iowa (Klug, 1982) contain the lowest occurrence of the conodont *Icriodus subterminus*. This conodont is first noted in the upper portion of the Rapid Member in Johnson County (Klapper, 1975), and correlation of the upper Rapid Member (and possibly lowermost Coralville Member) with lower Unit B strata is suggested. The laminated and brecciated interval in upper Unit B, by superposition, presumably correlates to most or all of the Coralville Member in Johnson County. Lower Unit C in north-central (Mason City core, figure 3) and central (Webster County core, Klug, 1982) Iowa records the first occurrence of the conodont *Pandorinellina insita*. This conodont also makes it first appearance in Johnson County in the State Quarry Limestone, and correlation of lower Unit C with the State Quarry (and possibly strata assigned to the upper "Coralville" in other areas of eastern Iowa) is suggested. The *insita* Fauna is defined as the fauna dominated by the name-giver in strata below the first appearance of *Ancyrodella rotundiloba*. The first occurrence of *A. rotundiloba* defines the base of the Lower *asymmetricus* Zone. Thus, the first occurrence of the *insita* fauna is regarded as equivalent to the Lowermost *asymmetricus* Zone (Klapper and Johnson, 1980). According to the recent definition of the International Subcommission on Devonian Stratigraphy, the Middle-Upper Devonian boundary is placed at the base of the Lower *asymmetricus* Zone (Ziegler and Klapper, 1982). The Middle-Upper Devonian boundary, therefore, probably should be marked somewhere near the top of Unit C (figure 3).

The upper portions of Units A, B, and C are characterized by unfossiliferous laminated and brecciated strata that apparently were deposited in tidal flat and restricted marine environments (see environmental criteria listed by Anderson and Wigg, 1974). The upper portion of each of these units records the regressive (shallowing) phase of cyclic deposition. Fossiliferous carbonate strata in the lower portions of Units A, B, and C record open-marine deposition during the transgressive (deepening) phase of each cycle. Although precise correlations are not yet established, it is reasonable to suggest that the Cedar Valley evaporites (anhydrite-gypsum) in the central Iowa subsurface correlate, at least in part, with the regressive portions of these three cycles (i.e., upper Units A, B, and C). Evaporite crystal molds are noted within some of the laminated/brecciated intervals in the Webster County core (Klug, 1982), indicating that evaporite deposition was coincident, at least in part, with the regressive phases of carbonate deposition. Some of the brecciated zones in north-central Iowa are intraclastic and probably formed by storm or tidal rip-up of shallow restricted marine and tidal flat deposits. However, jumbled breccias composed of angular clasts could conceivably have formed by solution-collapse of interbedded evaporite units within the sequence (such as described within the Wapsipinicon Formation).

Many water wells have been drilled into Units B and C in north-central Iowa. The porous, vuggy dolomites in the lower portions of each unit, if fractured, presumably would be productive water-bearing intervals. Carbonate rocks in the upper portions of Units B and C may also include productive horizons, although the common occurrence of thin shale beds and shaley strata in these intervals could retard groundwater flow to some degree. Packer tests are needed to test this contention. However, the relative vertical continuity of carbonate strata in Units B and C suggest that, in a general sense, these strata may form part of a single aquifer system. This system presumably would be confined below by the prominent "Rapid shale" in the upper part of Unit A. No prominent confining unit is identified within or above Units B and C in north-central Iowa, suggesting that these units may form the lower part of a large carbonate aquifer system which also includes "Upper Cedar Valley" strata. This proposed aquifer is informally termed the "upper aquifer" on figure 2. As the lower confining unit to this aquifer ("Rapid shale") disappears to the south and west, the upper and middle aquifers may merge into a single aquifer system. On a broader regional scale, however, additional confining intervals in the Cedar Valley sequence may further complicate the hydrologic relationships. In particular, the presence of relatively impermeable evaporites in the Devonian sequence of central Iowa may separate the Devonian aquifer into two or more subsystems and further influence groundwater flow and quality. In addition, Unit C in Webster County includes shales up to 20 feet (6 m) thick (unit 6 of Klug, 1982), suggesting that Unit C may become a prominent confining unit to the southwest of the study area.

"UPPER CEDAR VALLEY FORMATION"

Intervening carbonate strata between the top of Unit C and the base of the Shell Rock or Lime Creek formations are informally included in this report in the "Upper Cedar Valley Formation." "Upper Cedar Valley" strata reach thicknesses up to approximately 85 feet (26 m) in portions of Floyd County. This interval is disconformably overlain by the Shell Rock Formation in areas of Floyd, Butler, Worth, and Cerro Gordo counties. In western Cerro Gordo County, west of the area where the Shell Rock has been recognized, the "Upper Cedar Valley" interval is directly overlain by shales of the Lime Creek Formation. In that area the "Upper Cedar Valley" ranges from about 110 to 140 feet (33 to 42 m) in thickness. The possibility exists that some strata included in the "Upper Cedar Valley" may be correlative with the Shell Rock. The "Upper Cedar Valley" interval forms the bedrock surface over portions of Floyd, Mitchell, Butler, Cerro Gordo, and Worth counties (figures 1 and 2). It is particularly well exposed in Floyd County.

The "Upper Cedar Valley" interval was assigned to the Coralville Member of the Cedar Valley Formation by previous authors. However, the probable correlation of Unit B (and C?) with type Coralville strata in eastern Iowa (Johnson County) suggests that the "Upper Cedar Valley" sequence in north-central Iowa apparently is not represented in the Johnson County sequence. Therefore, use of the term "Coralville" for these strata is inappropriate, and new stratigraphic terminology probably should be established for the north-central Iowa sequence. Because these strata probably do not correlate with any part of the classic Cedar Valley sequence in Johnson County, they are provisionally included in an expanded Cedar Valley Formation and informally labelled "Upper Cedar Valley."

For the purposes of discussion, the "Upper Cedar Valley" sequence is subdivided into two stratigraphic units, Units D and E. Unlike Units A through C, Units D and E do not define major depositional cycles but are characterized by interbedded, fossiliferous marine carbonates and laminated, "sublithographic," and brecciated beds. As such, Units D and E may include a complex series of small-scale depositional cycles, although correlation of these minor cycles in north-central Iowa has proved difficult. In general, Units D and E include a higher percentage of limestone and fossiliferous marine carbonate strata than that noted in Units B and C.

Strata assigned to Unit D were examined in the Mason City core (figure 3) and at exposures in Floyd-Mitchell counties. The base of Unit D is drawn at the base of the first fossiliferous marine carbonate unit above the laminated or brecciated beds of upper Unit C. Unit D is 40 feet (12 m) thick in the Mason City core. The sequence there includes fossiliferous dolomite (in the lower 12 ft; 4 m), dolomitic limestone, and limestone interbedded with unfossiliferous carbonates, in part laminated, intraclastic, brecciated, or sandy. Unit D is less dolomitic to the east, and is dominated by limestone and dolomitic limestone in portions of Mitchell and Floyd counties (figure 5). The sequence includes some dense lithographic or sublithographic limestone beds in that area. Unit D is well exposed in the Charles City area of Floyd County, where limestones and argillaceous limestones are characteristic; thin shales are also noted. Fossiliferous limestones are well developed at Charles City and contain echinoderm debris, various species of brachiopods, gastropods, and branching and hemispherical stromatoporoids. The stromatoporoids locally form biostromal-like accumulations. Although stromatoporoids are locally noted in underlying Cedar Valley strata in northern Iowa, the widespread appearance of abundant stromatoporoids characterizes "Upper Cedar Valley" strata in north-central Iowa (Stock, 1982, 1984). South of the study area, abundant stromatoporoids are noted considerably lower in the stratigraphic section.

Unit E is 58 feet (18 m) thick in the Mason City core (figure 3); it marks the upper interval in the core. In ascending order it includes: 1) lower 24 feet (7.3 m), dolomite with minor dolomitic limestone, in part vuggy or stylolitic; in part fossiliferous, with stomatoporoids; interbedded laminated and intraclastic strata; 2) 7 feet (2.1 m), fossiliferous limestone with stromatoporoids; 3) 23 feet (7 m), dolomite with some dolomitic limestone, argillaceous to vuggy, fossiliferous in lower part; and 4) top 4 feet (1.2 m), limestone, stylolitic. Unit E contains proportionately less laminated, brecciated, and intraclastic strata than Unit D. Portions of Unit E are prominently stromatoporoidal in Cerro Gordo, northern Butler, and Floyd counties, and biostromes are locally developed. Unit E is dominated by dolomite and dolomitic limestone in central Cerro Gordo County, but it is predominantly a limestone (part "sublithographic") unit in Floyd, eastern Cerro Gordo, and northern Butler counties, where it also includes thin seams of shale (figure 6).

Strata included in Units D and E in this study have been assigned to various stratigraphic units by previous workers. Unit D strata in the Charles City area were informally included in the "Bloody Run" member of the Cedar Valley Formation by Belanski (unpublished field notes), although this term was never defined in the literature. Stainbrook (1944) and Koch (1970) included Unit D and E strata in Floyd and Cerro Gordo counties in the Coralville Member of the Cedar Valley Formation. Likewise, Mossler (1978) included a portion of the "Upper Cedar Valley" interval in the Coralville Member, and he recognized a "stromatoporoid biostrome facies" within Mitchell County that possibly correlates to a portion of Unit D. Relationships of "Upper Cedar Valley" strata to the Shell Rock Formation are not completely clarified. Kohls (1961) described the Mason City core (figure 3) and included the top 85 feet (26 m) within the Shell Rock Formation. The upper portion of Unit D and all of Unit E were, thereby, assigned to the Shell Rock Formation by Kohls. Koch (1970) described the Nora Member of the upper Shell Rock Formation in stratigraphic position above the Cedar Valley Formation (Unit E of this report) in portions of Cerro Gordo and Worth counties. However, Koch (1970) recognized lower Shell Rock strata (Mason City and Rock Grove members) above the Cedar Valley Formation in easternmost Cerro Gordo, western Floyd, and northern Butler counties. Koch proposed a westward overstepping of Shell Rock strata above an eroded Cedar Valley surface to explain these relationships. On the other hand, Belanski (1927) correlated lower Shell Rock strata into Cerro Gordo and Worth counties and suggested that these strata undergo significant facies changes to the north and west. Strata in those areas that Belanski correlated with the Mason City and Rock Grove members of the Shell Rock Formation were assigned to the Coralville Member of the Cedar Valley by Koch (1970, p.28-29), who stated that "the lithology of these beds is more comparable to beds that are unquestioned correlatives of the Coralville Member of the Cedar Valley Limestone in Floyd and Butler counties." Unit E includes strata that would be assigned to the Shell Rock Formation utilizing Belanski's correlations, but are assigned to the Cedar Valley Formation utilizing Koch's criteria.

One of Koch's (1970) reference sections (Williams Quarry) for the Shell Rock Formation falls along the east-west cross-section line (loc. 5, figure 1), where it apparently occupies a position roughly equivalent to "Upper Cedar Valley" strata farther west. Alternatively, the Shell Rock may occupy an

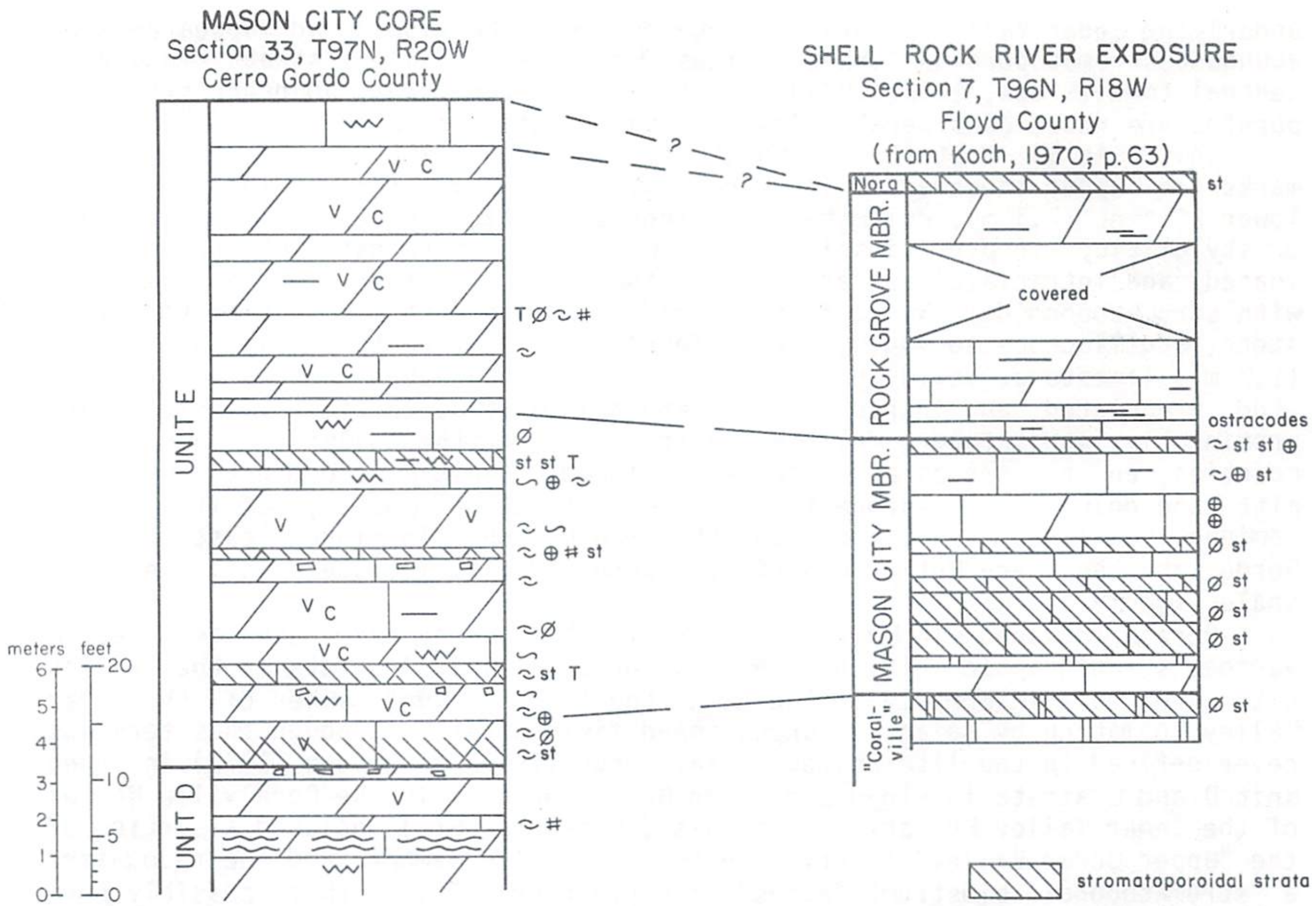

Figure 6. Lithostratigraphic comparison of the Shell Rock Formation of western Floyd County with Unit E in the Mason City core (figure 3). A possible correlation of the Mason City Member with the lower portion of Unit E is suggested. Lithologic symbols as in figure 3.

eroded channel or small basin cut into the "Upper Cedar Valley" sequence or may be structurally preserved.

Unit E strata in the Mason City core (figure 3) compares favorably with the Shell Rock Formation sequence exposed in western Floyd County (figure 6), and possible correlation of Unit E with the Shell Rock is suggested pending further study. Dense limestones in the top 4 feet (1.2 m) of the core (poor recovery) may correlate with the Nora or upper Rock Grove Member. The Nora is widely recognized in the Mason City area, where it characteristically includes stromatoporoid biostromes (Koch, 1970). However, the Nora undergoes a "facies change" northwest of Mason City, where stromatoporoids become less prominent (Koch, 1970, p. 38-39). The underlying 23.5 foot (7.2 m) thick interval in the Mason City core can be compared to the Rock Grove Member of the Shell Rock, although this interval was included in the Cedar Valley Formation by Koch (1970). This dolomite and calcitic dolomite interval in the Mason City core is partly argillaceous and vuggy, and includes some fossiliferous zones. The Rock Grove Member in western Floyd County, which ranges from about 20 to 25 feet (6 to 7.6 m) in thickness, is characterized by a sequence of dolomite, limestone, and dolomitic shale, and includes some fossiliferous zones. The similarity of this portion of the Unit E sequence at Mason City to the Rock Grove Member is noteworthy, although typical Rock Grove strata include some shale. Belanski recognized the Rock Grove in the Mason City area (1927, p.327) but suggested that the Rock Grove is "considerably modified" west of Floyd County, where it becomes less shaley and more dolomitic (1927, p. 360, 363). Belanski interpreted erosional beveling of Rock Grove strata beneath the Nora in Cerro Gordo County. At Mason City, Calvin (1897, p. 149) recorded a 28.5 foot (8.7 m) thick interval beneath Nora stromatoporoid-rich rocks that includes an upper "white limestone" and a lower dolomite (part vuggy); this sequence corresponds to the middle and upper portion of Unit E and may possibly be a lateral facies equivalent of the Rock Grove. The "white limestone" unit occurs throughout much of the Mason City area (where it is locally termed the "cement ledge") and was correlated with the Rock Grove Member by Belanski (Koch, 1970, p. 28). The lower dolomite interval was equated with the Mason City Member by Belanski (1927), and is locally termed the "Mason City beds." Vuggy and vermicular porosity in these beds may have resulted from dissolution of stromatoporoids (Koch, 1970). Although stratigraphic relations are not entirely clear, a tentative suggestion can be made that these beds are a western facies of the lower Rock Grove. Additional biostratigraphic studies are needed to clarify this relationship.

The lower 30.9 feet (9.4 m) of Unit E in the Mason City core are comparable, in part, to the Mason City Member of the Shell Rock Formation in western Floyd County, and possible correlation is suggested (figure 6). However, the basal portion of Unit E may correspond to stromatoporoidal strata beneath the Shell Rock Formation in Floyd County. Although correlations are not yet clarified, the general position of the Cedar Valley-Shell Rock contact is tentatively interpreted to correlate into the lower portion of Unit E. Lower Unit E strata in the Mason City core are characterized by a sequence of fossiliferous limestone, dolomite, and dolomitic limestone with zones of abundant stomatoporoids. The Mason City Member of the Shell Rock Formation in western Floyd County, where it ranges up to 22 feet (6.8 m) in thickness, is characterized by fossiliferous limestone and minor dolomite with several zones of abundant stromatoporoids (including biostromes). Unlike typical Mason City strata in Floyd County, lower Unit E in the Mason City core includes some laminated and intraclastic carbonate beds. However, intraclastic limestones are locally noted in the Mason City Member of Floyd County (Koch, 1970, p. 71, 73).

The similarity of the Unit E stratigraphic sequence at Mason City with the Shell Rock Formation to the east suggests possible correlation of these two units. The proposed correlation would thereby indicate an interpreted facies relationship between Unit E and typical Shell Rock strata. On the other hand, if the proposed correlation is in error and the Shell Rock unconformably overlies an eroded Cedar Valley surface (Koch, 1970), then at least 65 feet (20 m) of erosional relief must have been developed on the "Upper Cedar Valley" prior to the onset of Shell Rock deposition. Verificaton of either proposal requires additional biostratigraphic evidence. Disconformities occur at several positions in the "Upper Cedar Valley"-Cedar Valley

Formation sequence in north-central Iowa, especially within the shallowing portions of each of the major depostional cycles. The "Coralville"-Shell Rock unconformity noted by Koch (1970), which is commonly marked by an "undulating" or "irregular" surface, apparently does not differ substantially from other undulating or irregular surfaces noted within the Shell Rock and "Upper Cedar Valley" sequence (Belanski, 1928, p. 168; Koch, 1970).

"Upper Cedar Valley" strata exposed in the area of the town of Floyd, in Floyd County, apparently correlate to portions of Units D and E, based on gross physical relations, general elevations, and regional stratigraphic relationships (figures 1 and 2). The composite thickness of exposed "Upper Cedar Valley" strata in the Floyd area is about 65 feet (20 m). The lower 30 feet (9 m) of the exposed "Upper Cedar Valley" sequence in that area includes dolomites and dolomitic limestones, in part fossiliferous, stromatoporoidal, or laminated; this interval closely resembles Unit D strata at Mason City. The upper 35 feet (10.7 m) of the exposed sequence in the Floyd area is dominated by limestones, commonly dense and "sublithographic," and in part laminated, fossiliferous, and stromatoporoidal (one to two stromatoporoid-rich horizons are present); this interval closely resembles the upper portion of Unit D and the lower portion of Unit E at Mason City, but it contains significantly more limestone than noted at Mason City. An "Upper Cedar Valley" sequence similar to the upper interval at Floyd is noted beneath the Shell Rock Formation in southwestern Floyd and northwestern Butler counties (Belanski, unpublished notes; Koch, 1970). The basal member of the Shell Rock, the Mason City Member, is notably thinner in that area than in areas farther north, and the possiblity that the upper portion of the "Upper Cedar Valley" may share a facies relationship with lower Mason City strata in western Floyd County deserves additional study. Belanski (1928, p. 166) suggested that stromatoporoid biostromes in "Upper Cedar Valley" exposures in southwestern Floyd and northwestern Butler counties are "equivalent to similar stromatoporoid beds shown at Floyd," and we concur with this correlation.

The "Upper Cedar Valley" sequence at Mason City compares favorably to a portion of the Devonian sequence in central Iowa (Webster County) described by Klug (1982) and Tynan (unpublished report). Unit D is tentatively correlated with an interval of interbedded fossiliferous, vuggy dolomite (part calcitic) and laminated to brecciated dolomite and dolomitic limestone (unit 7 and much or all of unit 8 of Klug, 1982). This interval contains coral and stromatoporoid-rich beds, similar to Unit D in north-central Iowa. The overlying 65 to 75 foot (20 to 23 m) interval in the Webster County core is characterized by fossiliferous dolomite and dolomitic limestone with some interbedded laminated and brecciated dolomite. This interval closely resembles Unit E at Mason City. The lower half of this interval contains coral and stromatoporoid-rich beds, similar to lower Unit E strata in north-central Iowa. The upper half of this interval in Webster County is dominated by vuggy and stylolitic dolomite beds (sparsely fossiliferous); these beds are of similar thickness and lithology to upper Unit E strata at Mason City. Unlike the Unit E sequence in central Cerro Gordo County, which is overlain by shales of the Lime Creek Formation, probable equivalents of Unit E in central Iowa are overlain by a thick, unnamed dolomite-dominated sequence that apparently correlates with Lime Creek shales to the east. If, as suggested in this report, Unit E includes facies equivalents of Shell Rock strata, then the probable recognition of Unit E strata in central Iowa suggests that deposition during Shell Rock time was more widespread than previously proposed. The pronounced thickening of upper Middle and lower Upper Devonian strata in central Iowa (center of the Devonian Iowa Basin in Boone County) is difficult to reconcile if Shell Rock deposition were restricted to a small isolated basin in north-central Iowa.

Biostratigraphic relations of the "Upper Cedar Valley" sequence in north-central Iowa are not firmly established, and only preliminary microfossil sampling has been completed. Samples from Unit D at Charles City, Floyd County, and at Mitchell, Mitchell County, have yielded the conodont *Pandorinellina insita*. These occurrences of *P. insita* occur stratigraphically higher than the first occurence of *P. insita* in Unit C but below Shell Rock strata with *Ancyrodella gigas*, suggestive of the Middle *asymmetricus* Zone. Although zonally diagnostic conodonts have not yet been recovered from Unit D, stratigraphic constraints suggest possible inclusion of Unit D within the Lower *asymmetricus* Zone of early Frasnian (Late Devonian) age. *A. rotundiloba* has been recovered in upper "Coralville" strata at Milan, Illinois (Klapper et al., 1971). Unit E has not yet yielded conodonts, and its age is unclear. Additional conodont sampling is needed to verify whether or not Unit E is a partial facies equivalent of the Shell Rock Formation, as suggested herein.

The general absence of prominent confining units in the "Upper Cedar Valley" sequence in the study area suggests that hydrologic continuity between Units B through E may exist, and the "Upper Cedar Valley" is therefore included within the upper aquifer (figure 2). The "Upper Cedar Valley" sequence in areas of shallow bedrock displays prominent karst development in portions of Floyd and Mitchell Counties. These karstified areas are developed in regions where Units D and E are dominated by limestone, and prominent karstic terranes are generally absent in those areas where the "Upper Cedar Valley" bedrock surface includes signficant quantities of dolomite (see Libra et al., this report). Likewise, the bedrock surface of Cedar Valley (Units A,B,C) and Spillville strata in the eastern areas of north-central Iowa are not prominently karstified, where these strata are also dominated by dolomite. The stratigraphic and geographic distribution of limestones within the "Upper Cedar Valley" bears significantly on an understanding of karst distribution in north-central Iowa.

SHELL ROCK FORMATION

The type locality of the Shell Rock Formation is in western Floyd County along the Shell Rock River near Nora Springs where the formation is particularly well exposed (Belanski, 1927; Koch, 1970). Description of the stratigraphic sequence in that area is given by Koch (1970), and most details need not be reiterated here. Shell Rock strata are known to outcrop in portions of Butler, Floyd, Mitchell, Cerro Gordo, and Worth counties (ibid.). The Shell Rock Formation reaches a maximum thickness of 65 feet (20 m) in north-central Iowa.

The Shell Rock Formation is divided into three members, which in ascending order are the Mason City, Rock Grove, and Nora. These members are readily distinquished in the type area of the formation, but lateral variations are noted. "Rapid lithologic and faunal changes are the rule rather than the exception in Shellrock strata" (Belanski, 1927, p. 322). Although Koch (1970) interpreted the Shell Rock depositional basin to be of restricted geographic extent, the possibility that the Shell Rock shares a partial facies relationship with "Upper Cedar Valley" strata was discussed in the previous section. Once the complex of carbonate facies in the lower Upper Devonian sequence of northern and central Iowa has been more adequately studied, the possibility of Shell Rock facies equivalents in the dolomite-dominated sequence in other areas of Iowa can be more objectively evaluated.

A brief summary of the three members of the Shell Rock in western Floyd County is included to acquaint the reader with the gross aspects of the stratigraphic sequence. The Mason City Member overlies a "broadly undulating" surface on "lithographic" limestones of the "Upper Cedar Valley," and this surface generally has been interpreted as an erosional unconformity (Koch, 1970, p. 10). The Mason City Member is dominated by thick to massive bedded limestone, but dolomite (especially near the base), dolomitic limestone, and shale are also noted. It is generally fossiliferous, and stromatoporoid-coral biostromes (Stock, 1982, 1984) are locally developed in the lower portion. The member reaches thicknesses up to 22.5 feet (6.9 m) at Nora Springs. It thins to the east and south in Floyd County. Koch (1970) did not recognize the Mason City Member northwest of a line drawn mid-point between Nora Springs and Rock Falls along the Shell Rock River. However, Belanski (1927) correlated Mason City strata into Cerro Gordo County northwest of this line, where he suggested that it is represented by a more dolomitic facies. The general absence of characteristic shoreline and tidal flat carbonate sediments in the Mason City Member near its interpreted northwest margin (Koch, 1970) is noteworthy, especially if that margin represents the depositional limits of the member.

The Rock Grove Member in west-central Floyd County reaches thicknesses up to approximately 25 feet (7.6 m), but apparently thins to the south and north. Koch (1970) drew the western margin of the Rock Grove in eastern Cerro Gordo County, although Belanski (1927) correlated Rock Grove strata west of this margin. The Rock Grove Member in the type area is characterized by a sequence of three general lithogies, which in ascending order include: 1) argillaceous limestone and limestone with thin shale layers (ostracodes, bivalves, fish plates noted); 2) dolomitic shale and argillaceous dolomite; and 3) dolomite, in part with cross-laminations and brachiopod molds. The contact between the Mason City and Rock Grove members is marked by a change from thick-bedded fossiliferous limestone below to thin-bedded dense limestone and shale above (Koch, 1970, p. 12).

The Nora Member is the most widely recognized member of the Shell Rock Formation, and Koch (1970) interpreted westward overstepping of the Nora beyond the Mason City-Rock Grove edge above an eroded Cedar Valley surface. The Nora reaches thicknesses up to 19 feet (5.8 m) in the type area of western Floyd County. In that area it is characterized by stromatoporoid biostrome limestones in the upper and lower part, with an intervening shale or shale/fossiliferous limestone interval. The lower and upper Nora biostromal limestones are recognized in eastern Cerro Gordo County, but intervening strata include dolomite layers, in addition to shale and fossiliferous limestone. In the Mason City area of Cerro Gordo County and at exposures in Worth County, the Nora becomes increasingly dolomitic and less shaley. Biostromal or fossiliferous limestone and/or stromatoporoidal and vuggy dolomite characterize the sequence in that area. Where capped by younger Devonian rocks, the Nora is disconformably overlain by shales of the Lime Creek Formation in north-central Iowa.

The Shell Rock Formation is of early Late Devonian age (Frasnian) as indicated by the recovered conodont fauna (Anderson, 1964; 1966). The occurrence of *Ancyrodella gigas* in the Rock Grove Member suggests assignment to the

Middle *asymmetricus* Zone of early Frasnian age. Strata of this age are not represented in the eastern and southeastern Iowa Devonian sequence, where an erosional unconformity separates Cedar Valley and Lime Creek/Sweetland Creek strata.

The general lithologic continuity of Shell Rock and "Upper Cedar Valley" strata in north-central Iowa suggests that the Shell Rock interval may represent the uppermost portion of the upper aquifer in this report. However, the presence of shales, some in excess of 6 feet (2 m) in thickness, within portions of the Shell Rock sequence, especially in the Rock Grove and Nora members, would presumably impede vertical flow in the aquifer. Karst and incipient karst is developed on the Shell Rock surface in portions of western Floyd County. In this regard, the similarity of "Upper Cedar Valley" and Shell Rock strata is also noteworthy.

LIME CREEK FORMATION

The Lime Creek Formation is the uppermost Devonian rock unit exposed in Floyd County, and a discussion of its general characteristics completes this discussion of Devonian stratigraphy in north-central Iowa. The historical development of stratigraphic nomenclature in the Lime Creek sequence is summarized by Nelson (1939), and need not be reiterated. The Lime Creek Formation forms the bedrock surface over portions of western Floyd, western Butler, northeast Franklin, Cerro Gordo, and Hancock counties. Where covered by younger Devonian rock units (Sheffield Formation), the Lime Creek ranges from 125 to 155 feet (38 to 47 m) in thickness.

The Lime Creek Formation is divided into three members, which in ascending order are the Juniper Hill, Cerro Gordo, and Owen. The Juniper Hill Member is dominated by shale across north-central Iowa, although some dolomite or nodular limestone beds are noted locally. The Juniper Hill clay-shales are light to dark gray to olive gray in color, and are, in part, slightly calcareous or dolomitic. The unit typically lacks macrofossils, although lingulid brachiopods and sponges have been found. Megaspores are commonly noted in the basal beds of the member. The Juniper Hill is about 65 feet (20 m) thick in the type area of western Floyd County, and it varies from 20 to 70 feet (6 to 21 m) in thickness in Cerro Gordo and Franklin counties. Shale thicknesses generally decrease to the west, and only 5 to 15 feet (1.5 to 4.5 m) of Juniper Hill shale are recognized in western Hancock County, where the Juniper Hill presumably grades into a dolomite-dominated facies. The Juniper Hill overlies, with apparent disconformity, strata on the Nora Member (Shell Rock Formation) or "Upper Cedar Valley." A thin sandy dolomite with phosphatic nodules or abraded phosphatic fish debris locally occurs at the base of the Lime Creek (Koch, 1970).

The Cerro Gordo Member is dominated by shale in western Floyd and eastern Cerro Gordo counties, but interbedded limestones are also a significant component. The very light gray and blue-gray shales are very calcareous, and are sometimes characterized as "marls." The Cerro Gordo Member is extremely fossiliferous, containing an abundance of brachiopods, gastropods, bryozoans, corals, and many other fossils (Fenton and Fenton, 1924.) To the west, in central and western Cerro Gordo County, the Cerro Gordo Member is dominated by dolomite or limestone strata, but significant quantities of interbedded shale are present, especially in the upper portion of the sequence. The Cerro Gordo Member in Franklin County is dominated by limestone, with lesser quantities of interbedded dolomite and shale. The member is dominated by dolomite strata with minor shale and siltstone across Hancock County. Dolomite exposures of the Cerro Gordo Member in Hancock County include scattered to abundant stromatoporoids and other fossils (Koch, 1963). In general, shale-dominated facies of the Cerro Gordo Member grade westward into dolomite-dominated facies across north-central Iowa.

Upper Lime Creek strata are included in the Owen Member, which is a carbonate-dominated rock unit across north-central Iowa. Where capped by shales of the Sheffield Formation, the Owen ranges from 25 to 53 feet (8 to 16 m) in thickness. It is characterized by limestone, dolomitic limestone, and dolomite throughout its extent, and becomes more dolomitic to the west. The Owen is fossiliferous throughout, and stromatoporoids, corals, brachiopods, echinoderm debris, and other fossils are noted. Lower Owen strata are characterized by an abundance of stromatoporoids across north-central Iowa, and middle Owen strata are locally oolitic (Lynn, 1978).

Brachiopod and conodont biostratigraphy establishes a Late Devonian age for the Lime Creek Formation. *Palmatolepis gigas* has been recovered from the middle Juniper Hill-middle Cerro Gordo interval (Anderson, 1964); these occurrences characterize the *P. gigas* Zone (Klapper et al., 1971). Conodonts have not been recovered from lower Juniper Hill strata, although this interval may correspond to the *Ancyrognathus triangularis* Zone. The *A. triangularis* Zone is recognized in the lower Sweetland Creek Shale of southeast Iowa (ibid.), where it overlies an eroded surface on the Cedar Valley Formation. The Owen Member records the highest stratigraphic occurrence of stromatoporoids in the Iowa Devonian sequence. Stromatoporoids disappeared from the Paleozoic stratigraphic record at the Frasnian-Famennian boundary at a time of major faunal extinctions on a global scale. The Owen Member is tentatively assigned to the uppermost Frasnian.

The Juniper Hill Shale is a prominent confining unit for the underlying upper aquifer (Unit B through Shell Rock Formation) in Floyd-Cerro Gordo Counties. The Cerro Gordo Member in western Floyd and eastern Cerro Gordo Counties is predominantly a thick shale unit, where the member is included with the Juniper Hill as part of the confining unit for the upper aquifer. However, the Cerro Gordo Member is a carbonate-dominated rock unit in central and western Cerro Gordo, Franklin, and Hancock counties, and progressively loses it confining characteristics to the south and west in that area. The Owen Member is carbonate-dominated throughout its extent, and is locally used as the upper bedrock aquifer in portions of Franklin, Cerro Gordo, and Hancock counties. Where the Cerro Gordo Member is predominantly a carbonate rock unit, it forms, along with overlying Owen strata, part of a carbonate aquifer system informally termed the "Lime Creek aquifer." This aquifer is confined beneath Devonian shales of the Yellow Spring Group to the southwest in north-central Iowa.

CRETACEOUS SYSTEM

The Devonian bedrock surface is overlain by Quaternary strata over most of north-central Iowa. However, Cretaceous rocks locally overlie Devonian strata in this area. Cretaceous rocks unconformably overlie Cedar Valley and "Upper Cedar Valley" strata in portions of central Floyd, northeast Mitchell, northern Hancock, and southern Winnebago counties. They overlie Shell Rock strata in western Floyd County and Lime Creek strata in western Floyd and north-central Cerro Gordo counties. The distribution of Cretaceous rocks in Floyd County is discussed by Nelson (1939) and Stainbrook (1944). Recent detailed soils mapping by the U.S.D.A. Soil Conservation Service has identified Cretaceous rocks over broader areas of western Floyd County than previously recognized (Kermit Voy, 1983, personal communication).

Cretaceous rocks are preserved as erosional outliers across most of north-central Iowa, generally in topographically high regions, but also within paleokarst features and solutional channels (Calvin, 1903b, p. 334) developed on the Devonian carbonate surface. The total thickness of Cretaceous rocks does not exceed 40 feet (12 m) in most of north-central Iowa. However, Cretaceous rocks reach thicknesses up to 150 feet (45 m) in northwest Hancock County, where these strata are contiguous with the widespread Cretaceous sandstones and mudstones of the Dakota Formation in western Iowa. The Cretaceous rocks of north-central Iowa have been referred by various geologists to either the Dakota Formation, with which they correlate to the west, or the Windrow Formation, with which they correlate to the north and east. The Cretaceous rocks of north-central Iowa are assigned in this report to the Windrow Formation, following Andrews' (1958) usage in northeast Iowa and southeast Minnesota.

The Windrow Formation of north-central Iowa includes three general lithologies: 1) claystone and mudstone, generally red or yellow-orange but locally pink, brown, or white; silty or sandy; 2) sandstone, locally varying from very fine to very coarse grained; friable to indurated (calcite or ferric oxide cements); siltstone locally noted; and 3) conglomerates, characteristically including quartz, chert, and armored mud clasts in a sandy, ferric oxide (hematite or limonite) cemented matrix. Windrow Formation strata in north-central Iowa can include any or all of these general lithologies at specific localities, although a basal clay/mudstone unit 3 to 25 feet (1 to 7.5 m) thick occurs at many localities. Similar clay/mudstone units are noted above Windrow sandstones or conglomerates at some localities. X-ray diffraction of a red mudstone sample from western Floyd County revealed an illite and kaolinite clay mineralogy (approximately 64% illite, 36% kaolinite). Clay/-mudstone units in the Dakota Formation of western Iowa are of similar composition.

The Windrow sandstones are dominated by angular to rounded quartz grains, but chert grains are also signficant. Trace quantities of mica and lithic rock grains are noted. The sandstones are locally cross-bedded (Nelson, 1939). The Windrow conglomerates include clasts of quartz and chert, which range up to 3/4 inch (2 cm) in diameter. Silicified Silurian fossils have been noted in some of the chert clasts (Stainbrook, 1944), suggesting derivation from bedrock terranes to the east. Armored mud clast conglomerates are common at some Floyd County exposures. The mud clasts are round to elliptical in outline and reach maximum dimensions up to 2 inches (5 cm). These clasts commonly weather out on outcrop, leaving elongated vugs within the ferric oxide cemented rock. The Windrow sandstones and conglomerates are commonly cemented by limonite or hematite, giving these strata a deep red color. Massive limonite/hematite with scattered sand grains occurs within the conglomerates, and masses of limonite/hematite are locally developed on the eroded Devonian limestone surface. The Windrow ferric oxide cemented sandstones and conglomerates and massive limonite/hematite beds have been locally used as an iron ore in portions of northeast Iowa (where they overlie Ordovician limestones) and southeast Minnesota (on Ordovician and Devonian rocks).

The Windrow mudstones, sandstones, and conglomerates in north-central Iowa are compositionally identical to lower Dakota Formation rocks in western Iowa, with which they are undoubtedly related. These strata were deposited in braided fluvial systems that drained upland areas developed on Precambrian crystalline and Paleozoic bedrock terrains to the north and east (Witzke and Ludvigson, 1982). These aggrading fluvial systems flowed to the west and southwest across Iowa and Minnesota. They graded laterally into fine-grained meandering fluvial systems that aggraded across broad alluvial plains. Shoreline and deltaic facies migrated eastward across Iowa during deposition of the Cretaceous Greenhorn marine cyclothem, as the Western Interior Seaway progressively inundated eastern areas (Witzke and Ludvigson, 1982).

The Windrow Formation is only sparingly fossiliferous in north-central Iowa, and its Cretaceous age is largely inferred from its close lithologic similarity to undoubted Cretaceous rocks of western Iowa. However, Cretaceous angiosperm leaf fossils have been recovered in the Windrow Formation of southeast Minnesota. In addition, Cretaceous fossils have been found in iron-rich Windrow strata in western Floyd County. These include petrified wood (probably gymnopserms) and *Tempskya* (petrified fern "wood"). The occurrence of *Temspkya* conclusively dates the deposit as Cretaceous. In addition, exceptionally well rounded and polished quartz clasts, up to more than 3 inches (7.6 cm) in diameter, have been found within the iron-rich strata of Floyd County. The size grade of these clasts is anomalous with respect to the enclosing matrix and is difficult to reconcile with fluvial transport. The size grade and high polish of these clasts suggests that they might represent dinosaur gastroliths (stomach stones).

Karst typically is not well developed where the Devonian limestones are overlain by Windrow Formation strata. However, exhumation of Cretaceous rocks could locally re-expose ancient paleokarst surfaces on the Devonian carbonates. Where Windrow claystones/mudstones are well developed, they may serve locally to confine the underlying upper aquifer. The friable Windrow sandstones conceivably could yield water to shallow wells in portions of north-central Iowa.

HYDROGEOLOGIC CONCLUSIONS

Consideration of the Devonian stratigraphy of north-central Iowa suggests that several hydrogeologic units may be included within the larger Devonian aquifer system. Three aquifers potentially exist in the Devonian carbonate sequence of north-central Iowa below the Upper Devonian Lime Creek shale interval, although additional data is needed to verify or modify the hydrologic interpretations presented in this report. These three units are physically confined between prominent shaley beds.

The "lower aquifer" encompasses the Spillville Formation, the lowest Devonian formation in the area. Fractured and vuggy dolomites of the Spillville are apparently confined below by shaley strata at the base of the formation ("Lake Meyer member") or by underlying Maquoketa strata, and above by shaley Wapsipinicon strata (Kenwood Member). The Spillville Formation is geographically limited to the north and east by the outcrop edge in northeast Iowa and southeast Minnesota, to the south by its pinch-out against the "Bremer High," and to the west in western Floyd or eastern Cerro Gordo County where it is overlapped by younger Devonian strata. High heads and good water quality characterize this aquifer in the Floyd-Mitchell County area.

The "middle aquifer" is included within the lower portion of the Cedar Valley Formation (Unit A) in north-central Iowa, and it is apparently confined by shaley Wapsipinicon strata below and by the "Rapid shale" above. The fractured and vuggy dolomites yield water over large areas of north-central and northeast Iowa. The "middle aquifer" may merge with the "upper aquifer" to the west and south, where the "Rapid shale" is replaced by carbonate facies. The "upper aquifer" is included within the Cedar Valley-Shell Rock carbonate sequence in north-central Iowa (Units B through E), and is apparently confined below by the "Rapid shale" and above by the Lime Creek shales. This interval is typically dominated by dolomite in the lower portion and by limestone and dolomite in the upper portion. Two well-defined cyclic carbonate units are recognized in the lower interval (Units B and C). Limestone-dominated units in the upper interval (Units D, E, Shell Rock) display varying degrees of karstification in areas where they form the shallow bedrock. Water-quality problems are apparent in the "upper aquifer" in these areas in north-central Iowa. The upper portion of the Lime Creek Formation (Owen Member) is a carbonate unit across the area, and Lime Creek shales are replaced to the west in north-central Iowa by carbonate facies. In those areas the Lime Creek Formation is locally used as a shallow bedrock aquifer.

Additional study is needed to evaluate the hydrologic characteristics and water quality of the Devonian aquifers across north-central Iowa. A series of controlled test holes, with complete or partial core penetration, are needed to more accurately define the physical container for each aquifer. Controlled pump-packer tests within wells that have been constrained in terms of the physical stratigraphy are needed at each test site to evaluate head relationships, water quality, and flow systems within the inferred multiple aqufier system in this region. Detailed stratigraphic and hydrologic evaluations of data retrieved from all test sites could then be used to extrapolate the results over most of north-central Iowa. This sort of carefully collected hydrologic-stratigraphic information is needed to gain a better understanding of water-quality problems, flow systems and future water management of the Devonian aquifers in north-central Iowa.

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APPENDIX:

Description of Devonian Sequence in Mason City Core

CORE DESCRIPTION--Devonian sequence
Mason City, Cerro Gordo County, Iowa
Northwest States Portland Cement Company
section 33, T.97N., R.20W.
2 inch (NX) core; depths in feet
Description by Brian J. Witzke with assistance from Bill J. Bunker, Dec. 1983.

Abbreviations used: dol.--dolomite; ls.--limestone; sh.--shale; arg.--argillaceous; v.--very; lt.--light; m.--medium; dk.--dark; gr.--gray; brn.--brown; org.--orange; calc.--calcitic; xf-extremely fine; vf--very fine; f--fine; m--medium; c--coarse; xlln--crystalline; indet.--indeterminate; ft.--foot (feet); mm--millimeter; cm--centimeter; (c)--footages are approximate, problems with listed footages on core box or poor core recovery.

"UPPER CEDAR VALLEY FORMATION"

UNIT E

0-4 (c). Poor recovery. Ls., pale--v. lt. brn. gr., xf xlln with floating f-m dolo. rhombs; dense; abundant stylolites; calcite fracture fill.
4-5 (c). Dol. calc., v. lt. brn. gr., f-m xlln; stylolites and some faint arg. streaks or laminae.
5-5.6 (c). Dol. slightly calc., v. lt. brn. gr., f-m xlln, faintly laminated, differences in crystal size between irregular laminae spaced 2-20 mm.
5.6-7 (c). Dol., part calc., and dolomitic ls., lt. brn. gr., vf-m xlln, calcite void and fracture fill; arg. stylolites near base enclosing thin brecciated or intraclastic bed; 6.3 indet. brachiopod.
7-12 (c). Dol., v. lt. brn. gr., f-m xlln, porous to vuggy, pin-point porosity with scattered to abundant vugs 1-10 mm diameter; 7-8 calcite fracture and void fill; 10.5 faintly laminated.
12-14.5 (c). Dol., calc., and dolomitic ls., v. lt.-lt. brn. gr., vf-m xlln, dense; some arg. stylolitic streaks.
14.5-19. Dol., part calc., lt. gr.--lt. brn. gr., vf-m xlln, scattered stylolites, slightly arg.; upper half with abundant calcide void-vug fills and calcite spar patches, swirled and mottled textures in upper 0.4 ft.; indet. small fossil debris (?) molds scattered in upper half.
19-22.7. Dol., part slightly calc., v. lt. brn. gr., dense, vf-f xlln; lower half slightly arg., in part, faintly laminated (laminae 1/2-1 mm); scattered calcite fracture and void fill; prominent calcite void fil at 19.7; 19.1 arg. swirl; 19.2 indet. brachiopod; 19.5 subvertical calcite-filled burrow and 2 cup corals; 19.7 indet. brachiopod, bryozoan, *Favosites*; 20.4 indet. brachiopod.
22.7-24.8 (c). Dol., calc., vf-m xlln, lt.-lt. m. brn. gr. mottled, dense; slightly arg.; swirled and mottled texture; calcite fracture and void fill; scattered stylolites; indet. brachiopods at top.
24.8-25.6 (c). Dol., lt. m. brn. gr., vf xlln, dense; some stylolites and calcite spar patches.
25.6-26.5 (c). Dol., v. lt.-m. brn. gr., f-m xlln, mottled or swirled texture; arg. swirls.
26.5-27.5 (c). Dol., lt. m. brn. gr., vf-m xlln, dense, slightly arg.

27.5-30.7 (c). Ls., v. lt. gr.--v. lt. brn. gr., xf xlln; abundant stylolites and arg. stylolitic streaks throughout scattered every 5-30 mm; scattered small indet. fossil debris throughout most of sequence; 29.6 coral or stromatoporoid; top with ostracodes (?) and gastropod (?).

30.7-32.5 (c). Ls., slightly dolomitic, v. lt. brn. gr., dense, xf-f xlln, slightly arg.; some calcite patches; abundant arg. stylolites every 5 to 50 mm; arg. streak at 32; scattered to abundant branching and hemispherical stromatoporoids (to 4 cm) throughout; leisegang swirls near top; 31.7 *Favosites*.

32.5-34. Ls., v. lt. brn. gr., dense, xf xlln with scattered f-m dolo. rhombs; some dolomitic ls. near top, f-m xlln; stylolites common near base and top; faint burrow mottlings near middle; 32.6 crinoid debris; 32.9 scattered crinoid debris; 33.2 indet. brachiopod.

34-35.6 (c). Dol. and calc. dol., v. lt. brn. gr.--brn. gr., dense, f-m xlln; some calcite void fill and poikilotopic calcite.

35.6-39.2 (c). Dol., part calc., v. lt. brn. gr., vf-m xlln; slightly porous with some vuggy pores 1-5 mm; some poikilotopic calcite cements, calcite vug fill near top; indet. brachiopod molds and horizontal burrows near middle; gradational above.

39.2-40. Ls. dolomitic, and dol., calc., v. lt. brn. gr., dense, vf-m xlln; upper portion skeletal; lower portion slightly arg. and stylolitic; thin shaly ls. near base; indet. brachiopod, crinoid debris, bryozoan, and stromatoporoid (?) in upper 0.3 ft.; irregular swirled surface beneath skeletal ls. in middle.

40-40.7. Dol., slightly calc. lt. gr., vf-f xlln, dense to slightly porous; intraclastic, clasts of pale gr. and m. gr. dolomitic ls., clasts are subangular to rounded, 1/2-10 mm (most 1/2-2 mm).

40.7-41.3. Dol., v. lt. brn. gr., vf xlln, porous to vuggy; irregular chert nodule near top, chalky chert with brachiopods, overlain by thin intraclastic dol. as above.

41.3-42.3. Ls., dolomitic--dolo., calc., v. lt.-lt. brn. gr., f-m xlln; some poikilotopic calcite cements; faintly laminated in lower half.

42.3-44.5. Ls., dolomitic, and dol., calc., v. lt.--lt. m. brn. gr., f-m xlln, slightly arg.; part with arg. stylolitic streaks and arg. laminae; some calcite spar patches; fractured to slightly brecciated in middle.

44.5-51 (c). Dol., calc. dol., and dolomitic ls. (at base), v. lt.-lt. brn. gr., vf-m xlln, some m-c calcite; calcite vug fills (to 5 cm) scattered throughout; varies between dense, slightly porous, and vuggy; scattered stylolites; 46 cup coral; 46.6 brachiopod fragment mold; 49.2 horizontal burrow mottled in arg. dol.; 49.8 branching tabulate coral mold (2 cm); 50.5 brachiopod fragment mold; 50.9 stromatoporoid (?), 4 cm.

51-52.2 (c). Dol., calc. and dolomitic ls., v. lt.-lt. brn. gr., vf-f xlln, slightly arg., trace stylolites; calcite vug and fracture fill; horizontal and subhorizontal burrow-mottling throughout.

52.2-52.5 (c). Ls., dolomitic, v. lt.-lt. brn. gr., vf-m xlln, brecciated to intraclastic; rounded to angular clasts (1-40 mm) in calcite spar and m xlln dolomitic ls. matrix; flat pebble intraclasts (1 x 10 mm) in arg. matrix at top.

52.5-52.8 (c). Dol., calc., lt. brn. gr., vf-f xlln, small pores and calcite-lined vugs, calcite spar patches; small horizontal burrows throughout.

52.8-54 (c). Ls., dolomitic--dol., calc., at top, v. lt. brn., dense, xf xlln with m xlln calcite spar patches; stylolites; part arg. with arg. swirls; fractured near top with irregular arg. swirls; indet. brachiopod near base.

54-54.2 (c). Dol., v. lt. brn. gr., vf-f xlln, vuggy, brachiopod and crinoid debris molds (out of place?).
54.2-55 (c). Dol., v. lt. brn., dense, vf xlln, faintly laminated.
55-56 (c). Dol., v. lt. brn. gr., dense, vf-f xlln; scattered small vugs, part calcite filled; scattered brachiopod and crinoid debris molds.
56-57.7 (c). Dol., calc., grading upward into dol., v. lt. brn. gr., vf-f xlln; calcite fracture fill in lower part; slightly porous to vuggy in upper part with spiriferid brachiopods and cup corals noted.
57.7-58.4 (c). Dol., calc., and ls., dolomitic, v. lt. brn. gr., dense, vf xlln; calcite void and fracture fills, poikilotopic calcite cements; irregular swirled contact at top; scattered skeletal debris including brachiopods and stromatoporoid (1 cm).

UNIT D

58.4-58.8 (c). Ls., dolomitic, v. lt.-lt. brn. gr., vf xlln with c calcite spar and poikilotopic cements; calcite spar patches near base; brecciated at top, angular clasts 2-25 mm, matrix slightly arg.
58.8-59.5 (c). Ls., dolomitic, v. lt. brn. gr., vf-f xlln, slightly arg.; calcite fracture fill; trace of small fossil debris (?); brecciated or intraclastic 0.3 ft. from top in arg. matrix; shaly laminae, irregularly spaced 1-5 mm at top.
59.5-61.2 (c). Dol., lt. brn. gr., vf-f (some m) xlln, dense with a few scattered vugs; trace of calcite at top.
61.2-61.7 (c). Dol., lt. brn. gr., f. xlln, faintly laminated with laminae spaced 1-4 mm.
61.7-62.8. Dol., v. lt. gr.-lt. gr., vf-f xlln, abundant small vugs 1/2-5 mm (most 1-2 mm) throughout; vugs do not appear to be fossil molds.
62.8-63.2. Dol., v. lt. gr., vf-f xlln, slightly porous near top; scattered embedded quartz sand.
63.2-63.7. Dol., v. lt. gr., xf-vf xlln, some f xlln spots, dense; arg. streaks and swirls; burrows (?); trace of small skeletal debris (?); gradational above.
63.7-64. Ls., pale-lt. m. gr., arg.-v. arg., dense, xf xlln; includes nodular ls. in arg. ls. matrix; trace of small fossil frags (<2 mm), ostracodes (?), brachiopods (?), bryozoan.
64-66. Dol., calc.--ls., dolomitic, v. lt. brn.-v. lt. brn. gr., f-m xlln; faintly laminated throughout, laminae spaced 1-20 mm, some laminae slightly arg.; some scattered stylolites; calcite fracture fill at top; gradational above.
66-72. Dol., calc., v. lt.-lt. gr.-brn. gr., vf-m trace c xlln; slightly arg.-arg., stylolites scattered to common throughout; lt. m. gr. v. arg. swirls near middle; faintly laminated near base and middle, irregular laminae; some c calcite patches near middle.
72-72.5. Dol., calc., pale-v. lt. gr., dense, xf-vf xlln; m. gr. swirls and arg. streaks; traces of small intraclasts (1-3 mm) near top; faintly laminated at top; trace of pyrite blebs.
72.5-73.5. Ls., v. lt. brn. gr., slightly dolomitic, xf xlln, trace m. xlln dol. rhombs, dense; trace stylolites; intraclastic, scattered small rounded intraclasts 1-10 mm (most 1-3 mm), clasts rounded; small pelleted (?) clumps in places; becomes m xlln dolomitic ls. at top; brachiopods near base.
73.5-73.9. Ls., dolomitic, lt. brn., xf-m xlln, similar to unit below but with more abundant m xlln dol. rhombs.

73.9-74.4. Ls., slightly dolomitic, v. lt. brn. gr., xf-m xlln, stylolites, scattered dol. rhombs in matrix.

74.4-77 (c). Dol., calc., and ls., dolomitic, v. lt. gr.-v. lt. brn. gr., vf-m xlln, dense to pin-point porosity; some scattered calcite spar; arg. swirls near middle; faintly laminated top 1 cm.

77-78 (c). Dol., v. lt. gr., vf xlln, faintly to prominently laminated every 1/2 to 2 mm; very faintly laminated in upper 0.2 ft.

78-79 (c). Top 0.8 ft. is ls., dolomitic grading upward to dol., calc., v. lt. brn. gr., arg.; arg. swirls and horizontal burrows (?) in lower part; wispy arg. streaks and stylolites above. Basal 0.2 ft. is ls., v. lt. gr.-v. lt. brn. gr., dense, xf xlln; small fossil specks (1/2-2 mm) include ostracodes (?) and small bryozoans; planar hardground (to 1 mm relief) with pyrite-filled borings; scattered pyrite blebs at base.

79-80 (c). Dol., v. lt. brn. gr., vf-m xlln; scattered pin-point porosity in lower half; arg. parting near middle; large calcite filled vug near top; becomes denser and less porous upward; scattered stylolites in upper part.

80-82.3 (c). Dol., v. lt. brn. gr., vf-f xlln, pin-point porosity to vugular; vugs near base 1-15 mm (may be unrecognizable fossil molds); 0.4 ft. above base is an arg. intraclastic zone with subangular to angular clasts (1-25 mm); some scattered stylolites.

82.3-83.7 (c). Dol., v. lt. brn., vf-f xlln, prominently laminated (laminae 1/2-2 mm); pin-point porosity developed along alternating laminae; m. gr. shaly laminae near middle; laminae planar to slightly undulose.

83.7-84.9 (c). Dol., v. lt. gr., xf-f xlln, dense, arg.; irregular arg. mottlings and swirls throughout, resembling burrow mottles; scattered stylolites; become irregularly laminated to swirled in upper 0.5 ft.; some calcite spar near base.

84.9-85.3 (c). Dol., v. lt. brn. gr., f-m xlln, dense; scattered spiriferid brachiopods; 1 cm thick m. gr. shale parting at top.

85.3-86.1 (c). Dol., v. lt. brn. gr., dense, xf-f xlln; faint arg. mottlings; spiriferid brachiopod near middle.

86.1-86.8 (c). Dol., v. lt. brn. gr., xf-f xlln, fossil moldic to vuggy; abundant calcite void fill; crinoid debris molds and spiriferid brachiopods throughout; abundant well-preserved *Cyrtospirifer* (?) at top.

86.8-87 (c). Dol., v. lt. gr., dense, xf-vf xlln, faintly laminated with arg. streaks; sharp contact above.

87-88.4 (c). Dol., slightly calc.--ls., slightly dolomitic, v. lt.brn. gr., xf-vf xlln below becoming f-m xlln calcitic at top; faint mottled fabric, slightly arg.-arg. in lower portion.

88.4-90.3 (c). Ls., slightly dolomitic, lt. brn. gr., dense, f-c xlln, massive; generally featureless; stylolite near top.

90.3-90.5. Ls., dolomitic, and shale, calc., v. lt.-lt. m. gr., slightly silty.

90.5-91.2. Ls. and dolomitic ls., v. lt. gr.-lt. brn. gr., xf-m xlln; f-m calcite scattered in lower half; slightly arg. with stylolites in top half.

91.2-93.7 (c). Dol. and ls., dolomitic, pale gr.-v.lt. brn. gr., xf-vf xlln; lower 0.7 ft. is faintly laminated with arg.streaks (1/2-4 cm spacing), dense; 91.7-93 is dolomitic ls., pale gr., microporous; top 0.5 ft. as below, becoming laminated near top, arg. laminae and streaks spaced 2-5 mm, microbreccia clasts (0.5-1 mm) along some arg. partings.

93.7-96.5 (c). Dol., part slightly calc., v. lt. brn.-v. lt. brn. gr.; slightly porous (pores 1-5 mm) in lower two-thirds, becoming dense in upper one-third; porous subhorizontal burrow mottle molds (1 mm diameter) in lower 1 ft.; some dk. gr. mottles in dense dol. in lower 0.5 ft. (may include small 1 mm intraclast); arg. stylolitic streaks near middle; subvertical burrow mottles near middle; brachiopods noted 0.5 ft. up from base.

96.5-98.5 (c). Dol. and ls., dolomitic, v. lt.-lt. brn. gr., dense, xf-m xlln, some m-c calcite throughout; stylolites and arg. streaks in part.

CEDAR VALLEY FORMATION

UPPER UNIT C

98.5-100 (c). Dol. and ls., dolomitic, pale-v. lt. brn. gr., xf-vf xlln; flat-pebble intraclasts (to 2 cm) of laminated dol. at 98.8-99.0 and 99.4-99.6; faintly laminated at base and 98.0-98.3; top 0.6 ft. is microbreccia or intraclast conglomerate, clasts subrounded to rounded (1-10 mm) in arg.-v. arg. matrix.

100-101 (c). Dol., arg., and shale, calc., lt. m. gr., vf-f xlln, trace of fine quartz sand.

101-103.5 (c). Dol., calc. dol., and dolomitic ls., pale gr.-lt. brn.; abundant calcite in lower 1 ft.; partly laminated at 103.2; arg. at 102.5; lt. brn. calc. dol., lt. brn. in top 1.5 ft.; some calcite.

103.5-104.7. Dol., calc., and ls., dolomitic, pale-v. lt. brn. gr., abundant calcite fracture and void fill; fractured to slightly brecciated in lower 0.4 ft. (microbreccia near base, fractured to brecciated above); abundant calcite.

104.7-106.8. Ls. and dol., calc., pale-v. lt. brn. gr., xf-vf xlln, dense; featureless in lower half; upper half with calcite fracture fill and specks; abundant calcite spar fill near top.

106.8-107.2. Ls., dolomitic, pale gr.-v. lt. brn. gr., xf-vf xlln, some f-c calcite specks; laminated at base; becomes intraclast conglomerate at top; flat-pebble clasts 2 mm x 3 cm at angles to 45°; stylolitic streak at top.

107.2-115 (c). Dol., v. lt. brn., xf-f xlln, come m xlln; in part faintly laminated with arg. laminae and stylolitic streaks; some laminae f-m xlln laminae spaced 1-40 mm; 107.2-107.5 dol., lt. brn., prominently laminated, arg. streaks at top, top 0.1 ft. ls., dense, with f-m xlln specks; 107.5-108.6 dol., v. lt. brn. gr., dense, xf-vf xlln, some vf-f xlln mottlings and specks near top; 108.6-109.6 faintly to prominently laminated; 109.6-110.8 dol., v. lt. brn. gr., dense, with small pores and vugs, non-laminated; 110.8-112.3 faintly laminated, stylolitic streak at 111; 112.3-112.7 faintly laminated with small vugs 1-5 mm; 112.7-115 faintly laminated.

LOWER UNIT C

115-119.5 (c). Dol., v. lt. brn. gr., xf-f xlln, porous to vuggy, scattered calcite fracture and void fill; 115.5 stylolitic streaks; 116 vuggy; 116.3-116.9 denser dol.; 117.4 small fossil molds (?); 117.8 crinoid ossicle mold (?); 118.5 brachoipod and crinoid debris molds; 118.6 arg. streak with 2 small intraclasts (1-5 mm); 118.7, 119 stylolites.

119.5-122.5. Dol.-ls., dolomitic, v. lt.-lt. brn. gr., xf-m xlln, dense, calcite fracture fill, large calcite vug fills to 3 cm, part with m xlln calcite mottlings; 120.6 small calcite void fills (birdseye?); 119.7

crinoid debris; 120.6 burrowed (?) calcite mottlings, small calcite void fills (birdseye?); 121 stylolite.

122.5-136.8. Dol., v. lt. brn. gr., xf-vf xlln, some f xlln void lining, porous to v. porous, scattered to abundant fossil molds and vugs (to 5 cm); gradational above, poorly fossiliferous and dense at top; 123.8-124.4 denser, sparsely fossiliferous; 124.5, 124.8, 125.2, 126.9 spiriferid brachiopods; 125.5, 126.2, 127, 127.2, 127.5, 127.8 128.3, 129.3 indet. brachiopods; 128 crinoid debris; 129.5 crinoid debris, stylolite; 129.8 *Cyrtina?*; 130 stylolite; 130-130.3 abundant brachiopods, spiriferids, dogtooth spar; 130.8 abundant indet. brachiopods, small dk. gr. intraclast (2 x 10 mm); 130.9 *Cyrtina?*, indet. brachiopods, crinoid debris; 131.3 indet. brachiopods, microporous mottlings; 131.6 spiriferid brachiopods; 132.1 indet. brachoipod; 132.4 brachiopod, bryozoan, calcite spar; 132.5-132.8 highly fractured, brachiopod, crinoid debris; 132.8 crinoid debris, branching bryozoan; 133.3 *Atrypa*, crinoid debris, dogtooth spar; 133.7 crinoid debris; 134-134.6 brachiopods, bryozoans, crinoid debris; 134.9 brachiopods, arg. mottlings with small intraclasts (?); 135.2 arg. mottles, fossil molds; 135.4-135.7 burrow mottles, small intraclasts (1-2 mm); 136.6, 136.8 stylolites.

UPPER UNIT B

136.8-138.1. Dol., v. lt. brn. gr., xf-vf xlln, dense to porous, voids 1/2-3 mm, vugs to 15 mm; some arg. streaks and lt. brn.-m. gr. arg. mottlings; scattered microbreccia clasts (1-5 mm) at 137.8.

138.1-139. Dol., v. lt. brn. gr., xf-vf xlln, irregular arg. mottlings throughout; arg. and shaly streaks in lower 0.5 ft.; trace of quartz silt.

139-139.7. Dol.-shale, v. lt. m. gr., part microbrecciated or intraclastic with clasts 1-5 mm.

Note: Box 15 contains in excess of 10 ft. of core, but is labelled 140.4-147 (6.6 ft.); clearly footages are inaccurate.

139.7-142 (c). Dol., v. lt. brn. gr.-Ls., dolomitic, xf-m xlln, dense, part faintly laminated; becomes laminated, dense, pale gr., xf xlln at top; stylolitic streaks; shaly partings near top; calcite void fill.

142-143 (c). Dol., lt. brn. gr., slightly porous, arg. mottlings and stylolitic streaks; scattered fractured intraclasts or microbreccia near middle, clasts 1-15 mm; porous to v. porous, voids 1-15 mm.

143-145 (c). Dol. and calc. dol., v. lt.-lt. brn. gr., xf-m xlln, some arg., shaly, and stylolitic streaks, scattered arg. mottlings and m-c xlln calcite; microbreccia at base.

145-146 (c). Dol., v. lt. brn. gr., xf-f xlln, faintly laminated with scattered arg. laminated streaks; becomes non-laminated above.

146-147 (c). Dol., pale-m. gr., arg. to shaly, dense to slightly porous; part microbrecciated (clasts 1-5 mm) with wavy arg. mottlings; scattered mottled shaly streaks and partings.

147-152 (c). Dol., lt. brn. gr., vf-m xlln, faintly laminated throughout (1-10 mm spacing); a few laminae are microbrecciated (clasts 1-2 mm) in middle portion; porous to vuggy in lower 0.5 ft.; top 0.5 ft., middle 1 ft., and bottom 0.5 ft. are porous to vuggy with some calcite void fill; a few scattered arg. streaks.

152-153. No sample.

153-155.2. Dol. and calc. dol., xf-m xlln, dense to slightly porous; 153-153.8 dol. and calc. dol., dense to slightly porous at top, some stylolites, calcite fracture fill, and irregular arg. mottlings; 153.8-154.2 dense calc. dol., some stylolites and arg. mottlings; 154.3 wavy laminated, intraclasts in shaly matrix; 154.4-154.9 fractures, brecciated to intraclastic, clasts 1-15 mm, calcite fracture fill, shaly mottlings; 154.9-155.2 laminated.

155.2-157.3. Brecciated to mottled mixture of pale gr. xf xlln dol. and m. gr. calc. shale; breccia clasts 1-10 mm; dol. beds mottled with breccia and shale near base and middle.

157.3-160. Dol. and calc. dol., v. lt. brn. gr., vf-m xlln, faintly laminated throughout, laminae spaced 1-15 mm; some laminae microporous with m xlln calcite; slightly petroliferous; 158.1 calcite spar fill; arg. laminae become more abundant in top 0.7 ft.

160-164.1. Dol., calc. dol., dolomitic ls., and calc. sh., wavy arg. streaks throughout; 160-162 dol., v. lt. gr.-lt. brn. gr., xf-vf xlln, dense, arg., scattered lt. m. gr. irregular mottlings 1-15 mm, mottled to microbrecciated, irregular shaly streaks in lower half; 162-163.2 shale and shaly dol., calc., microbrecciated at base, clasts 1-5 mm, trace silt and vf sand; 163.2-164.1 fractured, brecciated, intraclastic, clasts 1-10 mm, irregular arg. mottlings, stylolitic.

164.1-164.3. Dol., v. lt. brn. gr., vf xlln, dense to slightly porous.

164.3-164.7. Dol. and calc. dol., lt. brn., laminated, arg. laminae spaced 0.4-10 mm, non-petroliferous.

164.7-165.8. Ls., dolomitic-dol., v. lt. brn. gr., xf-vf xlln, dense, microbrecciated to fractured or intraclastic throughout; irregular laminations, mottlings, microbreccia, wavy arg. streaks, and stylolitic streaks in top 0.4 ft.; lower 0.7 ft. with wavy laminae, laminae drape over irregular surface at 165.3; lower 0.3 ft. with some f-c xlln ls. mottlings.

165.8-166.9. Dol., v. lt. gr., xf-vf xlln grading upward in top 0.2 ft. to dol., v. lt. brn. gr., vf-f xlln; m. gr. mottlings and irregular m.-dk. gr. streaks, scattered quartz silt and vf sand throughout; wavy contact at top with 1/2 inch relief.

166.9-167.1. Sh., lt. m. gr., calc., and dol., calc., v. arg.; trace of f quartz sand.

167.1-168.6. Ls., dolomitic and dol., calc., vf xlln, dense, some f-m xlln ls. mottlings, calcite void fills; some m. gr. arg. streaks and partings; 167.1-167.4 ls., pale gr.-lt. brn. gr., dense, arg. and stylolitic streaks, irregular wavy laminations (4 mm spacing), pale laminae fractured; 167.4-167.6 dol., calc., pale gr., xf xlln, trace of arg. intraclasts 1-5 mm; 167.6-167.9 contains fractured arg. intraclasts (1-50 mm) in v. sandy calc. matrix (silt to m sand, rounded to subrounded quartz grains).

168.6-170. Dol., v. lt. gr., arg., xf xlln; scattered to abundant breccia clasts, clasts angular to subrounded (1-20 mm), dol. clasts, pale org. gr., dense, part fractured and filled with arg. matrix material; 168.6-168.9 ls., dolomitic, v. lt. brn. gr., dense, with some ls. intraclasts, rounded, pale gr., calcite-filled fractures cut through matrix and clasts, arg. streaks and some m xlln ls. mottling; 169 dense, non-brecciated dol. with stylolites.

170-177.4. Dol., lt. brn. gr.-lt. brn., vf-f xlln, faintly to prominently laminated throughout, dense with some microporous laminae, thin arg.

streaks separate laminae, laminae spaced 1-10 mm, petroliferous (very similar to Spring Grove lithologies).

177.4-179.4. Dol., lt. brn. gr., vf-f xlln, part porous to vuggy, scattered stylolites, possibly contains indet. small fossil molds.

179.4-180. Dol., lt. brn. gr., vf-f xlln, dense, faintly laminated throughout, some microporous laminae, some arg. laminae and stylolites, laminae spaced 1-10 mm, petroliferous.

LOWER UNIT B

180-194.2. Dol., lt. brn. gr., vf-f xlln, some m xlln dol. and calcite spar void lining, massive, abundant vuggy and fossil-moldic porosity, vugs to 4 cm; 180 slightly arg., stylolitc mottled, fractured; 180.6, 180.9, 181.2, 181.8, 182.2, 184.4 stylolites and stylolitic mottlings; 180.6, 181.8, 182.7 crinoid debris molds; 182.7 arg. and microspar mottlings; 183, 183.3, 184.1 indet. brachiopods; 184.5-185.6 dense dol., fewer vugs; 185.7 stylolite, crinoid debris molds; 186.1 brachiopod, crinoid debris molds; 186.4 brachiopods, microporous mottlings; 186.5 brachiopods; 186.9 crinoid debris, stylolite; 187.3, 187.7 stylolites, crinoid debris, brachiopod; 188 moldic and dolomitized crinoid debris, *Atrypa*, stylolite; 188.3 stylolite, dogtooth spar; 188.6 crinoid debris molds, stylolite; 188.7 crinoid debris, brachiopod, dogtooth spar, stylolite, 189 brachiopod; 189.3 stylolite, vug with trace spar; 189.5 large *Schizophoria*; 189.7 arg. mottlings, crinoid debris; 189.9-190.5 small crinoid-moldic with microporous mottlings, stylolites near top; 190.5-191 small crinoid debris molds, brecciated to mottled fabric in matrix of lt. m. brn. gr. arg. dol.; 191.1 microporous f-m xlln dolomitic mottling (to 5 cm) in coarser matrix, rounded intraclasts (dense) scattered to 15 mm diameter; 191.3 crinoid debris, brachiopod; 191.7 crinoid debris, brachiopods, *Atrypa*; 192 dogtooth spar; 192.1 nice *Atrypa*; 192.4 stylolite; 192.6 crinoid debris, brachiopod, dogtooth spar; 193.2, 193.3 crinoid debris, *Atrypa*; 194.1 crinoid debris, brachiopods.

UPPER UNIT A

194.2-195. Dol., calc., v. lt. brn. gr.-lt. gr., xf-m xlln, slightly arg., some m. gr. arg. mottles, calcite dogtooth spar void lining; top 0.1 ft., dol., lt. m. gr., laminated and swirled mottling (resembles caliche); 194.3-194.6 ls., dolomitic, breccia, xf-f xlln, lt. brn. dol. clasts (1-50 mm), non-laminated calc. dol. bed capped by thin arg. dol. noted; 194.6-194.65 shaly bed, m. lt. gr., abundant m xlln dol. rhombs, some quartz sand; 194.85-195 ls. and dol. microbreccia, clasts 1-10 mm.

195-197.2. Ls. and calc. dol.; 195-196.5 ls., v. lt.-lt. brn., sublithographic, some birdseye zones, calcite void fill, arg. streaks at top and bottom, stylolites top 0.5 ft., mottled with m. gr. f-m xlln ls. in top 0.2 ft.; 196.5-197.2 dol., calc., and ls., lt. brn. gr., xf-f xlln, becomes sublithographic at top, faintly laminated near top, some calcite fracture fill.

197.2-199. Dol., calc., below, grades up to ls., dolomitic, lt. brn. gr.-v. lt. gr., f-m xlln, some arg. streaks in lower part; faintly laminated top 0.3 ft.; 198.2-198.5 mottled zone, may be horizontally burrow mottled (burrows 2-3 mm x 5-20 mm); gradational below.

199-208 (c). Dol., part calc., becomes more calc. upward, lt. brn.-v. lt. brn. gr., vf-m xlln, dense to microporous; 199-204 slightly arg. with some arg. laminae, weakly petroliferous; 204-208 scattered vugs, part calcite filled; 206.3, 208 dk. gr. to black carbonaceous or coaly beds.

208-219.3 (c). Dol,. lt. gr., xf xlln, arg.-v. arg., dense, hard, generally featureless, scattered quartz silt grains; 208-208.6 calc. dol. and dolomitic ls., lt. brn. gr., with calcite fracture fill; 206.8 calcite void fill; 208.8, 209.7, 213, 213.1, 215.7 shale partings, lt. org. gr., silty, 2-5 mm thick.

LOWER UNIT A

219.3-222.1. Dol., v. lt. gr.-v. lt. brn. gr., dense, vf xlln, slightly arg., some arg. streaks in upper 0.5 ft., slightly porous to slightly fossil-moldic; 220.4 indet. brachiopod; 220.9 crinoid debris molds; 221 pyrite-lined vug; 221.4 indet. brachiopod, crinoid debris.

222.1-225.7. Dol., v. lt. brn. gr., vf-f xlln, microporous and fossil-moldic throughout; slightly arg. with scattered arg. streaks; crinoid debris molds throughout; 224.2 chalcedony filled vug; 225 indet. brachiopods; 225.2 favositid coral molds (15 x 50 mm), *Atrypa* and other brachiopods, branching bryozoans, chalcedony spherules along some fossil molds; 225.6 indet. brachiopods, 1 cm silicified tabulate coral.

225.7-234. Dol., v. lt. gr.-v. lt. brn. gr., vf xlln, dense, slightly arg., scattered discontinuous m. gr. arg. streaks throughout every 1-50 mm, becomes arg. laminated at 225.7-229.7 and 230.5; 225.7-227.1 scattered horizontal burrows; 225.9 shaly partings (4 mm); 226-226.15 dol., lt. brn. gr., microporous with common crinoid debris molds (1-10 mm).

234-247. Dol., v. lt. gr.-v. lt. brn. gr., vf xlln, dense, a few small vugs (1-15 mm), slightly arg., generally featureless to massive; top 6 ft. with scattered discontinuous thin m. gr. shaly streaks; 237 thin hard m. gr. shaly parting; 237.4 dol. intraclast or void filling (2 cm); gradational contact above.

247-257.3. Dol., v. lt. gr.-v. lt. brn. gr., vf xlln, dense to slightly porous, slightly arg.; sparsely fossiliferous throughout; scattered to common horizontal and subhorizontal burrows (1 mm diam. x 5-10 mm long), especially 248-251, 253, 256.7-257.3; 248-251 larger burrows to 10 mm diam. x 50 mm long; 251 vertical burrow (5 x 15 mm); 247.3 slickenside; 251.6 crinoid debris, bryozoan, trilobite free check; 254.5 bryozoan; 254.7 two spiriferids, small strophomenid, bryozoan; 255.2 branching bryozoans.

257.3-274.8. Dol., lt. gr., vf xlln, dense, slightly arg.; lower 1 ft. with small brachiopods, fenestellid and branching bryozoans; largely unfossiliferous above; 273.8 v. large spiriferid; 267 subhorizontal burrows to 2 cm.

274.8-279.3. Dol., v. lt. brn. gr., slightly porous with some vugs, very fossiliferous; partially silicified brachiopods (*Atrypa*) abundant; orthid, spiriferid, strophomenid brachiopods noted; small crinoid debris molds; branching and fenestellid bryozoans; cup coral noted; slightly arg. top 0.7 ft.; 275.5 hardground with 1 cm relief, hardground with small borings.

279.3-279.6. Dol., lt. brn. gr.-m. gr., arg.-v. arg., intraclastic, clasts 1-15 mm.

279.6-285.3. Dol., v. lt. brn. gr., vf xlln, dense to slightly porous, slightly arg. with scattered arg. streaks in lower 2 ft.; very fossiliferous in top 4 ft., abundant brachiopods (partially silicified), some small crinoid debris molds, *Atrypa* and other brachiopods; 281.2 trilobite pygidium.

285.3-285.5. Dol., m. dk. gr., dense, vf xlln, dense, arg.

WAPSIPINICON FORMATION (?)

285.5-286.7. Dol., v. lt. gr., xf xlln, slightly arg., swirled to brecciated texture, v. dense; 0.1 ft. relief on upper surface, fractured, irregular.

286.7-290. Dol., calc., v. lt.-lt. gr., xf-f xlln, arg., dense; becomes increasingly arg. in upper 1.0 ft. (including lt. m. gr. sh.); intraclastic near middle, clasts 5-10 mm; some calcite void fill; sandy to v. sandy; 287 pronounced irregular surface with 0.1 ft. relief, overlain by m. gr. calc. shales.

290-291.6. Dol. and calc. dol., v. lt.-lt. gr., dense, xf-vf xlln, slightly arg., part silty to sandy; calcite void fill in lower 0.2 ft.; 1 cm relief at upper contact.

291.6-294. Dol., lt.-lt. m. gr., arg. to v. arg., dense to slightly porous; brecciated or intraclastic, clasts angular to rounded (1-10 mm); includes unbrecciated arg. dol.; part with arg. streaks.

294-295.5. Dol., v. lt. gr., arg.-v.arg., part silty to sandy, wispy arg. streaks in lower portion, slightly brecciated to burrowed (?) at base.

295.5-297.7. Dol., calc., lt. brn., wispy arg. streaks or laminations prominent, dense; 295.5-296.1 dol., calc., v. lt.-m. gr., arg., some stylolites, brecciated at base and top, part arg. laminated, becomes shaly upward; 0.5 ft. zone near middle, ls., dolomitic or dol., calc., v. lt. brn. gr., dense, vf xlln, slightly arg., small intraclasts (?).

297.7-298. Dol., lt.-m. gr., xf xlln, thinly-bedded at base; above dol., lt. gr.-org. gr., part arg., with breccia clasts (1-20 mm), matrix partly sandy.

298-300.7. Dol., pale-v. lt. gr., vf xlln, silty, part v. silty-sandy, arg.-v. arg., disseminated pyrite in basal 0.4 ft.; lithology extends into fractured Maquoketa dol. up to 0.4 ft.

MAQUOKETA FORMATION

300.7-311 (core continues below). Dol., lt. gr., vf-m xlln, microporous to vuggy, small echinoderm debris, partially silicified brachiopods (orthids?) noted; small branching bryozoans; some pyrite void fill; 307 silicified cup coral; becomes cherty (chalky chert) at 311.